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Investigation on the influence of linearity and bandwidth on vehicle handling

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Investigation on the Influence of Linearity and Bandwidth on Vehicle Handling

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Declaration

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Abstract

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Vehicle Handling is a subject which is much debated by Vehicle Dynamicists, with regards to driver preferences. Linearity and Bandwidth are 2 handling characteristics that define vehicle handling. Vehicle development is a complex and costly exercise, which often involves test drivers fine tuning the handling characteristics of a car. Vehicle handling development is costly and time consuming, especially when little or no mathematically testing and modelling is done. In modern vehicle development the mathematical modelling is a vital process in fine tuning handling as well as cutting costs. Linearity and Bandwidth are investigated to analyse the parameters that affect them, and why they are important for vehicle handling.

Bandwidth refers to the frequency at which the car can respond to the driver's instruction through the steering wheel. The importance of this is investigated by comparing the response of the human driver with the response of a car. Primary data is collected from volunteers, and compared with results from mathematical models constructed in Microsoft Excel. Linearity is investigated by stressing a tyre in an instron machine, and varying the internal tyre pressure to observe the effects.

The results show a significant difference in response frequencies between the human driver and the car itself. The instron testing did provide results demonstrating the important effect tyre pressure has on a car wheel's vertical stiffness, which is a factor for cornering ability.

Keywords: Vehicle Handling, Linearity, Bandwidth, Response Frequency, Mathematical modelling, Tyre

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I would like to take this opportunity to thank the following individuals for their contribution to the work involved with this investigation. The idea was first suggested by Damian Harty who helped construct the original investigation. Dr David Trepess became my Director of Studies, and guided the investigation to its completion ensuring that the project was on course. I would also like to thank Dr Gary Wood who provided much of the insight into the work involved with this investigation, as well as providing tutoring in vehicle dynamics. Further thanks are given to James Jarvis, who provided instruction into operating the instron machine, which was integral to the research undertaken in this investigation.

Alex Gilbert

Table of Contents

List of Figures

Nomenclature

Symbol	Description	Units
A	Acceleration	m/s^2
ARB	Anti-Roll Bar	
Ay	Lateral Acceleration	g
AyG	Lateral Acceleration Gain	
a	CG Location from Front Axle	
ax	Forward Acceleration	m/s^2
ay	Lateral Acceleration	m/s^2
a3	Change of Stiffness with Slip	N/deg
a4	Change of Progessivity of Stiffness/Load	1/kN
b	CG Location from Rear Axle	
bar	pressure	bar
CG	Centre of Gravity	
Cf	Coefficient of Friction	
Cr	Critical Damping Coefficient	
Cs	Suspension Damping Coefficient	
Cα	Cornering Stiffness	kg/radian
c	Coil	
D	Mean Diameter	m
DNK	Date Not Known	
D1	Distance from Chassis to Spring	m

D2	Distance from Chassis to Wheel	m
d	Wire Diameter	m
dB	deciBel	dB
deg	degrees	deg
ECU	Electronic Control Unit	
F	Force	N
F A-L	Anti-Lift	N
FL	Force from Left	N
FM	Front Roll Resistance Portion	
FR	Force from Right	N
FWT	Fractional Weight Transfer	N
F1, FD	Internal Reaction to Fr and FL	N
Fadhesive	Friction due to Adhesion	N
Fc	Centrifugal Force	N
Fdeformation	Friction due to Deformation	N
Ff	Friction Force	N
Fthrust	Forward Thrust	N
Ftotal	Total Friction	N
Fv	Vertical Force of Object	N
Fwear	Friction due to Wear	N
Fx	Longitudinal Force	N
Fy	Camber Thrust	N
Fz	Vertical Load	N

Fzc	Contribution due to Damping	N
Fzk	Contribution due to Stiffness	N
f	Maximum Shear	N/m^2
fn	Natural Frequency	rad/s
g	Acceleration due to Gravity	9.81 m/s^2
Hz	Frequency	Hz
h	height	m
h1	Hole 1	
h2	Hole 2	
h3	Hole 3	
IC	Instant Centre	
Izz	Moment of Inertia of Plane Area	Length^4
in	inches	in
KT	Total Spring Stiffness	N/m
Ks	Spring Stiffness	N/m
Kt	Tyre Spring Stiffness	N/m
Kw	Wheel Rate	N/m
Kz	Radial Tyre Stiffness	N/mm
K1	Stiffness of Spring 1	N/m
K2	Stiffness of Spring 2	N/m
kg	Kilograms	kg
kph	Kilometres per Hour	kph
LF	Left Front	

LR	Left Rear	
l	Wheelbase Length	m
lb	pounds	lb
l/R	Ackermann Angle	radians
Ms	Sprung Mass	kg
Mus	Unsprung Mass	kg
M1	Moment created by Inertial Force	Nm
m	mass	kg
m	metres	m
mm	millimetres	mm
mph	Miles per Hour	mph
m/s	metres per second	m/s
mt	Mass of Tyre	kg
N	Newtons	N
N	Number of Active Coils	
N	Yawing Moment	kg.m
pa	Pascal (pressure)	pa
psi	pounds per square inch (pressure)	psi
R	Path Radius	m
RC	Roll Centre	
RF	Right Front	
RM	Roll Rear Resistance Portion	
RR	Right Rear	

r	Radius of Wheel	mm
r	Yaw Rate	rad/s
r	Yawing Velocity	rad/s
rad	radians	rad
rad/s	radians per second	rad/s
r1	Distance from Bearing to h1	m
r2	Distance from Bearing to h2	m
r3	Distance from Bearing to h3	m
S	Spring Spacing	mm
SAE	Society of Autotmotive Engineers	
SMCG	Sprung Mass Centre of Gravity	
s	seconds	s
svsa	side view swing arm	
T	track length	m
TM	Total Roll Resistance	
t	Torsion Bar	
t	track length	m
u	Longitudinal Velocity	m/s
V, v	Vehicle Speed	m/s
Vz	Rate of Tyre Penetration	mm/kg
v	Lateral Velocity	m/s
vx	Longitudinal Velocity	m/s
vy	Lateral Velocity	m/s

W	Load or Weight	kg or N
wb	Wheelbase Length	m
Wbrake	Weight Transfer due to Braking	N
X	Deflection	m or mm
YRG	Yaw Rate Gain	
Z	Point of Tyre	
α	Slip Angle	radians
β	Cvehicle Slip Angle at CG	radians
γ	Camber Angle	radians
Δ	Steer Angle Front Wheels	radians
δ	Toe Angle	radians
δz	Tyre Penetration	mm
ζ	Radial Damping Ratio	
θ	angle	radians
λ	Determinant	
Φ	Castor Angle	radians
ω	Rotational Speed of Wheel	rad/s
1/R	Path Curvature	1/m

1.0 Investigation of Vehicle Handling with Linearity and Bandwidth

Vehicle handling is a subject in vehicle dynamics which is much debated. There are differences of opinion to driver preferences, which centre on steering wheel inputs. Linearity and Bandwidth are the 2 important factors that influence a driver's perception of vehicle handling. Vehicle handling is a subject which is subjective, but linearity and bandwidth can be assessed objectively. This investigation is important for the study of these factors, and how to assess their effect on vehicle handling.

The investigation will be limited to quantitative data, objective research and so will be using mathematical models to evaluate vehicle handling and tyre performance. Primary data will also be collected from volunteers for a response test for the investigation into bandwidth. This study is limited to these investigations, whilst a vehicle test is not completed.

Past studies include an investigation called "Vehicle Handling Assessment Using a Combined Subjective-Objective Approach" in 1998 by D. A. Crolla, D. C. Chen, J. P. Whitehead and C. J. Alsted. As the title suggests it is a study into vehicle handling, which tests car handling by varying parameters on the car and asking test drivers to give their opinions to the result.

The aim is to provide an insight into vehicle handling by investigating linearity and bandwidth. The main objectives include:

- To research information concerning vehicle handling and contain this in a literary review.
- To examine Linearity in Vehicle Handling.
- To examine the difference in Bandwidth between Vehicle Handling and the Driver's input.
- To examine vehicle parameters that can affect Linearity and Bandwidth.
- To perform an experiment that tests Tyre performance under load conditions.

The project begins with a project brief, Chapter 1.0 which outlines the aims of the investigation. The literary review, Chapter 2.0, involves chapters on Tyres, Vehicle Models, Existing Research and Vehicle Handling. To keep the review concise, there is more included in the appendices on these subjects, as well as chapters on Vehicle Dynamics and Grip and Balance.

The research of this investigation begins at chapter 3.0. Chapter 3.0 is Research Methodologies, and describes the methods used in the following investigation. The research is conducted in the following 2 chapters.

Chapter 4.0 is an investigation into the response frequency of a human being. This is required to judge the frequency response difference between a car and its driver.

Chapter 5.0 contains 3 mathematical models in Microsoft Excel, 1 of which investigates vehicle handling in a mathematical manner and with that provides a numerical value for the frequency response of the car, building from chapter 4.0. The other 2 models investigate parameters of the tyres that affect vehicle handling.

Chapter 5.0 also includes an experiment to load a tyre in compression and measure the displacement of that tyre. The test will be repeated for different internal tyre pressures, and the effects will be observed and assessed.

Chapter 6.0 is the conclusions of this study, and will assess the success and outcome of the investigation. Chapter 6.0 will also include recommendations for future development into this research subject.

An appendix includes chapters from the literary review and parts of the research that were concised for the main report. The appendix also includes the project plan when the investigation was taking shape, as the literary review was beginning. A list of references for information and images follows the appendices. Both the Appendix and References have title pages.

2.0 Literary Review

2.1 Tyres

2.1.1 How a Car turns into a Corner

When a car is in motion, it relies on the contact between the tyres and the road surface. The modern tyre is a complicated design with many layers and aspects to its construction. However, it can be summarised as being a strong and durable material, which needs to grip the road surface and soft enough to provide damping for the car over rough road surfaces.

2.1.1.1 Sip Angle

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Figure 2.1.1.1 - Slip Angle, Bottom View

Haney, P. (2003) The Racing & High-Performance Tire. 1st edn. Warrendale, Pa: TV MOTORSPORTS and SAE. P20.

As a car turns a corner, it can be described that the path the vehicle takes is an arc of a circle. Even though the radius of this arc may change, at any instance the path is thought to be constant. To maintain the arc that the vehicle follows, the vehicle must accelerate towards the centre of the arc. The vehicle has mass, and so it requires a force to accelerate towards the centre of this arc. The cornering force which tyres generate can be called Lateral Force, Side Force, or even Grip. This information is taken from Haney, P (2003) p20 - 21, as in Figure 2.1.1.1 (left). When the four tyres combine the Lateral Forces combine which then act of the Centre of Gravity (CG) of the vehicle.

Tyres produce lateral force with a Slip Angle. A Slip Angle occurs when an input is made to the steering wheel, to change direction from straight ahead. The Slip Angle is the angle between where the car is travelling, and where the tyre is pointing. It is important to note, as Haney. P (2003) p21, that “*the term ‘slip angle’ is slightly misleading because at small slip angles there may be absolutely no slip or sliding in the contact patch.”*

It is important to note that the front tyres act differently to the rear. The front tyres develop a slip angle when there is a steering input. This generates lateral forces on the front tyres, and so the front of the car turns and the entire car rotates in the same direction. The rear tyres are fixed, and so have no steering input to develop a slip angle. The rear tyres resist by developing their own slip angles and hence lateral forces.

Further information about how the tyre's elasticity generates a slip angle is available in the Appendix Tyres (AT.1).

2.1.2 Tyre Behaviour

Tyres are components that change shape due to the elasticity of the material. Under stress the tyre can behave in different ways. Haney, P (2003) p91 states that "*Rubber friction, mainly due to adhesion and deformation, exhibits viscoelastic effects and is sensitive to compounding variations, vertical loading, sliding speed, and temperature.*"

2.1.2.1 Lateral Force vs. Slip Angle

Part of how a car turns into a corner can be described by the use of a Lateral Force vs. Slip Angle graph. The shape of the line on the graph is dependent on the tyre.

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Figure 2.1.2.1 - Lateral Force vs. Slip Angle graph

Haney, P. (2003) The Racing & High-Performance Tire. 1st edn. Warrendale, Pa: TV MOTORSPORTS and SAE. P94.

Figure 2.1.2.1 is a detailed diagram of the shape this graph may take. There are 3 distinct gradients of the graph. The first is the Elastic or Linear region, which occurs at small slip angles. An increase in Slip Angle will result in a proportional increase in Lateral Force. The tread of the tyre is not sliding on the road. This is the gradient on the graph where the tyre stiffness is calculated. A tyre with stiffer tread and sidewalls will result in a steeper gradient to this section of the graph.

The next gradient on the graph is called the Transitional region. This occurs with greater slip angles than the linear region, and the tyre is sliding on the road surface. An increase in slip angle results in less of an increase in lateral force.

The final gradient on the graph is the Frictional region, which occurs after the peak of the curve. Any increase in slip angle will reduce the resultant lateral force, so the contact patch is sliding, which will cause the tyre to heat and wear. These notes are from Haney, P (2003) p94-95.

2.1.2.2 Longitudinal Forces

During acceleration and braking the sidewall of the tyre deforms, so the contact patch moves. During acceleration and braking Longitudinal forces are generated, causing longitudinal slip between the tyre tread and the road surface. For fast acceleration, the wheels may slip (wheel slip), and so the tyre will rotate faster than if there were no slip for the car travelling at the same acceleration. The opposite is true for heavy braking, where the tyre rotates less than if there were no slip. Notes are from Haney, P (2003) p95-96.

2.1.2.3 Combined Forces

It is important for a tyre manufacturer to examine the behaviour of a tyre with both lateral and longitudinal slip. This is however difficult to research, because tyre manufacturers keep this information secretive. Therefore these graphs from Haney, P (2003) p97 display general values, but do illustrate the findings.

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Figure 2.1.2.3a - Combined Braking and Cornering

Haney, P. (2003) The Racing & High-Performance Tire. 1st edn. Warrendale, Pa: TV MOTORSPORTS and SAE. P97.

Figure 2.1.2.3b - Combined Driving and Cornering

Haney, P. (2003) The Racing & High-Performance Tire. 1st edn. Warrendale, Pa: TV MOTORSPORTS and SAE. P97.

The term for slip is defined by

$$slip = \frac{\omega r - v}{v} \quad [1]$$

ω is the rotational speed of the wheel

r is the radius of the wheel

v is the speed at which the vehicle is travelling

Haney, P (2003) p96-97 describes that the graphs show how the “*lateral force falls off rapidly with any additional slip due to acceleration or braking.*”

2.1.2.4 Friction Circle

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Figure 2.1.2.4a - Friction Circle

Haney, P. (2003) The Racing & High-Performance Tire. 1st edn. Warrendale, Pa: TV MOTORSPORTS and SAE. P97.

A Friction Circle is a useful model to illustrate how lateral force reduces with the addition of driving or braking force. The graph shown is only a semi-circle, but a full circle shows lateral forces for both a left and right hand turn.

The 3 arrows show the forces of driving, braking, and lateral, when those are the only forces that are present. When there is a combination of forces, maximum lateral force is not available. The example has shown that adding driving power to the tyre reduces the tyres lateral force. This is what happens when powering out of a slow corner.

The Figure 2.1.2.4b shows an actual Friction Circle of a race car as it travels around a race track. One obvious vehicle performance characteristic of this graph is that it shows the race vehicle stops better than it accelerates. This is a characteristic shared by most vehicles.

The peak lateral forces have little to no longitudinal force. A combination of longitudinal and lateral force produces a dot on the graph with a limited lateral value.

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Figure 2.1.2.4b - Friction Circle Data Collection

Trackpedia (2010) Data Collection and Analysis [online] available from <http://www.trackpedia.com/wiki/Data_Collection_and_Analysis> [26 February 2013]

2.1.2.5 Benefits of Wider Tyres

If there are 2 tyres, one is narrow, one is wide. For the same internal pressures and vertical load both the contact patches will be the same area. However, the wider tyre's contact patch will be shorter and wider. Wider tyres provide a benefit to lateral deformation, because lateral tread deformation builds up along the length of the contact patch.

The contact patch of the wider tyre with the same slip angle will begin to slip at approximately the same distance from the leading edge as with the narrower tyre which has a longer contact patch. However, a wider and shorter contact patch will have more of its length stuck to the road, and so it has a larger proportion of its overall area is gripping the road surface than with a narrower and longer contact patched tyre. For the same load and slip angle, a wider tyre will generate more grip than a narrower tyre. Haney, P (2003) p101-102 presents some illustrating data about this. It examines various tread widths of tyres. The assumptions of these results are that slip starts 1.5 inches (3.8mm) into the contact patch, the load on the tyre is 500lb (226.8kg) and the pressure of the tyre is 20psi (1.38bar).

Tread Width (in)/(mm)	6 / 152.4	8 / 203.2	10 / 254	12 / 304.8
CP Length (in)/(mm)	4.17 / 105.9	3.13 / 79.5	2.50 / 63.5	2.08 / 52.8
CP Area Gripping (%)	36	48	60	72

Further information is available in the Appendix Tyres (AT.4).

2.1.3 Balance and Control

Figure 2.1.3 displays a car that is steering through a corner, the car is maintaining a circular path. A slip angle is generated by the front tyres, so the chassis turns. This in turn causes the rear tyres to also generate a slip angle. The car is not spinning around, meaning that the forces acting on the car are in equilibrium, the car is balanced. The forces that equal are as follows:

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Figure 2.1.3 - Car on a Circular Path

Haney, P. (2003) The Racing & High-Performance Tire. 1st edn. Warrendale, Pa: TV MOTORSPORTS and SAE. P117.

(Torque or Moment created by force of front tyres) x (front tyres distance ahead of CG) = (Torque or Moment created by force of rear tyres) x (rear tyres distance behind CG)

The front and rear tyre forces can be combined at the Centre of Gravity (CG), this is called the lateral force. The front and rear tyres may not have the same slip angles and yet they continue to balance. Balance is determined by the relationship between the front and rear slip angles. Notes are from Haney, P (2003) p117.

2.1.3.1 Oversteer and Understeer

Oversteer and Understeer are often confused terms as different people refer to them meaning different things. To begin with oversteer and understeer are defined by the relationship between the front and rear tyres and the relationship of each tyre between Yaw Rate Gain (YRG) and Lateral Acceleration Gain (AyG).

To best use a definitive definition of Oversteer and Understeer it is wise to turn to Blundell, M and Harty, D (2004) p408-414.

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Figure 2.1.3.1 - Departures from Linearity Possibilities

Blundell, M and Harty, D. (2004) The Multibody Systems Approach to Vehicle Dynamics. 1st edn. Oxford: Butterworth-Heinemann. P413.

Figure 2.1.3.1 image (b) displays when YRG reduces proportional to AyG this is neutral, meaning that the car is able to hold a tight line as instructed by driver. There will be reduced stability and control at the limit of adhesion. The driver will have the response of steering more, and reducing the vehicle speed. It can be satisfying for more able drivers, but unsafe for some as a progressive departure from the intended course may be unnoticed by drivers who are not fully paying attention until control is fully lost, and the car poorly rejects disturbances from the road.

Figure 2.1.3.1 image (a) displays when YRG reduces more than AyG this is a Push departure, meaning the car takes a new and wider line from the line instructed by the driver. There is reduced control at limit of adhesion, but increased stability. When this occurs the driver response is to steer more and reduce speed. This is considered safe, as the front of the car hits the obstacle, which means the front crash structure encounters it. This is subjectively called understeer. Understeer can also be defined when the front tyres achieve a higher slip angle than the rear tyres.

Figure 2.1.3.1 image (c) displays when YRG reduces less than AyG, so the car keeps rotating this is called loose departure, meaning the car’s line is wider than the neutral line. A loose departure car has negative stability, so there is increased control at the limit of adhesion, and the driver response is to reduce speed and steer less. It is unsafe for most drivers as the car is rotating, however it is considered to be fun. This is subjectively called oversteer, even though the car is objectively understeering from the neutral line. Oversteer can also be defined when the rear tyres achieve a higher slip angle than the front tyres.

Further information is available in the Appendix Tyres (AT.5).

2.2 Vehicle Models

Term	Symbol	Units	Sign
CG location	a, b	m	Always +
wheelbase	l	m	Always +
Mass of vehicle	m	kg	Always +
Yawing Moment	N	kg.m	+ for clockwise
Lateral Force	F_F, F_R, Y_F, Y_R	kg	+ to right
Lateral Acceleration	a_y	m/s^2	+ for RH turn
Lateral Acceleration	A_Y	g	+ for RH turn
Path Radius	R	m	+ for RH turn
Path Curvature	1/R	1/m	+ for RH turn
Vehicle Velocity	V	m/s	+ for forward
Yawing Velocity	r, r_a, r_b	Radian/sec	+ for clockwise
Lateral Velocity	v, v_F, v_R	m/s	+ to right
Longitudinal Velocity	U	m/s	+ for forward
Steer Angle Front Wheels	Δ	Radian	+ for clockwise
Slip Angles	α_F, α_R	radian	+ for slip to right
Vehicle Slip angle at CG	β	radian	+ for slip to right
Cornering Stiffnesses	C_F, C_R	kg/radian	Always -
Ackermann Angle	l/R	radians	+ for RH turn

2.2.1 Bicycle Model

The Bicycle model is a simple model. It doesn't account for lateral or longitudinal load transfer. It can investigate the effects of varying cornering stiffness for front and rear tyres, location of the Centre of Gravity (CG), wheel base dimensions and geometric steer angle (at the steering wheel) on the path and attitude of the vehicle which is determined by Yawing and Sideslipping motions.

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Figure 2.2.1 - Bicycle Model (2 degrees of freedom)

Milliken, W. and Milliken, D. (1995) Race Car Vehicle Dynamics. 1st edn. Warrendale, Pa: TV MOTORSPORTS and SAE. P127.

Figure 2.2.1 displays the basic variables on the Bicycle Model, and how the Vehicle Slip angle at the CG (β) is calculated.

Milliken, W. and Milliken, D (1995) p127 explain the basic events of a car turning. "*When an automobile makes a turn it normally goes through 3 phases. The first is the turn entry, for example from a straight. In this phase the yawing velocity and the lateral velocity (relative to the vehicle y-axis) build up from zero in straight running to their values in the steady turn. This is called the transient turn-entry phase where r and v are changing with time. The second phase is steady-state cornering phase where r and v and the vehicle and tyre slip angles are constant and the vehicle is moving along an unvarying path radius, R (or path curvature defined as 1/R). The final phase is turn exit where the yawing and lateral velocities are changing with time as they return to zero for straight running, transient turn-exit.*"

2.2.2 Ackermann Steering Angle

l/R is used for a small angle approximation for the required steering angle (δ in radians). As the wheelbase l is increased the steering angle increases proportionally when the radius R is constant.

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Figure 2.2.2 - Ackermann Steering Angle (wheelbase angle)

Milliken, W. and Milliken, D. (1995) Race Car Vehicle Dynamics. 1st edn. Warrendale, Pa: TV MOTORSPORTS and SAE. P128.

The wheelbase angle or Ackermann Steering Angle is the geometric steer angle required of a car with wheelbase l, whilst turning radius R. This is a model for low speeds where external forces due to accelerations are neglible. The Ackermann Angle is related to basic yaw damping of the vehicle, which is important for vehicle handling.

2.2.3 Yaw Damping

Milliken, W and Milliken, D (1995) p202-204 explain the importance of yaw damping with the use of more models. "*The yaw damping produces the largest stabilizing moment on the vehicle in a steady turn or disturbance. It also accounts for the decrease experienced in directional stability as the speed is increased.*"

Figure 2.2.3a - Yaw Moment due to Ackermann Steer Angle

Milliken, W. and Milliken, D. (1995) Race Car Vehicle Dynamics. 1st edn. Warrendale, Pa: TV MOTORSPORTS and SAE. P203.

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Figure 2.2.3b - Yaw Damping and Path Curvature Stiffness

Milliken, W. and Milliken, D. (1995) Race Car Vehicle Dynamics. 1st edn. Warrendale, Pa: TV MOTORSPORTS and SAE. P203.

The vehicle has constant V and A_Y whilst in a steady turn.

$$r = \frac{V}{R} = A_Y(\frac{g}{V}) \quad \text{[2]}$$

r is in radians/second.

Lateral velocities are produced by the yawing velocity at the front and rear wheels (+ra and –rb). Vector addition of the lateral velocities and forward velocity, V equates induced slip angles at the front and rear displayed as α_F and α_R. Lateral forces at the wheels are created shown as $-Y_F$ and $+Y_R$. These produce a negative yawing moment, N.

$$-N = Y_F a + Y_R b = C_F \propto_F a + C_R \propto_R b \quad \text{[3]}$$

$$-N = \frac{C_F r a^2}{V} + \frac{C_R r b^2}{V} = \frac{r}{V}\,(C_F a^2 + C_R b^2) \quad \text{[4]}$$

$$N = \left(\frac{\Delta N}{\Delta r}\right) r = \frac{-r\,(C_F a^2 + C_R b^2)}{V} \quad \text{[5]}$$

Milliken, W and Milliken, D (1995) describe the effect of these equations. "*This moment tends to decrease any yawing velocity, r. It is analogous to a rotational dashpot (damper). It increases with* a^2 *and* b^2 *and with the cornering stiffnesses,* C_F *and* C_R*. Also it decreases with forward velocity, V. In line with aircraft practice it is called yaw damping and defined as ΔN/Δr, the rate of change of moment with yawing velocity. In steady-state, it is equivalent to the path curvature stiffness.*"

2.3 Existing Research into Vehicle Handling

A paper published by SAE titled "Vehicle Handling Assessment Using a Combined Subjective-Objective Approach" by D. A. Crolla, D. C. Chen, J. P. Whitehead and C. J. Alsted in 1998 is a study to determine the preferences of test drivers. The abstract states that "*one of the long-running themes throughout vehicle dynamics research has been a desire for a better understanding of the correlation between subjective and objective measures of vehicle handling.*"

2 test cars were driven by 8 test drivers with differing vehicle parameters affecting handling. The drivers assessed manoeuvres on ratings from 1-3 (better), 4 (same), 5-7 (worse). Don't know was an option, so drivers didn't give results they didn't understand, which could influence the results.

49 manoeuvres were tested and each had separate ratings from each driver. The manoeuvres tested cornering, accelerating, braking, all of which had different tests for differing speeds. From here the results were analysed with statistical mathematics. Mean values were plotted for each manoeuvre with 95% confidence intervals showing how much the test drivers agreed with one another.

The conclusions of this study include a paragraph stating "*overall, this work has contributed to the subjective-objective correlation debate in several significant areas. However, there is still some way to go before unequivocal links between subjective ratings and objective metrics exist over a wide range of handling.*"

2.4 Vehicle Handling

Vehicle Handling is a much debated engineering subject (Blundell 1999) "*For a modern commercial road vehicle the handling and road holding are aspects of vehicle performance that not only contribute to the customers' perception of the vehicle quality but are also significant in terms of road transport safety. There is often confusion over the use of terminology when referring to vehicle handling. The road holding or stability of a vehicle can be considered to be the performance for extreme manoeuvres such as cornering at speed, for which measured outputs such as the lateral acceleration, roll angle and yaw rate can be used to indicate performance. The handling quality of a vehicle is thought to be more subtle and to indicate the feeling and confidence the driver has in the vehicle owing to its responsiveness and feedback through the steering system.*"

2.4.1 Linearity

Linearity is the relationship between steering input and lateral force (how much the car turns). It refers to the Lateral Force vs. Slip Angle graph, shown in Figure 2.4.1.

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Figure 2.4.1 - Lateral Force vs. Slip Angle graph

Haney, P. (2003) The Racing & High-Performance Tire. 1st edn. Warrendale, Pa: TV MOTORSPORTS and SAE. P94.

There are 3 areas displayed on this graph, the first being the Linear region. This shows a linear relationship between steering input and the rate at which the car turns. Some vehicle dynamicists prefer a larger linear region as this is suited to high performance vehicles.

Other dynamicists prefer a progressive linear region. The impact of this reduces the influence of the transitional region. Linear handling has is a limit to the linearity, where tyres start losing lateral force for increasing steering input. This can shock less experienced drivers, and so considered unsafe. A progressive gradient is considered safer as the shock of reaching the transitional region is less.

2.4.2 Bandwidth

Cars have a natural frequency in yaw, the limit to how fast they can turn. Bandwidth is a general term defining the maximum frequency the car can handle. The Bandwidth limit is also referred to as -3dB, approximately 70%.

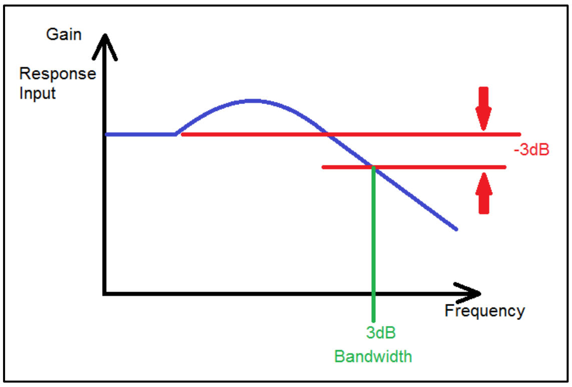

Figure 2.4.2 - Resonant Frequency (Bandwidth Limit)

Figure 2.4.2 shows the relationship between the Gain or response input relative to the frequency. It shows the resonant frequency of the car and how the bandwidth is taken from this.

The importance of Bandwidth is evident on motorsport and high performance vehicles. When a car turns, it turns in yaw, and the Bandwidth Limit is the limit to how fast the car can turn in yaw.

A car can't steer at more than 0.5Hz typically. A person driving the car can make a steering input much quicker than just 0.5Hz. Inexperienced drivers expect the car to react instantly to their instruction, which is a problem. The driver can get confused when the car reacts slowly. This is a problem in emergency manoeuvres such as an elk test. In motorsport a vehicle with higher bandwidth will react to the driver faster, which gives that driver and car an advantage.

2.4.3 Factors that can affect Vehicle Handling

Linearity is a factor that is based on tyres and how they grip the road surface. It is difficult to model linearity without conducting extensive tyre testing for various slip angles. It is also affected by speed.

Bandwidth is gained by having low mass and wider tyres. Lower mass requires less force to turn it, and wider tyres provide a larger contact area for the tyres to grip the road surface. Linearity and bandwidth can be affected simply by adjusting tyre pressures. The pressure provides the stiffness of the tyre, and so can greatly affect the road holding capability.

2.4.4 Handling Preferences

CarandDriver.com (2013) lists the preferences that automotive manufacturers take when design the handling for their cars. The website describes a conversation with Matt Becker, Vehicle Attributes Manager at Lotus. He says that "*A good-handling car responds in a linear way to deliver the amount* *of directional change that the driver is asking for, while providing all the information that the driver requires about the level of grip the car is delivering.*

"*The moment the tire starts to lose traction, the grip shouldn't suddenly fall off a cliff and give you a big surprise.*"

A similar conversation with Uli Phundmeier, M3 Chassis Engineer at BMW says that "*Good handling is a well-controlled body, good steering response, good steering feedback, and well-balanced integration—with all of the different systems tuned together so that none is sticking out.*"

2.5 Literary Review Conclusions

The behaviour of tyres is important for this investigation. There are a number of ways in which tyres can be investigated, some of which have been discussed in the literary review. It has been discussed that a wider tyre is beneficial for lateral deformation, and so a lateral tyre will grip the road surface better than a narrower tyre. A tyre will perform differently depending on applied slip angle relative to the lateral force it produces, therefore investigating the effect of internal tyre pressure is an important direction for this investigation.

Vehicle models are tools that help to describe performances. This investigation will use models. The models featured in this literary review are formed from mathematical equations. Whilst a model cannot be considered to be entirely accurate, the usefulness also must not be overestimated. Models help to develop systems, and assess performance characteristics, as will occur with this investigation.

Whilst many researchers have investigated vehicle handling, there have been many different approaches to the subject. It is clear that tyre inflation pressure has not been investigated solely for vehicle handling. This does provide challenges as vehicle handling and the effects of tyre inflation pressure will have been researched extensively, however much of the data regarding tyre performances is kept by the tyre manufacturers as it is their intellectual property.

Vehicle handling is a highly discussed and debated science. The literary review does clearly define the characteristics which are called Linearity and Bandwidth. Using descriptions from engineers in the field of handling preferences can be made for these characteristics. It is also clear that the tyres can affect both of these characteristics, which shows how important it is to investigate tyre pressure and its effects on vehicle handling.

3.0 Research Methodologies

To conduct this investigation a variety of research methods are used. There are 3 main research parts which involve collecting primary data and analysing that data. The following points describe the data collection methods, and how that data is then evaluated for the end results. The results will provide the insight to the final conclusions.

3.1 Research Methods

The first evaluation is an evaluation of response frequency, and how that of a car differs from a human. This test will gain data on human response frequencies. The response frequencies of a car will not be measured, but an approximate value will be assumed to compare to the human response. The human response frequency is a simple exercise of moving a hand-held device that can measure how quickly it is shaken. This data will then be calculated to frequencies and compared. A car's response frequency will be calculated in the second part of the evaluation.

The second part of the evaluation is a parametric mathematical model in excel, using basic vehicle values to produce a 2 degree-of-freedom model that can calculate the Natural Frequency and Damping Ratio of the vehicle for a range of vehicle speeds. This model will assess the vehicle handling, and so can provide insight to the importance of tyres on vehicle handling and performance, as well as a comparison for vehicle response frequency.

The third part of the evaluation is a Tyre Instron test, which tests the vertical force of a tyre, as the tyre pressure changes. This will gather primary data, which needs to be evaluated, to show how tyre pressures can affect how a car tyre performs differently with different internal pressure. The aim of this test is to calculate the spring stiffness of the tyre and relate it to tyre pressure.

3.2 Data Types

All of the data acquired and assessed will be quantitative. The first evaluation will assess human response frequency, and so will require volunteers to provide this information. This is an exercise in responses, and so it will not require the use of a survey, or any format requiring an opinion.

The second evaluation is based upon mathematical equations to predict vehicle handling characteristics. There is not any primary data involved, but will use estimated vehicle properties to produce a vehicle handling model. This is to show how certain parameters, namely tyres can affect handling characteristics.

The third evaluation will record primary data from an instron test, which will compress a tyre to evaluate the displacement of the tyre. This data will then use known equations to produce spring stiffness values.

3.3 Methods of Analysis

The first evaluation is a comparison that will compare the difference in response frequencies between a human and a car.

The second evaluation will demonstrate how certain vehicle parameters can affect vehicle performance. Mathematical models are constructed in excel, which utilise equations to graphically demonstrate vehicle performance.

The third evaluation will again use mathematical equations to analyse the acquired data from the instron testing. The force versus extension will be plotted graphically, and from that spring stiffness will be calculated to provide values for the vertical stiffness of the tyre. The vertical stiffness of the tyre will be related to tyre pressure to provide insight into how tyre pressure affect tyre stiffness, and so how tyre stiffness affects vehicle handling.

3.4 Potential Sources of Data

The first evaluation will acquire data from volunteers, who will take part in a test that involves moving a device as fast as possible to measure the response frequency. An average response frequency will be calculated, as a number of volunteers are required.

The second evaluation does not acquire its own primary data, but merely uses estimated vehicle parameters which when used in the mathematical model will provide insight into vehicle performance.

The third evaluation will acquire primary data from instron tyre testing. This involves stressing a car tyre on an instron machine, applying a force and recording the displacement of the tyre relative to the applied compressive force. This test will be using an instron machine that displays the extension and applied force.

4.0 Difference in Bandwidth Test

Bandwidth is a term used to describe frequency. The Bandwidth frequency is a -3dB of the maximum Response Input. A car has a bandwidth frequency, which refers to how fast it can respond to driver inputs. This is an important factor as a sport car will always need to respond quickly to driver inputs. The response is dependent upon the vehicle speed and slip angle. For an average car the faster it is travelling, the slower it will react, and a greater steer input will cause the tyres to slip more, whereas a smaller steering input will allow the car to react quicker.

The Bandwidth of a car is a property that can only be investigated by testing a car, however it can be predicted using mathematical models. It is known that the human driver can react more quickly than the car can react to that driver's inputs.

A good test for a car is the slalom test, which involves driving a vehicle in a slalom fashion between equally spaced cones. This is normally used to assess body roll, but can show the car's ability to change direction. The frequency at which this happens is decided by the speed at which the car is travelling, as the faster it travels, the less time the car has to turn in for the next cone.

4.1 Human Response

The driver of the vehicle has to see the road ahead, and interpret that into instructions to the steering wheel. These instructions are the result of the human body to work relatively quickly. The human driver will have a response frequency far greater than that of the car. An ongoing online survey conducted by HumanBenchmark.com (2012) that tests the reaction time of its volunteers states that the average reaction time is 0.215 seconds. The reaction time is far greater than that of the steering response of a car.

The driver has to input their response into the steering wheel. This can be affected by factors such as the radius of the wheel, and how "heavy" the steering feels. A larger wheel will mean the driver's hands have to move a greater distance, increasing the time for 1 input. A larger wheel does have the effect of creating more torque from the driver, which is useful for heavier vehicles such as vans and lorries. A sports car will typically have a relatively small wheel to reduce the time for 1 input, as well as reducing the torque from the driver. This will make the steering feel "heavier", which is a term used for steering which has more resistance to turn. Factors such as the steering feel as wheel size will affect the steering input frequency and its magnitude.

The Highway Code (2007) p42-43 publishes Typical Stopping Distances. This lists the stopping distances, and thinking distances for speeds up to 70mph. For the 70mph speed (112kph), the Highway Code lists a thinking distance of 21m. This means it takes the driver 21m to apply the brakes after seeing an emergency, which is covered in 0.675 seconds. Now this 675 milliseconds is drastically more than the 215 milliseconds stated by HumanBenchmark.com. However, the Highway Code does list this as a thinking time, whereas the HumanBenchmark.com performs an online survey where the participants are expecting the test, and can be prepared for it. The thinking distance is a general guide which depends on driver attention.

4.2 Problems due to Differences in Response Frequencies

A car will need a high steering response frequency if it is a high performance sports car or a race car. These vehicles will need to be agile and change direction quickly by inputs from the driver. A high response frequency is still useful for normal road cars. In an emergency situation such as an oversteer or understeer manoeuvre the driver will need to have control of the vehicle.

If a driver is presented with an elk test, this requires a quick response from both the driver and the car. An elk test involves driving a car at motorway speeds (70mph) in a straight line, when a large animal (an elk) is in the car's immediate path. The animal is too close to the car for the brakes to stop the car fully, and so an evasive manoeuvre is required.

4.3 Road Vehicle Response Frequency

In a personal interview Damian Harty, Senior Research Fellow in System and Vehicle Dynamics, stated that "*a car typically can't steer at more than 0.5Hz*" (Gilbert, A 2013). This is supported by a lecture delivered as part of module M26MAE Vehicle Dynamics, relating to Yaw Frequency a value of 0.5 is OK but not the quickest, above 1.0 is good (Wood, G 2013). 0.5Hz would suggest a reaction time of 2 seconds, whereas 1Hz would suggest just 1 second.

4.4 Human Response Frequency Test

This test is going to achieve primary research in measuring human response frequencies. It will be a simple test, which only requires a smooth surface and a smartphone app. For this the iPhone 5 will be using an app called Vibration developed by Diffraction Limited Design LLC. It uses the phone's internal accelerometer and gyroscope to evaluate the vibration and rotation the phone is experiencing.

This test will involve shaking the hand held device, the phone, as fast as possible. This will determine how quickly the volunteer can move the phone. It will record a change in direction, which will act like peaks and troughs of vibration amplitude. Calculating the response frequency of the volunteer is a simple matter of counting the number of complete oscillations, and dividing by the total time for the test. Due to the precision of the device, each oscillation will be measured to 0.25 oscillations.

Each volunteer will give willing consent, and informed of the importance of this test. They will also be made aware of the procedure and final results.

The results recorded by Vibration can be sent via email. This email include the data in an excel worksheet. It features the magnitude of a motion recorded against the time when it happened. This is useful as the magnitude can be plotted against time in a graph such as Figure 4.4a.

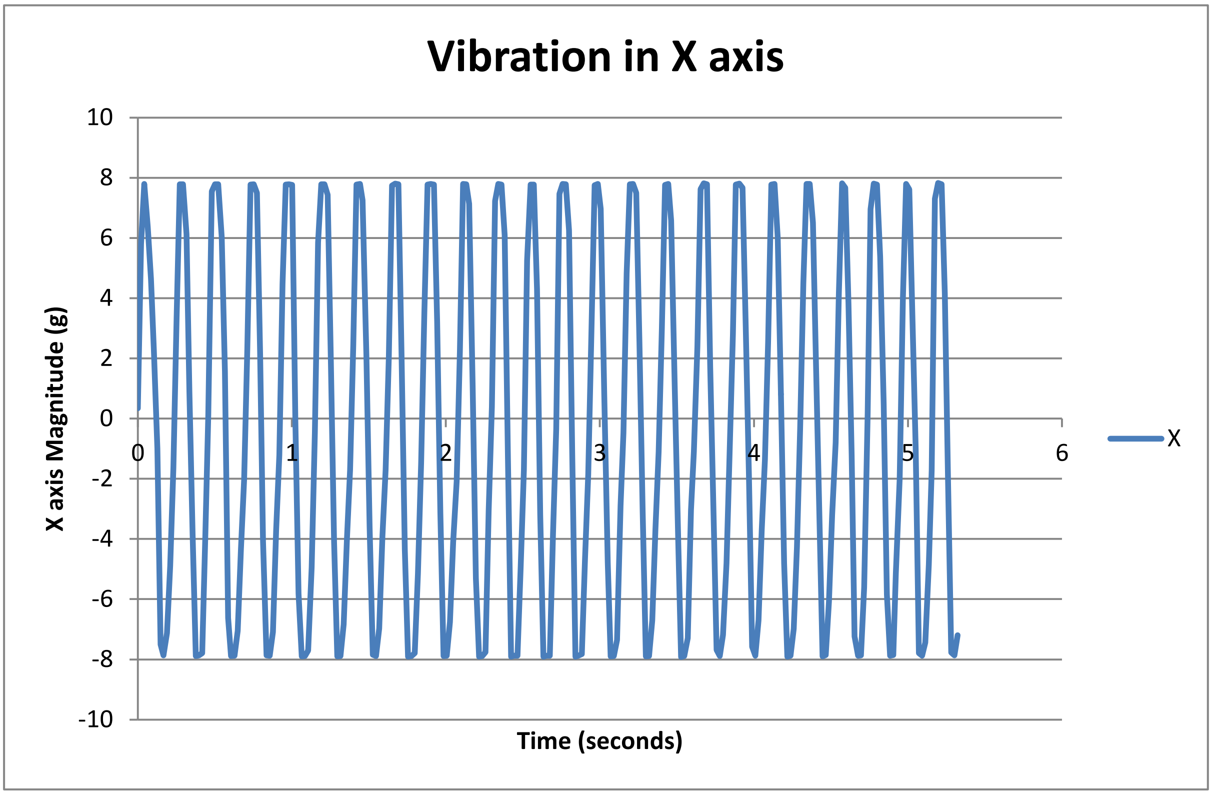

Figure 4.4a - Vibration of Phone

This graph displays the number of full oscillations, and the excel worksheet gives an exact time when the experiment stops, so the frequency can be measured from this. This example shows a total of 23.5 oscillations over 5.32 seconds. This gives a frequency response of 4.42Hz.

To ensure a level of standardisation across the testing the phone must complete full oscillations for the test to qualify. The surface the phone will move across is a workbook which is portable and will maintain a constant coefficient of friction for all the tests. The surface is marked with masking tape as shown in Figure 4.4b.

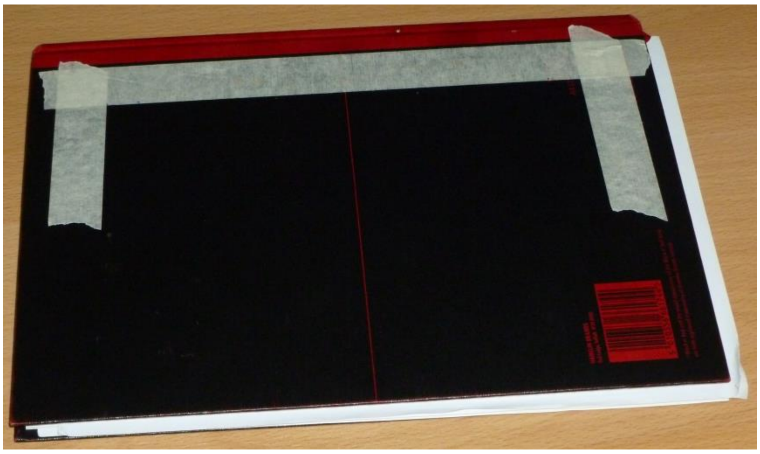

Figure 4.4b - Workbook marked with Masking Tape

The thin red line across the centre of the book is the centre of the masking tape. The phone has a width of 60mm. For a test to qualify the phone must move 200mm, which due to the width of the phone means the space between the 2 parallel lines is 260mm. The phone simply needs to cross the inner edge of the masking tape at either side for all oscillations as displayed in Figure 4.4c.

Figure 4.4c - Phone and Testing Parameters

For this test only people who are physically fit will participate, more specifically those who can drive. All participants are fully aware of the data being recorded. This test does not intend to harm or manipulate its participants.

4.4.1 Results

The results of the testing produces many excel graphs, which are located in Appendix Bandwidth. The frequency response of the participants is represented in the following Table 4.4.1.

Table 4.4.1 - Human Frequency Response Test Data

	No. of Oscillations	Time (seconds)	Frequency Response
Test Person 1	29.75	5.3369	5.57Hz
Test Person 2	25.00	5.3358	4.69Hz
Test Person 3	24.75	5.3322	4.64Hz
Test Person 4	26.00	5.3474	4.86Hz
Test Person 5	26.75	5.3092	5.04Hz
Test Person 6	18.75	5.3406	3.51Hz
Test Person 7	24.00	5.3306	4.50Hz
Test Person 8	27.00	5.2860	5.11Hz
Test Person 9	23.00	5.3193	4.32Hz
Test Person 10	26.75	5.3249	5.02Hz

The results of the test are very descriptive, with a mean average Frequency response of 4.73Hz. The maximum frequency response was 5.57Hz, and the minimum was 3.51Hz.

4.5 Conclusions

The results of the human response frequency test show an average frequency response of 4.73Hz. This gives an average reaction time of 0.211 seconds. When compared to the reaction time stated by the highway code of 0.675 seconds, the test conducted here is a significant increase. The 0.215 seconds from Human Benchmark.com is very closely related to the results of this test.

The results of the human response frequency test share the conclusion drawn from the results of HumanBenchmark.com, and that is the human response frequency is far greater than the response frequency of a car, which is said to be 0.5Hz. This can be alarming for inexperienced drivers, who panic when the car does not react quickly enough in a hazardous manoeuvre such as an elk test or sharp corner.

5.0 Mathematical Models and Tyre Testing

5.1 Mathematical Model of Tyres in Excel

It is possible to create a parametric model representing the performance of tyres using Microsoft Excel 2010. This will be beneficial as it demonstrate the factors that affect tyre performance.

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Figure 5.1 - Inflation Pressure vs. Cornering Coefficient

Wong, J.Y. (2008) Theory of Ground Vehicles. 4th edn. Hoboken, New Jersey: John Wiley & Sons. P36.

Figure 5.1 is a graph from Wong, J. Y (2008) p36. It displays the relationship between the inflation pressure of the tyre and the cornering coefficient. The cornering coefficient is Cornering Stiffness (N/deg) divided by Normal Load (N). As the inflation pressure increases, the cornering coefficient also increases. It is not a linear relationship, as the gradient decreases. The graph also displays that Radial Tyres perform better than Bias Tyres.

5.2 Purpose of Models

The purpose of the models is to adjust tyre parameters to see how they affect the performance of the car. The models are constructed from mathematical values that are used in mathematical equations that build up performance characteristics.

The vehicle values include Mass (m), Moment of Inertia of Plane Area (Izz), Centre of Mass location (a and b), Cornering Stiffness of Tyre Front and Rear ($C\alpha F$ and $C\alpha R$), Mass of Tyre (mt), Radial Tyre Stiffness (Kz), Radial Damping Ratio (ζ), Tyre Penetration (δz) and Rate of Tyre Penetration (Vz).

The results of the calculations involve matrix calculations and eigenvalue evaluations. As the excel model is parametric the basic vehicle values can be altered without the need to re-construct the model. This will benefit the evaluation of tyres as the tyre parameters can be altered to evaluate the performance characteristics of the car. The performance characteristic the model calculates shows the vehicle handling in a mathematical form.

Firstly an excel model is used to evaluate how the tyre's cornering stiffness changes relative to vertical load. The vertical load (Fz) is related to tyre pressure. Secondly the factors that equate the value for Fz will be investigated, to see how the tyre pressure can be affected. The final model will be the vehicle handling model, which models the car's performance in yaw.

5.3 Equations that Construct the Models

Each model is made of mathematical formulae which calculate numerical values. The following explanations show these equations and how they are used.

5.3.1 Model 1 – Tyre Linearity Model

Model 1 is a mathematical formula by Hans Pacejka which is commonly referred to as the magic formula. It is only 1 part of the formula that is relevant here, the Cornering Stiffness part which can be represented by, and is listed by Blundell and Harty (2004) p305:

$$BCD = a3(\sin(2 * \tan^{-1}(\frac{Fz}{a4}))) \quad [6]$$

Fz = Vertical Load (N)

a3 = Change of Stiffness with Slip (N/deg). The typical range is 500 to 2000.

a4 = Change of progressivity of stiffness / load (1/kN). The typical range is 0 to 50.

The Pacejka magic formula is favoured by many vehicle dynamicists, and especially in this project due to its lateral force equation benefits (Blundell 2000) "*The magic formula model used here has produced an accurate representation of the lateral force generated in the tyre as a function of slip angle.*"

5.3.2 Model 2 – Calculating Fz Model

Fz is the value used to represent tyre pressure. It is actually the parameter of Vertical Tyre Load (N). The tyre can be thought of as either a pressure vessel that gets its force from internal pressure or as a mass spring damper system. It is the mass spring damper system that is used in this model. The tyre has both spring like qualities as well as damping properties. Blundell and Harty (2004) p258-260 provide the equations for this model.

$$Fz = Fzk + Fzc \quad [7]$$

$$Fzk = -Kz * \delta z \quad [8]$$

$$Fzc = -Cz * Vz \quad [9]$$

$$Cz = 2 * \zeta\sqrt{Mt * Kz} \quad [10]$$

Mt = Mass of the Tyre

Kz = Radial Tyre Stiffness

ζ = Radial Damping Ratio

δz = Tyre Penetration

Vz = Rate of Change of Tyre Penetration

Vertical force or tyre load (Fz) is taken as negative of the normal force.

Fzk is the contribution due to Stiffness, and Fzc is the contribution due to damping.

5.3.3 Model 3 – Vehicle Handling Model

The cornering stiffness of the tyre does have an effect on vehicle handling in the form of yaw rate (Blundell 2000) "*The first set of variations concentrates on looking at a range of values for individual parameters in the Fiala data file. In Fig. 27 the yaw rate has been plotted to indicate the change in vehicle response for systematic changes in cornering stiffness. The plots indicate that going from low to high cornering stiffness leads to increased rates of change in yaw rate and could indicate the sort of design variations investigated in establishing how responsive a vehicle is.*"

Model 3 begins with the equations of motion for a body that is constrained to move in a plane. These equations are provided by lecture notes as part of module M26MAE Vehicle Dynamics in relations to an assignment (Wood, G 2013).

$$\sum Fx = m\,\dot{vx} \qquad [11]$$

$$\sum Fy = m\,\dot{vy} = m(r\;vx + \;\dot{vy}) \qquad [12]$$

$$\sum Mz = \;Izz\,\dot{r} \qquad [13]$$

m = Mass	vx = Longitudinal Velocity	vy = Lateral Velocity
r = Yaw Rate	Izz = Second Moment of Area	α = Slip Angle

The equations of motion will now incorporate a linear Cornering Stiffness Cα into the Lateral Force equation of motion.

$$\sum Fy = C\alpha f *\; \alpha f + C\alpha r *\; \alpha r \qquad [14]$$

The values of a and b will now be incorporated into the Mz equation of motion. These are the values that describe where the Centre of Gravity is between the 2 axles, a for the front axle and b for the rear.

$$\sum Mz = a * C\alpha f * \alpha f - b * C\alpha r * \alpha r \qquad [15]$$

The front and rear slip angles are functions of the vehicle motion states.

$$\alpha f\; = \arctan\left(\frac{vy + ra}{vx}\right) + \;\delta \qquad [16]$$

$$\alpha r = arctan(\frac{vy - rb}{vx}) \qquad [17]$$

The lateral Force equation then becomes:

$$C\alpha f *\; \alpha f + C\alpha r *\; \alpha r = m(r\;vx + \;\dot{vy}) \qquad [18]$$

$$C\alpha f * \left(\frac{vy + ra}{vx} + \delta\right) + C\alpha r * \left(\frac{vy - rb}{vx}\right) = m(r\ vx + \dot{v}y) \quad [19]$$

$$\left(\frac{C\alpha f + C\alpha r}{m\ vx}\right) * vy + \left(\frac{C\alpha f * a - C\alpha r * b}{m\ vx} - vx\right) * r + \left(\frac{C\alpha f}{m}\right) * \delta = \dot{v}y \quad [20]$$

This calculates a moment equation of:

$$a * C\alpha f * \alpha f - b * C\alpha r * \alpha r = Izz * \dot{r} \quad [21]$$

$$a * C\alpha f * \left(\frac{vy + ra}{vx} - \delta\right) - b * C\alpha r * \left(\frac{vy - rb}{vx}\right) = Izz * \dot{r} \quad [22]$$

$$\left(\frac{a * C\alpha f - b * C\alpha r}{Izz * vx}\right) * vy + \left(\frac{a^2 * C\alpha f + b^2 * C\alpha r}{Izz * vx}\right) * r + \left(\frac{-C\alpha f}{Izz}\right) * \delta = \dot{r} \quad [23]$$

The 2 equations both contain vehicle states, yaw and sideslip which are coupled.

$$\begin{bmatrix} \frac{C\alpha f + C\alpha r}{m * vx} & \frac{C\alpha f * a - C\alpha r * b}{m * vx} - vx \\ \frac{a * C\alpha f - b * C\alpha r}{Izz * vx} & \frac{a^2 * C\alpha f + b^2 * C\alpha r}{Izz * vx} \end{bmatrix} \begin{bmatrix} \frac{vy}{r} \end{bmatrix} = \begin{bmatrix} \frac{\dot{v}y}{\dot{r}} \end{bmatrix} \quad [24]$$

This matrix can be rewritten for eigenvalue solution.

$$\begin{bmatrix} \frac{C\alpha f + C\alpha r}{m * vx} - \lambda & \frac{C\alpha f * a - C\alpha r * b}{m * vx} - vx \\ \frac{a * C\alpha f - b * C\alpha r}{Izz * vx} & \frac{a^2 * C\alpha f + b^2 * C\alpha r}{Izz * vx} - \lambda \end{bmatrix} \begin{bmatrix} \frac{vy}{r} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad [25]$$

The determinant of the matrix gives the eigenvalues as follows.

$$a11 = \frac{C\alpha f + C\alpha r}{m * vx} \quad [26]$$

$$a21 = \frac{C\alpha f * a - C\alpha r * b}{m * vx} - vx \quad [27]$$

$$a12 = \frac{a * C\alpha f - b * C\alpha r}{Izz * vx} \quad [28]$$

$$a22 = \frac{a^2 * C\alpha f + b^2 * C\alpha r}{Izz * vx} \quad [29]$$

This means that the determinant can be evaluated as roots of a quadratic equation.

$$(a11 - \lambda)(a22 - \lambda) - a21 * a12 = 0 \quad [30]$$

$$\lambda^2 + (-a11 - a22)\lambda + (a11 * a22 - a21 * a12) = 0 \quad [31]$$

The quadratic equation is:

$$\lambda = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A} \quad [32]$$

And the values are defined as:

$$A = 1 \quad [33]$$

$$B = (-a11 - a22) \quad [34]$$

$$C = (a11 * a22 - a21 * a12) \quad [35]$$

Because this model will provide 2 sets of Real and Imaginary numbers, there will be 2 lines on all graphs. The Root Locus Plot is where the Real parts are plotted against the Imaginary Parts, and this evaluates the stability of the vehicle and whether oscillations in Yaw can be damped. The Real Part needs to stay negative, as this means the system is stable. If there is an Imaginary Part then the vehicle will oscillate in Yaw.

The model will also provide a graph of Natural Frequency in Yaw, this is a demonstration of vehicle response in yaw, and how quickly it can turn. It is said that a value of 0.5Hz is satisfactory, but not good. The higher the number the faster the car can react. The Natural Frequency is calculated by:

$$Frequency = \sqrt{(Real\ Part)^2 + (Imaginary\ Part)^2} \quad [36]$$

The final graph is Damping Ratio in Yaw. This describes how the car will dampen any oscillations in yaw because the vehicle will act like a pendulum, with no spring to stop the oscillation. For the purpose of this test 0.7Hz is the lowest safe value for a car at high speed to respond to an input. If the value is lower the vehicle will cause the driver to react to the car, which is not desirable. The higher the number the faster the car can dampen oscillations. The Damping Ratio is calculated by:

$$Damping\ Ratio = \cos(\arctan\left(\frac{Imaginary\ Part}{Real\ Part}\right)) \quad \textbf{[37]}$$

5.4 Assumptions, Limitations and Refining the Model

The final vehicle handling model assumes that the tyres are linearized. In reality the tyres would experience a transitional phase around 0.3G of cornering, and there would be a different vehicle response, however for the purposes of this evaluation the tyre linearization is an acceptable assumption. This model also assumes that the car complies with the ground. There are no vertical ground inputs and so the stiffness and smoothness of the road is not a factor.

It is assumed that vx varies slowly, and so is considered to be 0. This is a much more convenient formulation as the tyres are the primary force-generating parameters, and they are aligned to the body. It is also assumed that camber is 0, and so has no effect on the formula. A car would have an overall camber of 0, unless it was constantly travelling in a curved path. Most cars will have the left and right wheels equally and oppositely cambered.

This model is a 2 degree-of-freedom model, and so there are limitations to its precision. This model does not assume body roll. This model is simply a representation of cornering stiffness, and so whilst assuming would make the model more precise, it would not provide more insight into cornering ability.

The model is already refined by using the equations provided by H. Pacejka. The model will evaluate the vehicle handling with respect to velocity. The model could be further refined by introducing roll, however as discussed this would not provide any more relevant data.

5.5 Information from Model

Vehicle handling is a performance characteristic that is difficult to quantify. Other performance characteristics can be mathematically represented. The model produces real and imaginary values, when these values are plotted against each other in a Root Locus Plot the relation between the values describes Yaw Stability and the Yaw Decay. These are handling characteristics that are important for giving the customer confidence in driving. The Root Locus Plot also describes the Yaw Response to a change in yaw, which is related to the importance of bandwidth.

The model can also display graphs for the Natural Frequency of the vehicle in Yaw, and the Yaw Damping. These are graphs which are very relevant to the importance of Bandwidth. To examine Linearity the Linear Cornering Stiffness per Tyre can be evaluated, which will graphically show how changing the Cornering Stiffness ($C\alpha$) of the tyre can affect the tyre's response to an input.

5.6 Parameters that can be Adjusted in the Model

Whilst many of the parameters such as mass, centre of mass location and second moment of area can be adjusted, this would not provide an insight to tyre performance. For this investigation only parameters involving the tyres will be adjusted. These include the mass of the tyre, Radial tyre stiffness and values concerning tyre penetration. These values directly affect the cornering stiffness values.

It is important to note that for these models Cornering Stiffness is in fact not a constant value, even though the models will consider it as such. A paper published by SAE titled "The Effect of Tire Characteristics on Vehicle Handling and Stability" by R. Wade Allen, T.T. Myers, T.J. Rosenthal and D.H. Klyde in 2000 is a study that examines how tyres can affect vehicle handling. The background states that "*$Y_\alpha = dF_y/d\alpha$ is defined as the cornering stiffness. If cornering stiffness is normalized with respect to vertical load, $Y^*_\alpha = Y_\alpha/F_z$, this ratio is defined as the cornering stiffness coefficient and tends to be relatively constant over a range of tires. Cornering stiffness coefficient generally decreases as a function of vertical load as illustrated in Figure 2, which is another generic property of tires.*" For this reason, a constant value of Cornering Stiffness can be assumed, without it dramatically reducing the accuracy of the models created for this investigation.

5.7 Results

The results of the 3 excel models display different results. Each graph demonstrates the effect that a certain parameter has on the end result. Each model is an evolution of the previous model, as to examine the parameters that affect tyre performance, and how tyres can therefore affect vehicle handling.

5.7.1 Model 1 Results

The graph of model 1 is a single line, which shows the relationship between the vertical force, Fz applied to the tyre and the resultant tyre cornering stiffness.

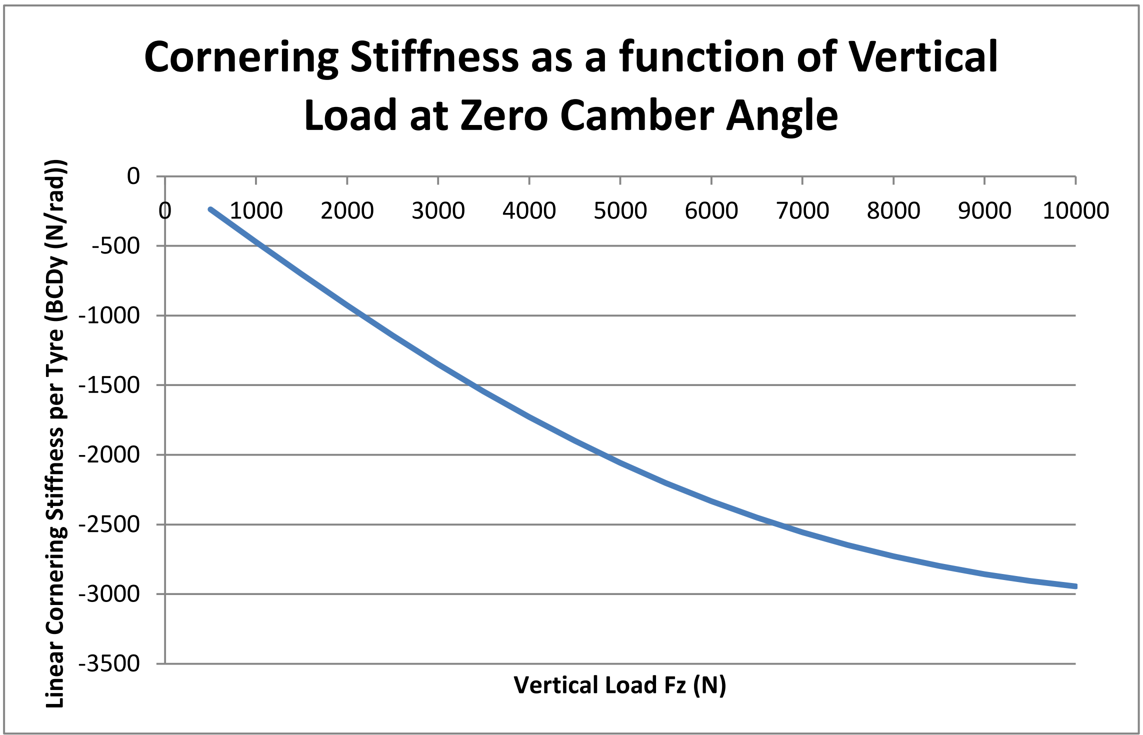


Figure 5.7.1 - Cornering Stiffness as a function of Vertical Load

The graph displays a fairly linear relationship up to approximately 5000N. From here the gradient of the graph begins to decrease, as the curve flattens. This shows that for the lower vertical loads the tyres react in a linear fashion, as the cornering stiffness (BCDy) react proportionally. As the vertical force increases, the tyres react less which suggests the tyres are losing their ability to grip the road. This effect can also be seen as slip angle is increased. The graph has a maximum Vertical Load of 10,000N. At this point the gradient is approaching 0 from a negative gradient, and so the shape of the graph would reach a peak, or for the negative gradient a trough, and then the gradient would become positive.

5.7.2 Model 2 Results

The model has 5 parameter, 4 of which will be evaluated. For the purpose of evaluation each parameter will be adjusted whilst the other 4 remain at a constant value. The fixed values for the parameters are as follows:

Mass of Tyre	17	Kg
Radial Tyre Stiffness	30	N/mm
Radial Damping Ratio	30	
Tyre Penetration	5	mm
Rate of Tyre Penetration	12	mm/kg

The values are estimations and are not based on a real tyre. These values are here to demonstrate the relationship each has on the vertical tyre force.

5.7.2.1 Varying the Mass of the Tyre

All parameters except the mass of the tyre will be fixed at the stated values. The mass of the tyre will range from 8kg to 27kg.

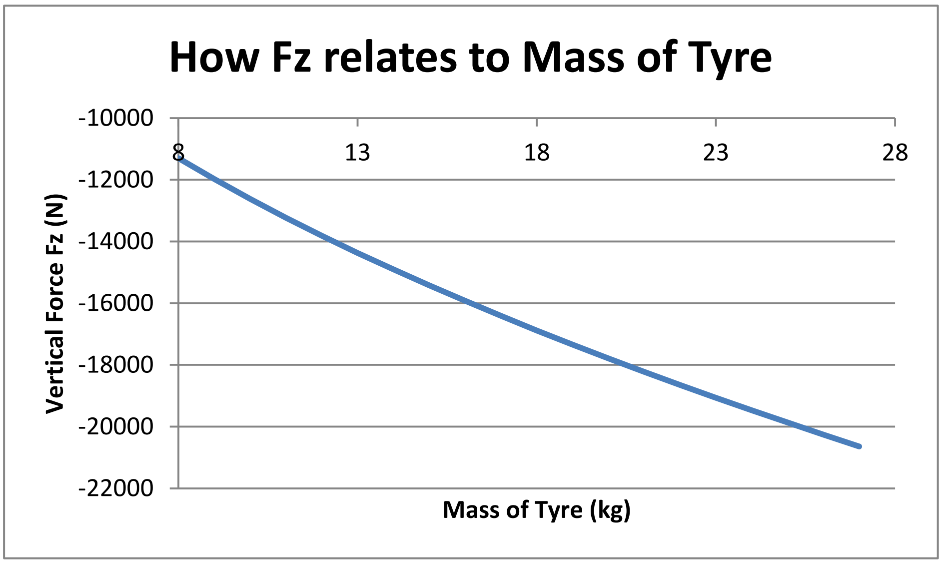


Figure 5.7.2.1 - Varying Mass of Tyre

The gradient of the graph is negative, and as the mass of the tyre increases the negative magnitude increases. This shows that as the mass is increased, the vertical force is also increased. The vertical force describes the force that the tyre exerts. The graph is fairly linear, with a range of values from -11,300N to -20,600N.

5.7.2.2 Varying the Radial Damping Ratio

All parameters except the Radial Damping Ratio will be fixed at the stated values. The Radial Damping Ratio will range from 20 to 58. As this test is varying a damping ratio, the value has no units.

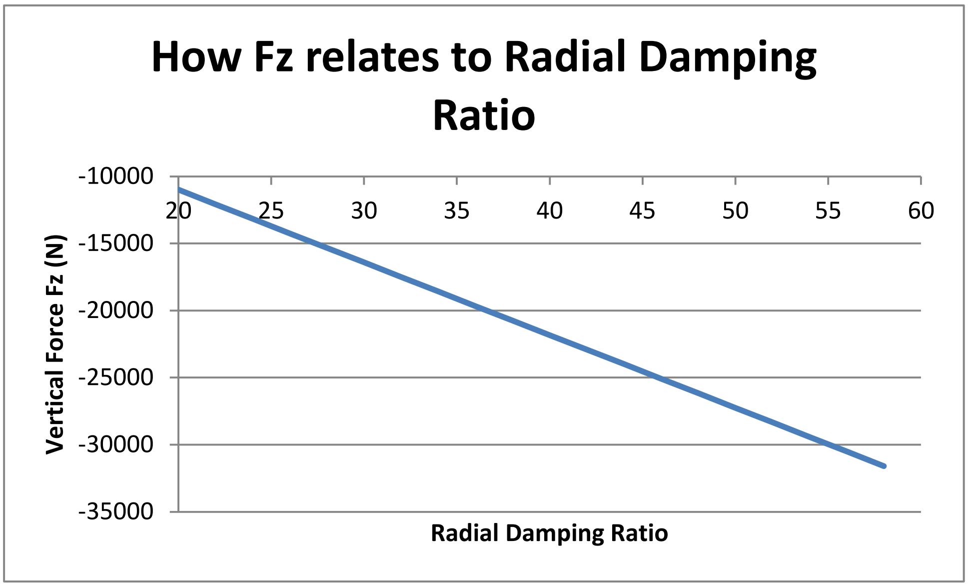


Figure 5.7.2.2 - Varying Radial Damping Ratio

The gradient of the graph is negative, and as the Radial Damping Ratio increases the negative magnitude increases. This shows that as the Damping Ratio is increased, the vertical force is also increased. The graph is fairly linear, with a range of values from -10,900N to -35,600N.

5.7.2.3 Varying the Tyre Penetration

All parameters except the Tyre Penetration will be fixed at the stated values. The Tyre Penetration will range from 0.5mm to 10mm. The Tyre Penetration is the deflection of the tyre.

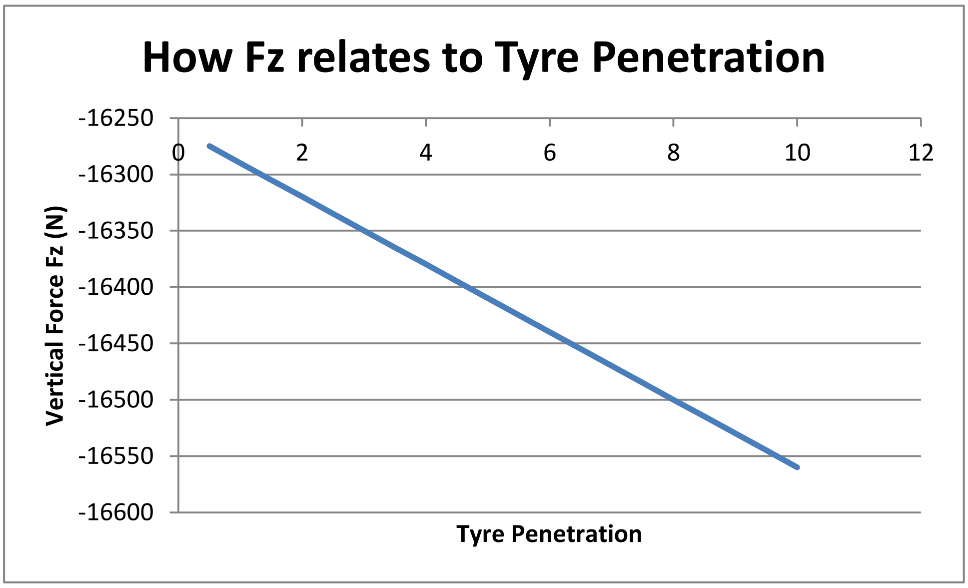


Figure 5.7.2.3 - Varying Tyre Penetration

The gradient of the graph is negative, and as the Tyre Penetration increases the negative magnitude increases. This shows that as the deflection is increased, the vertical force is also increased. The graph is fairly linear, with a range of values from -16,200N to -16,600N. The difference between the minimum and maximum tested values is small compared to other parameters.

5.7.2.4 Varying the Rate of Change of Tyre Penetration

The Rate of Change of Tyre Penetration is how much the tyre deflects relative to the applied load. All parameters except the Rate of Change will be fixed at the stated values. The Rate of Change will range from 1mm/kg to 20mm/kg.

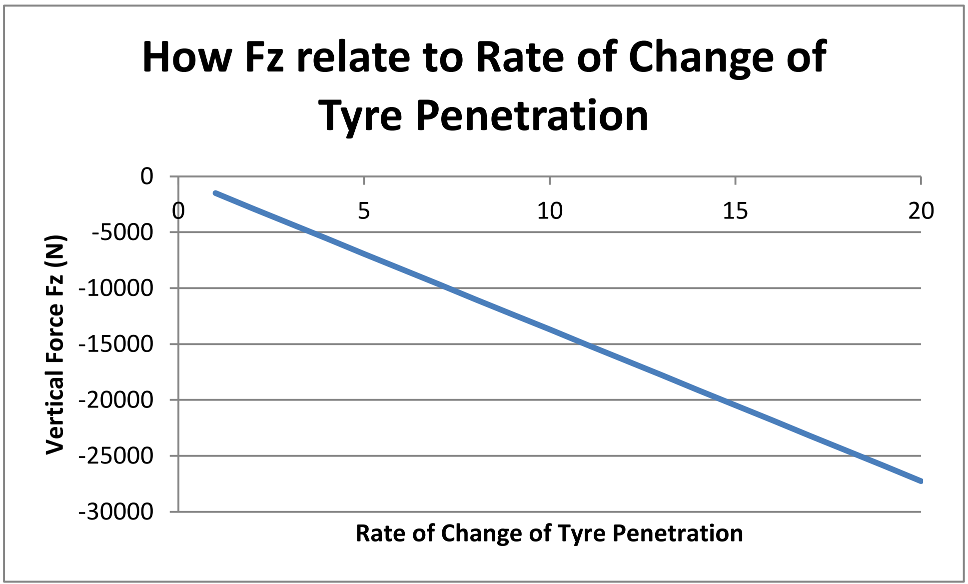


Figure 5.7.2.4 - Varying Rate of Change of Tyre Penetration

The gradient of the graph is negative, and as the Rate of Change increases the negative magnitude increases. This shows that as the magnitude is increased, the vertical force is also increased. The graph is fairly linear, with a range of values from -1,500N to -27,200N.

5.7.3 Model 3 Results

The model has 6 parameters that can be changed, however for the purpose of this test only the Tyre cornering stiffness will be changed (CαF and CαR). Mass (m) will be fixed at 1800kg, Second Moment of Area (Izz) will be fixed at 3150kgm^{-2}, CG distance from front axle (a) will be fixed at 1.37m, and CG distance from rear axle (b) will be fixed at 1.39m. These values are approximations and do not represent an actual car. They do however represent a front engine sport saloon car. This is because this vehicle type will have good handling due to the approximately even weight distribution, relatively low mass and stiff chassis. The tyres will be the only variables.

5.7.3.1 Test 1 -110,000N/rad

The first test will be of high cornering stiffness in the tyres. Both front and rear tyres are set at -110,000N/rad.

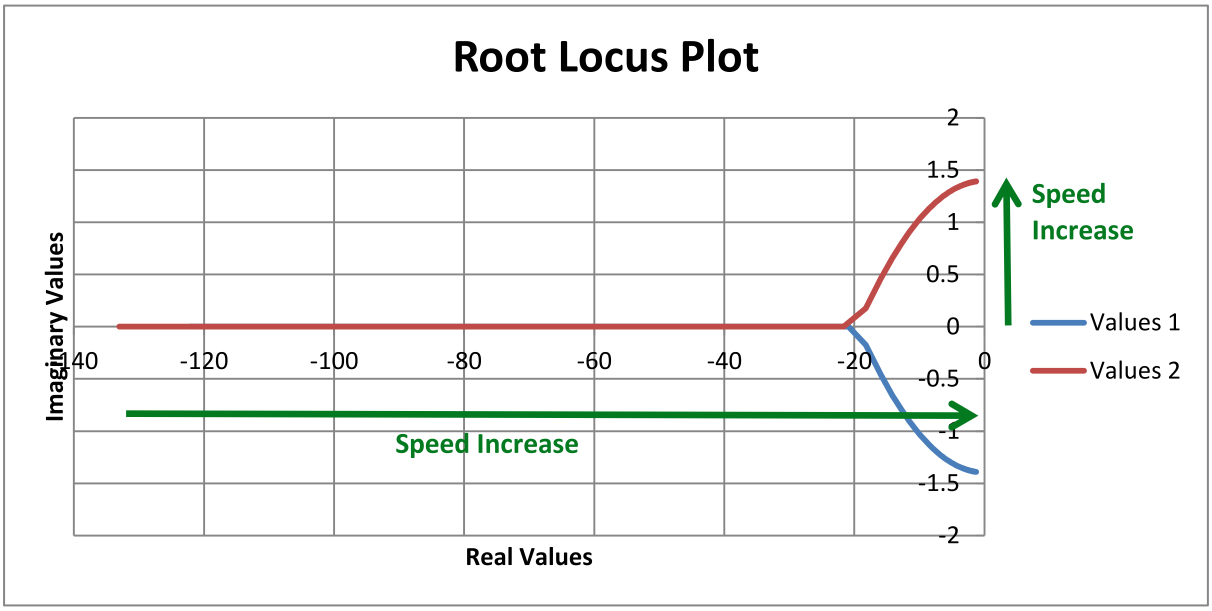


Figure 5.7.3.1a - Test 1 Root Locus Plot

The Root Locus Plot shows initially a very quick response, as the values have a 0 imaginary value and are far from the imaginary axis. At all vehicle speeds the real value remains negative, which means the system is stable. As the speed increases the imaginary value becomes positive, so there is now an oscillatory decay to the yaw motion. For all the speeds tested the real value does not ever become 0, this is good as the yaw motion remains damped, and is not sustained. These are all features of a vehicle that has good handling characteristics. The first imaginary positive value occurs at 7m/s.

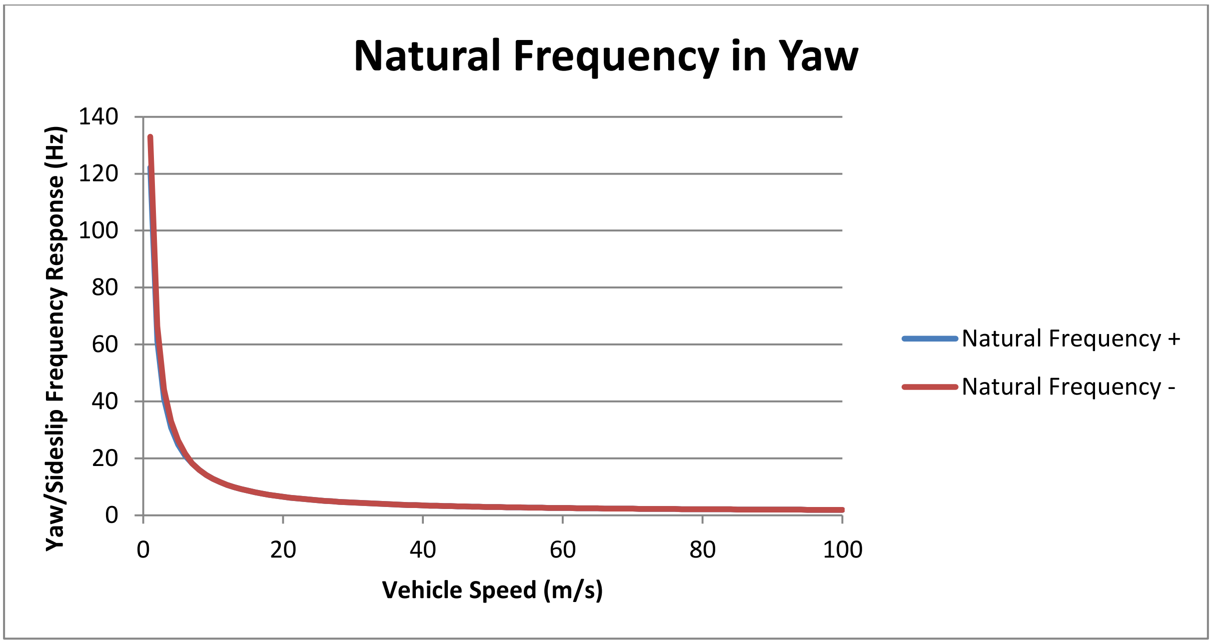


Figure 5.7.3.1b - Test 1 Natural Frequency in Yaw

The faster the vehicle speed the lower the Natural Frequency. At the fastest speed tested the frequency measured 1.89Hz. It is considered that a value above 1.0 is good. The Natural Frequency is used to describe the car's ability to respond to driver inputs.

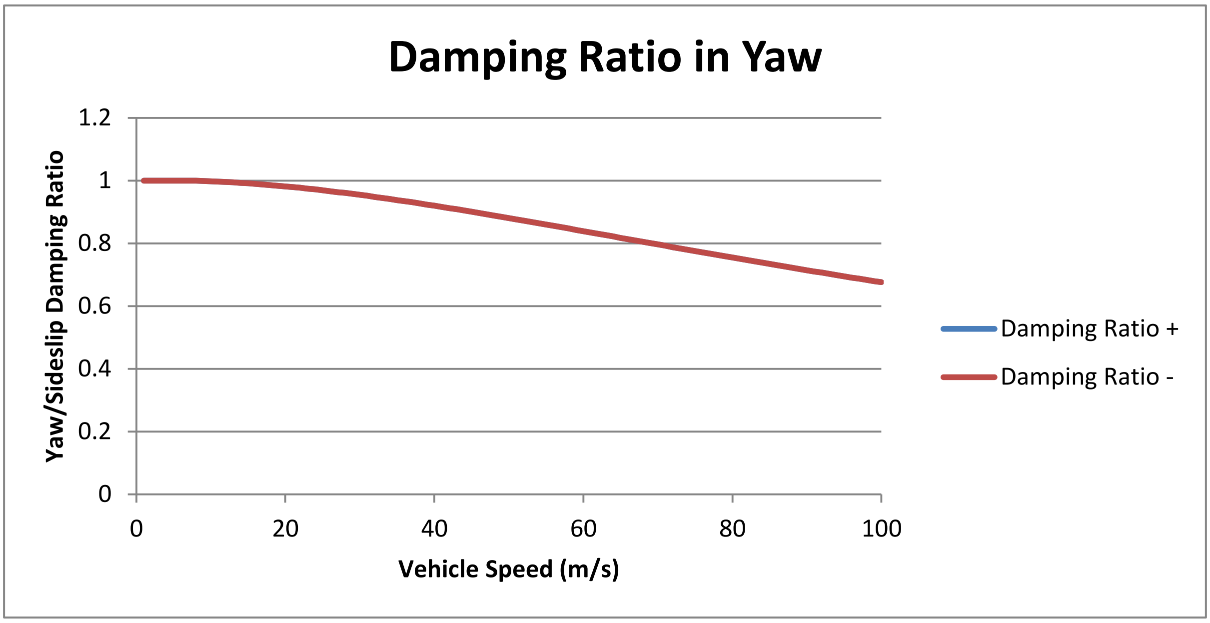


Figure 5.7.3.1c - Test 1 Damping Ratio in Yaw

The faster the vehicle speed the lower the Damping Ratio. The Damping Ratio describes how quickly any oscillations in Yaw will be damped. A value of 0.7 is the lowest acceptable ratio, any lower and the vehicle will “hunt around” which forces the driver to react to the car which is undesirable. The mathematical model shows that the value nearest to 0.7 is achieved at 93m/s, which is 208mph. This speed exceeds the maximum velocity designed for a sport saloon.

The conclusions of this first test show that the graphs represent ideal results. All 3 graphs show favourable handling characteristics.

5.7.3.2 Test 2 -50,000N/rad Front and Rear

The second test will reduce the cornering stiffness of both the front and rear tyres to -50,000N/rad.

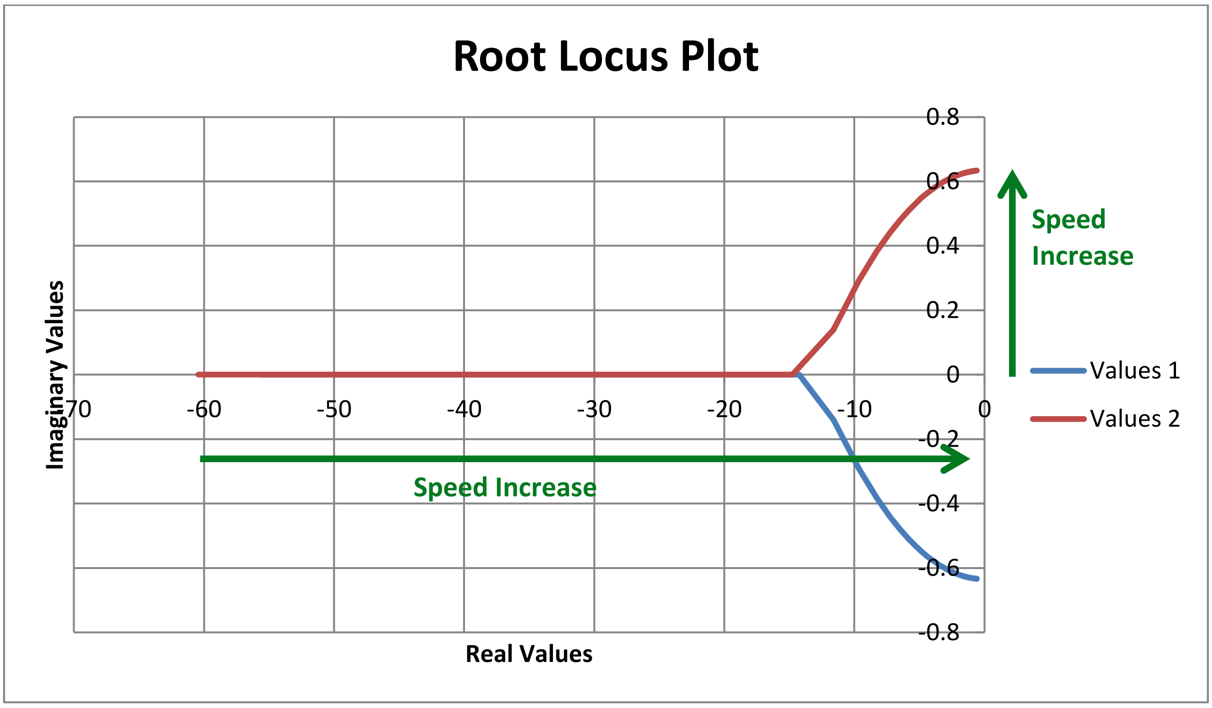


Figure 5.7.3.2a - Test 2 Root Locus Plot

The shape of the Test 2 Root Locus Plot is very similar to the first, it shows a stable oscillation when the imaginary values become positive, and before that there is a fast response. At no point does the real value become positive, so the oscillatory motion is always decaying. However, the first imaginary positive value occurs at 5m/s, this may only be a 2m/s difference, but this means the yaw motion becomes oscillatory sooner.

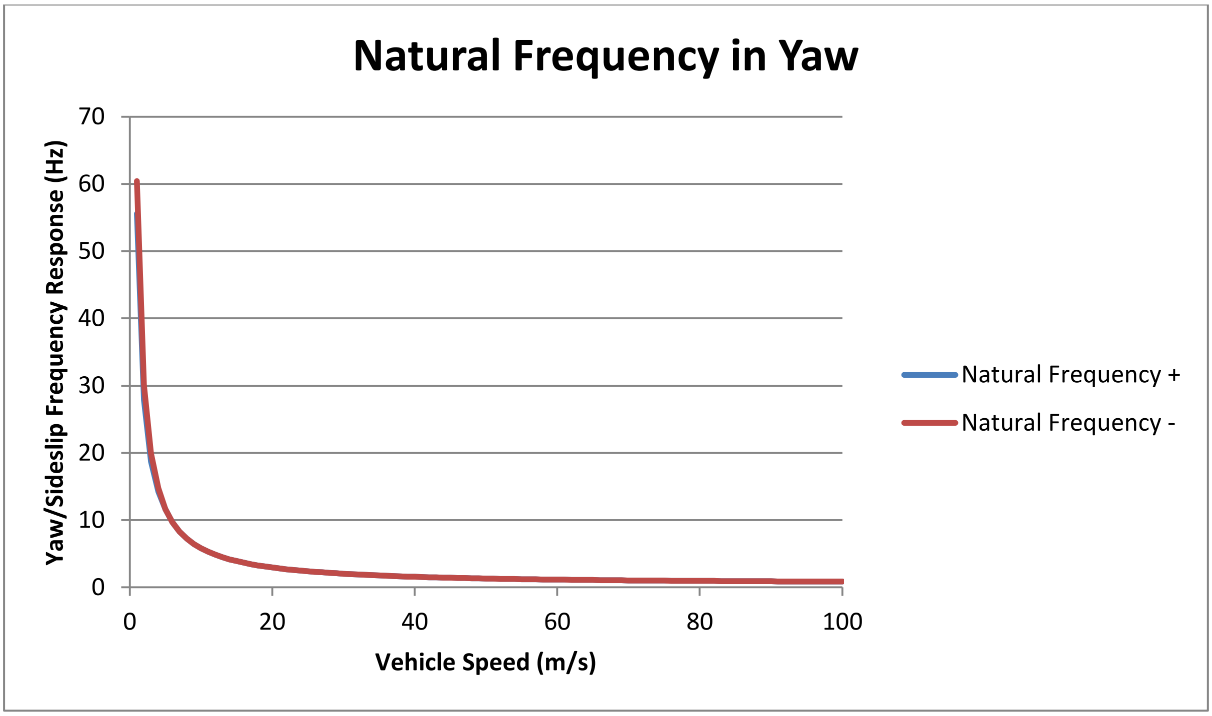


Figure 5.7.3.2b - Test 2 Natural Frequency in Yaw

The Natural Frequency in Yaw is now smaller. The frequency reaches 1.0Hz at 74m/s which is 165.5mph. At the fastest speed tested the Natural Frequency drops to 0.86Hz. The value must not go below 0.5Hz as this would be very slow to respond to driver inputs. Whilst these values still represent acceptable handling characteristics they do show a deterioration in response frequency.

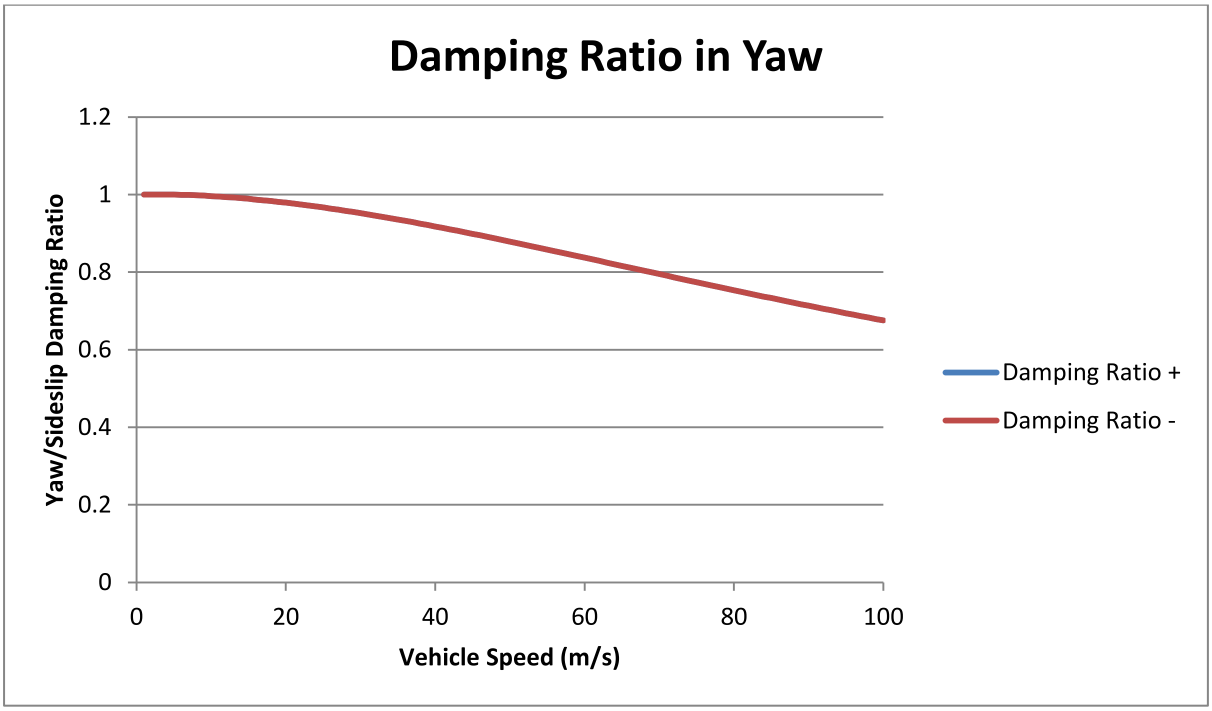


Figure 5.7.3.2c - Test 2 Damping Ratio in Yaw

The Damping Ratio in Yaw has not changed. The speed at which the Damping Ratio reaches 0.7 is still 93m/s. Therefore changing both tyres appears not to have an effect on Damping Ratio.

5.7.3.3 Test 3 -50,000N/rad Front, -110,000N/rad Rear

For Test 3 the tyre values will be changed independently, the front tyres will have a value of -50,000N/rad, and the rear will have a value of -110,000N/rad.

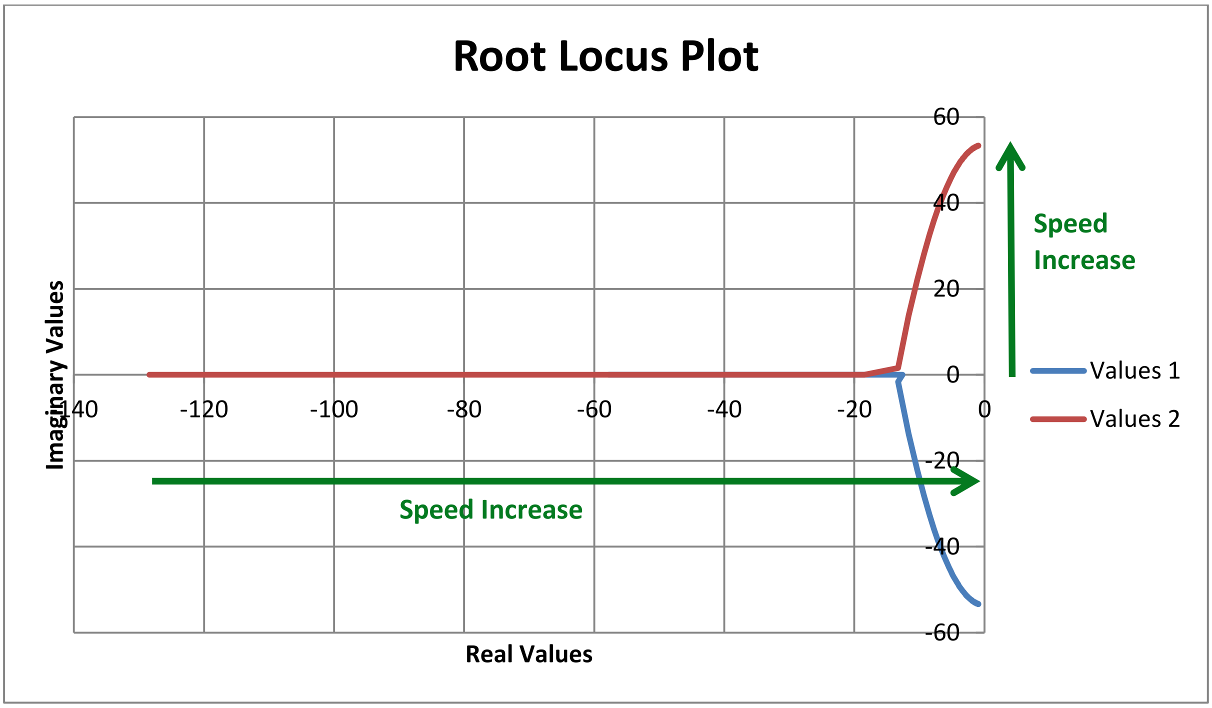


Figure 5.7.3.3a - Test 3 Root Locus Plot

The Root Locus Plot takes a familiar shape, however the imaginary values are far greater. The greater the imaginary values the greater the loss in damping. Whilst the system is still damped, the car will take longer to settle itself after a movement in Yaw.

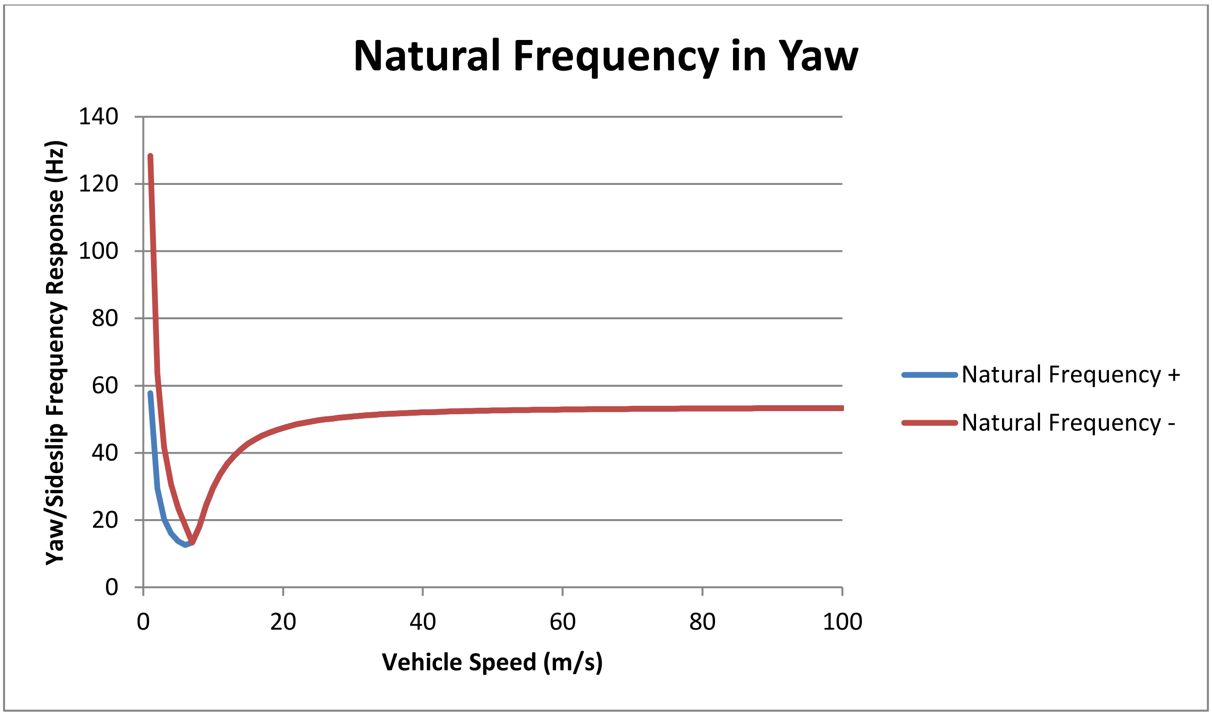


Figure 5.7.3.3b - Test 3 Natural Frequency in Yaw

The Natural Frequency is a far more erratic display. At no point do the values near 1.0, the lowest value is 12.5Hz at 6m/s or 13.4mph. After this the frequency increases sharply and levels at approximately 53Hz. These are not values of normal car behaviour and suggest that the car will respond quickly to driver input, but there is little to no damping to control the oscillations in yaw.

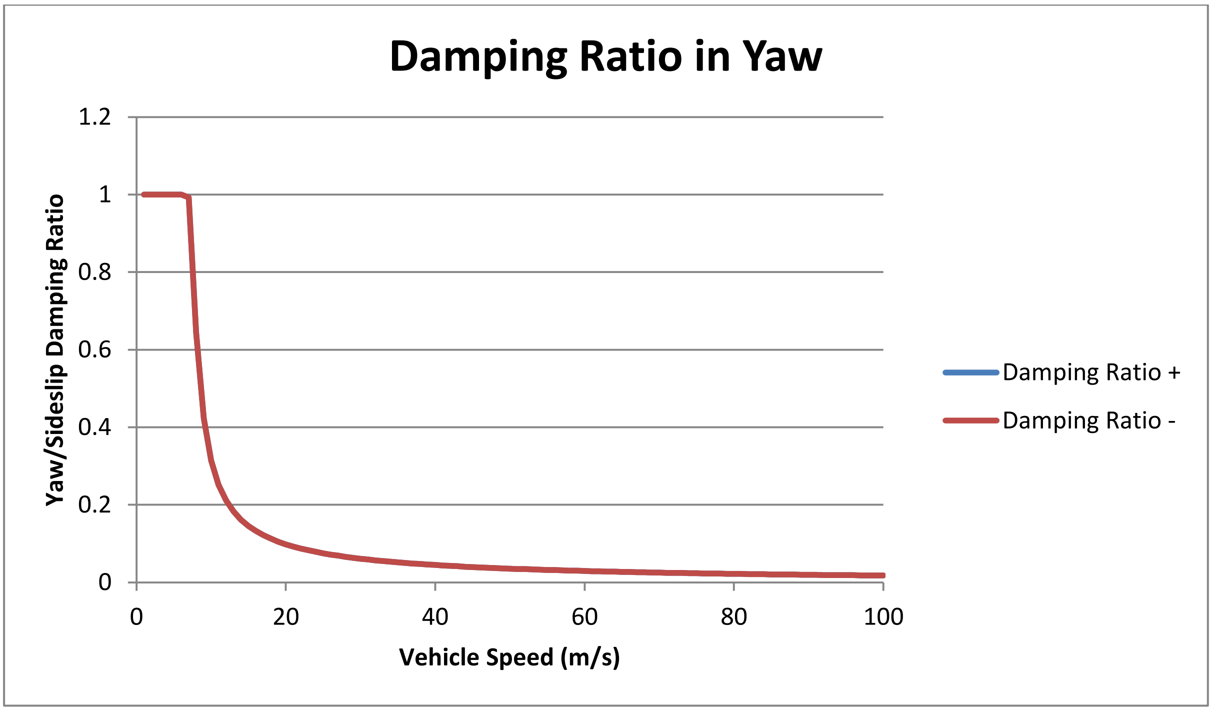


Figure 5.7.3.3c - Test 3 Damping Ratio in Yaw

The Damping Ratio graph confirms the lack of damping. The system is critically damped up to 6m/s, but then drops to below 0.1 at 20m/s which is 44.7mph. This is very worrying as the car will likely be very nervous as it responds to drier inputs very quickly, and there is not sufficient damping to control the yaw motion.

The conclusion of differing the cornering stiffness between front and rear tyres is that the handling is degraded. These are the characteristics of an unsafe vehicle.

5.7.3.4 Test 4 -110,000N/rad Front, -50,000N/rad Rear

The previous test demonstrated a greater cornering stiffness for rear tyres. Test 4 demonstrates a car with greater front cornering stiffness.

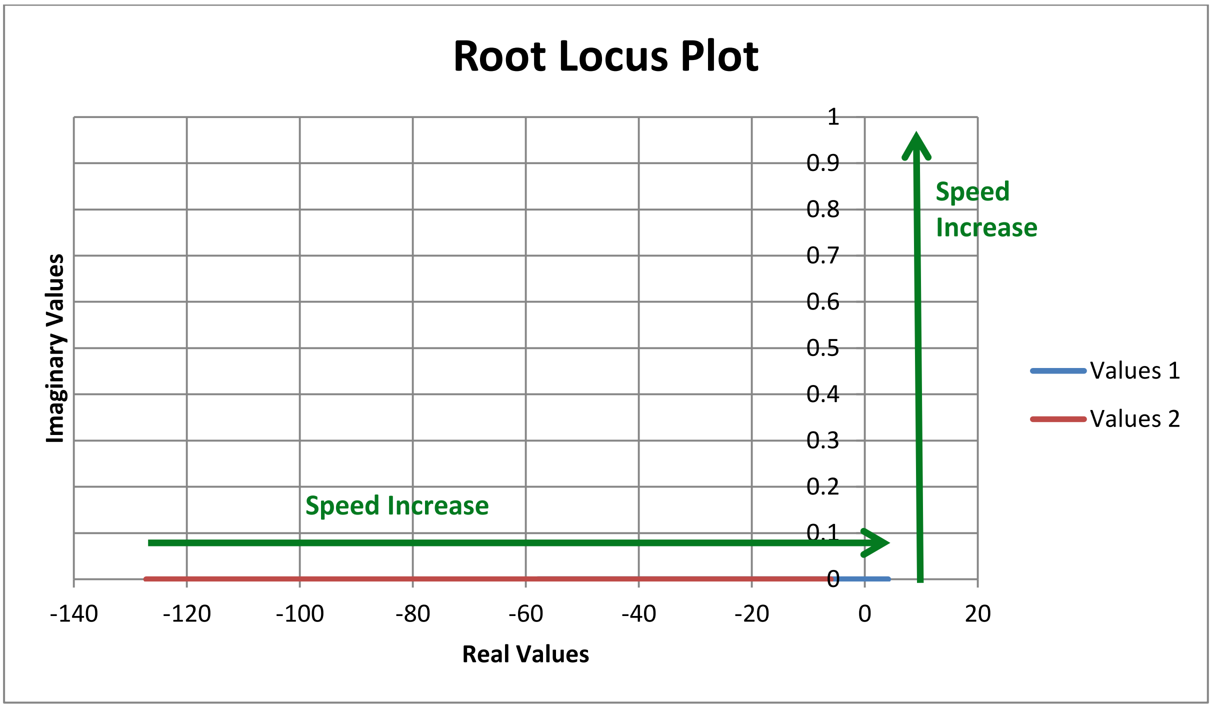


Figure 5.7.3.4a - Test 4 Root Locus Plot

This is the most concerning Root Locus Plot yet. There are no positive values for the imaginary parts, which suggests the system is critically damped at all speeds. The Real values do become positive at 17m/s or 38mph which means the system in unstable and the vehicle will experience exponential growth in yaw oscillations.

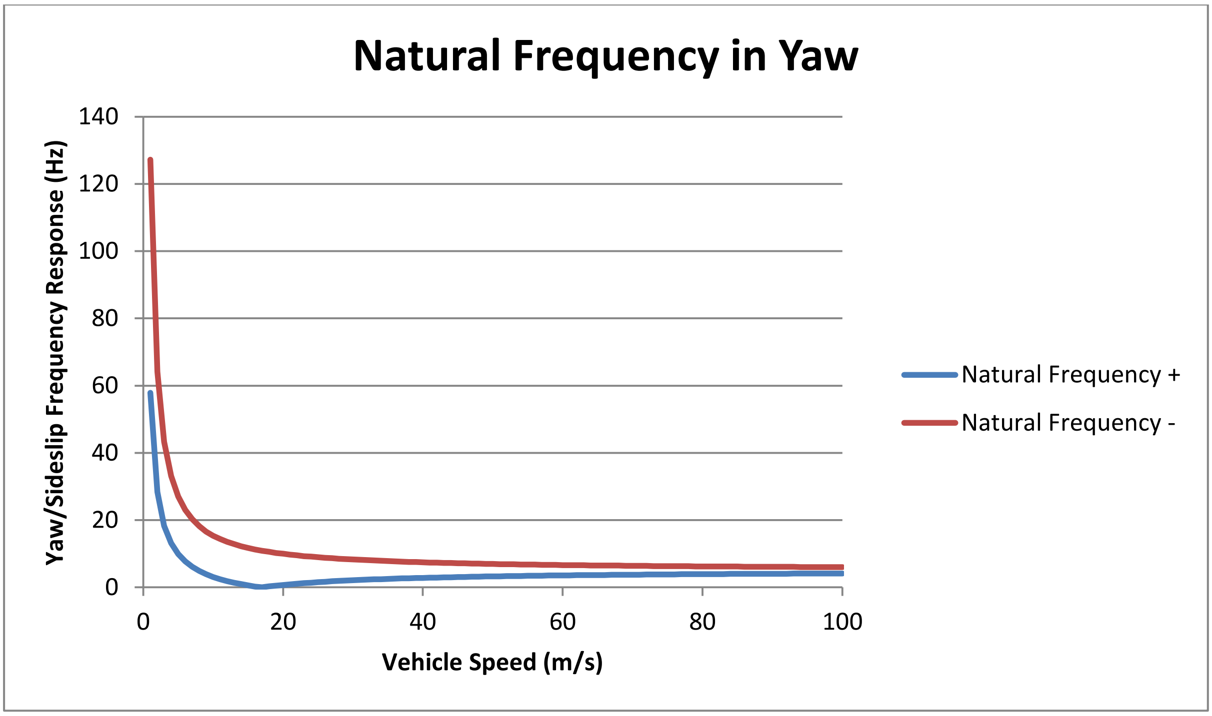


Figure 5.7.3.4b - Test 4 Natural Frequency in Yaw

The Natural Frequency result takes a similar shape to previous results, however the lowest value achieved is 6.0Hz. This frequency remains considerably higher than previous tests. This frequency suggests the car will react quicker than the driver, which is not a desirable characteristic.

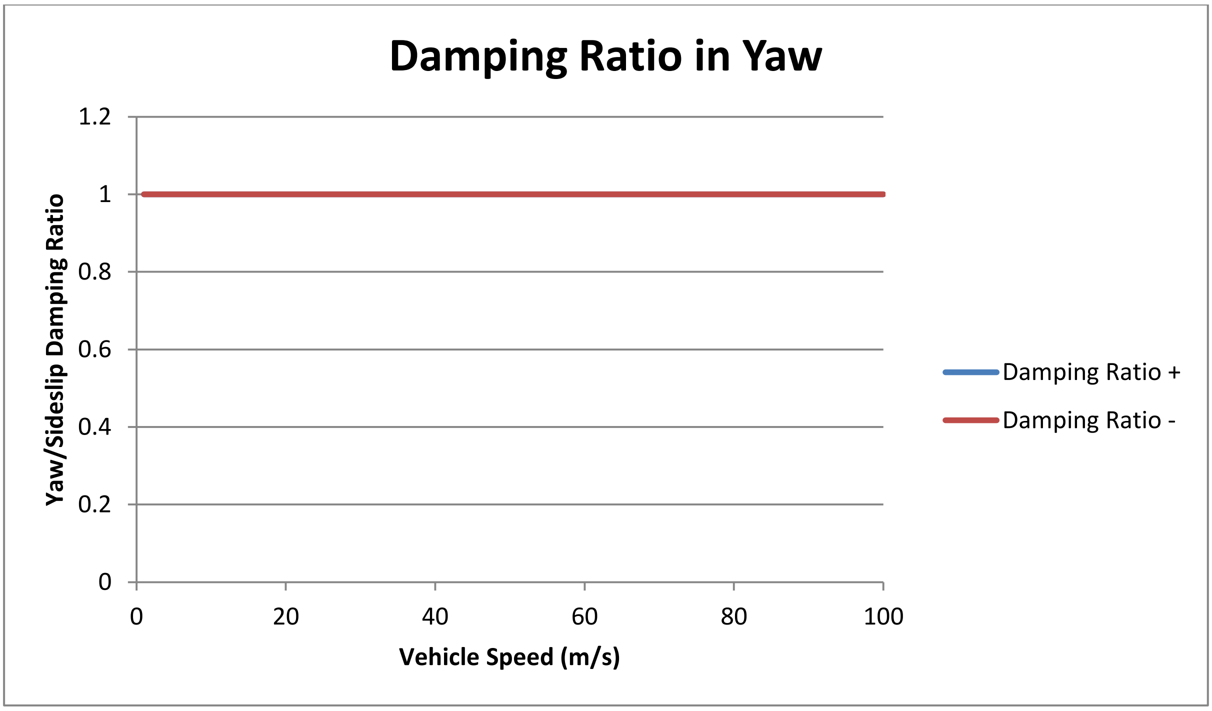


Figure 5.7.3.4c - Test 4 Damping Ratio in Yaw

The Damping Ratio for all tested speeds in 1.0. This means the system is always critically damped. This confirms the results of the Root Locus Plot.

The conclusion of Test 4 is that this system is unstable with undesirable handling characteristics. For this vehicle type with an evenly distributed weight and stiff chassis with greater cornering stiffness for the front tyres the car will be considered unsafe.

5.8 Conclusions

Model 1 demonstrated that the Cornering Stiffness of the tyre is affected by the vertical load applied to it. The relationship is linear at first, when the vertical load is below 5kN, but the then gradient noticeably changes and the vertical load increasing does not produce a proportional response in tyre cornering stiffness.

The value of Fz which is vertical load can be affected by parameters of the wheel itself. The conclusion of Model 2 is that all the parameters that build up a mathematical model do have an effect on the vertical tyre force. The relationships are all identical, as the parameters increase in magnitude, so do the negative vertical force.

Model 3 is a mathematical model that can represent vehicle handling by affecting the parameter of cornering stiffness, as it was the dependant variable in model 1. Whilst there are other parameters that can greatly affect handling such a mass, centre of gravity location and second moment of area, the tyres are the parameter that are most easily changed. The tyres do affect the handling response of a car significantly, as unbalancing the tyre cornering stiffness between front and rear can result in unstable and unsafe vehicle handling.

The models represent mathematical formulae that can be used to model parameters on cars, in this case tyres. The models demonstrate the importance of tyres in vehicle handling and so it will be necessary to assess tyre pressure on tyre performance.

5.9 Tyre Instron Test

The Instron machine will be used to gain data on how tyre inflation pressure affects the deflection of the tyre. This will be used to evaluate the vertical spring stiffness of the tyre. From this primary data a relationship between vertical spring stiffness and tyre inflation pressure can be evaluated.

5.10 Testing Procedure

The testing procedure will occur as follows:

- Set car tyre to desired inflation pressure when out of instron machine, so it is unloaded.
- Put tyre in instron, between the plates that will hold it in position. The plates will need to hold the tyre without moving it, but also so it won't deflect the tyre.
- Reset the Gauge length (deflection measurement) and Balance Level (Compressive Load).
- Increase Compressive Loads by 100N increments, and record the Extension (deflection) and Compressive Loads.
- Restart procedure with next tyre inflation pressure.

5.10.1 Apparatus of Test

Figure 5.10.1a - Instron Machine

The Instron Machine is the testing apparatus that will apply the load to the tyre. The results of extension and compressive load are displayed on a separate computer. The applied compressive load is varied by a hand operated device. The results are recorded by hand, to be later assessed using Excel.

The Car tyre is from a Formula Student car. The Tyre is the Hoosier 19.5 x 6.5-10 Road Racing Wet. This is a tyre that is commonly used in the Formula Student series.

Figure5.10.1b - Test Tyre

The Tyre Inflation Pressure will be recorded by use of a Tyre Pressure Gauge. The gauge used for this test measures in psi, so the increments of inflation pressure will be in 5psi from 30psi to 10psi. Afterwards these pressures are converted to SI units.

5.11 Parameters of Test

The tyre is from a formula student vehicle that has a weight of approximately 4kN. As this is 1 tyre, the maximum load will be a quarter of that force, meaning the maximum load will be 1kN.

The maximum pressure is 30psi (2.068 bars), and the minimum for this test is 10psi (0.689 bars). The increments will be in 5psi (0.345 bars).

The tyre will not record a deflection with no applied force. With a maximum load of 1kN, the increments of applied Compressive Load will be 100N. Therefore the first measurement will takes place at 100N.

5.12 Results

The results recorded Extension (mm) against the Compressive Load (N). The exact recordings are in the Appendix Instron.

5.12.1 Force vs. Deflection

This test is the primary data achieved by the Instron testing of a race tyre. It will later be evaluated for the purposes of calculating spring stiffness.

The X axis will represent Compressive Load, which is measured in Newtons (N). This is how much force the instron machine is applying to the tyre, which in turn causes it to deflect. The Y axis will represent Extension, which is measured in millimetres (mm). This is the deflection of the tyre as a result of the applied force.

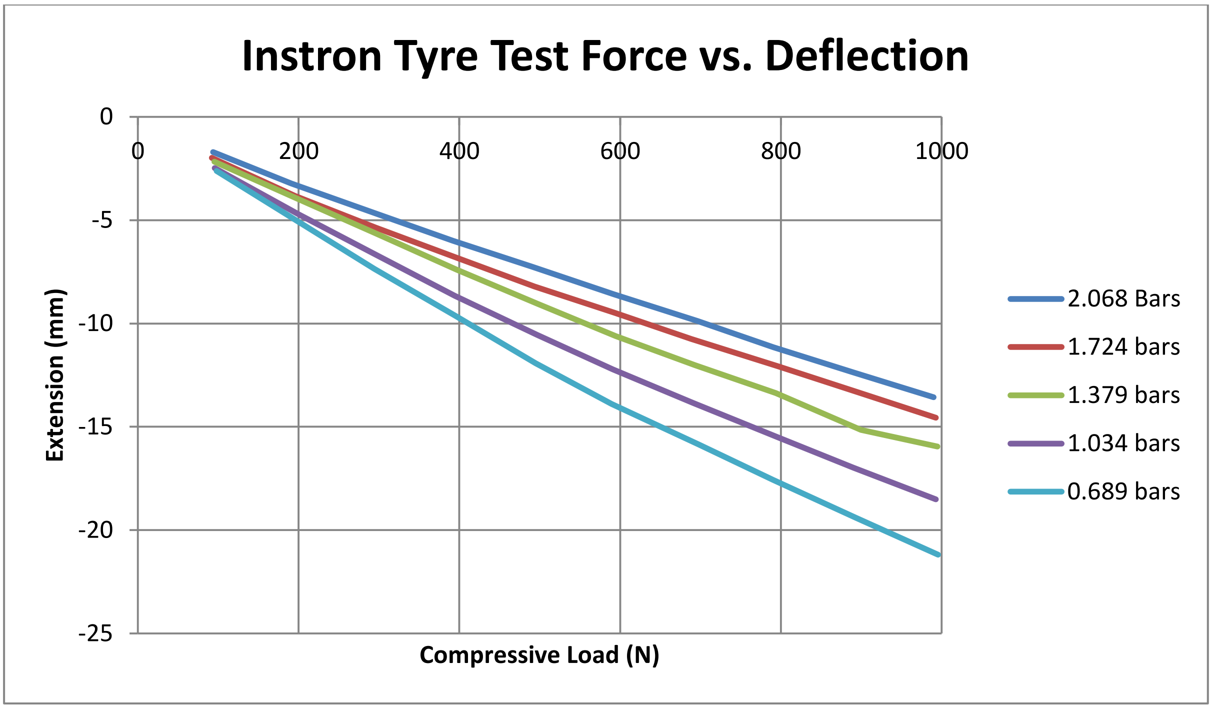


Figure 5.12.1 - Instron Tyre Test Force vs. Deflection

The 5 lines represent different tyre inflation pressures that are tested. Each line demonstrates a linear relationship between Compressive Load and resulting extension. The lines are not perfectly linear, but this is to be expected as there can be slight variations in how much the tyre deflects. However, there is a clear decreasing extension for an increase in load. This is therefore a negative gradient, the extension is recorded as the distance between the plates of the instron, so the distance is decreasing.

The relationship between Compressive Load and Extension is that of a linear relationship and negative gradient. Each line exhibits predictable values, with increasing negative numbers. The observation of the greater the applied force the greater the tyre will deflect is demonstrated to be true. These results demonstrate the effect that tyre pressure has on the tyres deflection due to applied force.

Each line represents a different tyre pressure, and it is clear that the highest tyre inflation pressure of 2.068 bars deflects less for a certain compressive load than that of any lower pressured tyre. A general observation can be stated here, the higher the tyre inflation pressure, the less the tyre deflects for an applied force. It is also true that the lower the tyre inflation pressure the more the tyre will deflect.

The tyre pressure of 1.379 bars appears to show slight discrepancies, the gradient is not constant, however, this is not a major concern as the overall relationship can be said to regular and linear. Using the minimum and maximum values for compressive load and extension, the general gradient for each tyre pressure can be calculated.

Table 5.12.1 - Force vs. Deflection Gradients

Tyre Pressure (bars)	Compressive Load (N)		Extension (mm)		Gradient
	Minimum	Maximum	Minimum	Maximum	
2.068	93.4	990	-1.701	-13.57	-0.01324
1.724	92	993	-1.986	-14.56	-0.01396
1.379	95.21	994.7	-2.173	-15.96	-0.01533
1.034	95.55	993	-2.478	-18.5	-0.01785
0.689	97.73	995.7	-2.623	-21.18	-0.02067

As the table displays, the greater the tyre inflation pressure the smaller the negative gradient.

5.12.2 Vertical Spring Stiffness

This evaluation places the primary data acquired in spring force equations. The Vertical Spring Stiffness is the desired output, but the primary data needs to be evaluated first. Firstly the Equivalent Stiffness is calculated which is a simple calculation of:

$$Stiffness = \frac{Force}{Load} \qquad [38]$$

This however is not the vertical stiffness of the tyre. The instron machine compresses the race tyre between 2 plates. The deflection is therefore from 2 sides of the tyre, which is not how a tyre will deflect on a car that is being driven. It will only deflect as the point where the tyre is in contact with the road. This can however be calculated using the following Spring Stiffness in Series equation from Milliken, W. and Milliken, D (1995) p769.

$$^1/_{KT} = {}^1/_{K1} + {}^1/_{K2} + {}^1/_{K3} \cdot \cdots \qquad [39]$$

As the tyre is compressed on 2 sides it can be considered there are effectively 2 springs at work, K1 and K2. It can also be assumed that as both springs are exerted to the same force and they are the same stiffness, they deflect the same amount. Therefore K1 equals K2.

$$^{1}/_{K1} = \frac{^{1}/_{KT}}{2} \qquad \textbf{[40]}$$

The X axis will represent Compressive Load, which is measured in Newtons (N). This is how much force the instron machine is applying to the tyre, which in turn causes it to deflect. The Y axis will represent Vertical Spring Stiffness of the Tyre, which is measured in Newtons per Metre (N/m). This is the Spring Stiffness of the tyre as a result of the applied force.

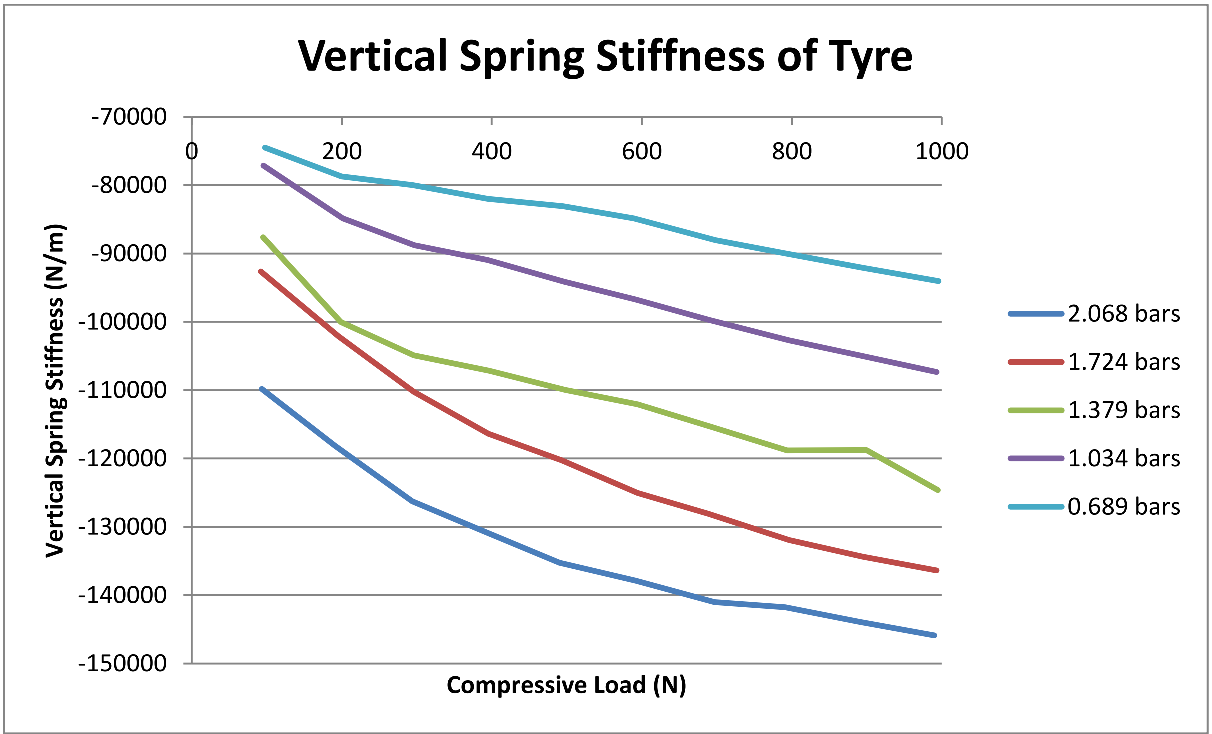


Figure 5.12.2 - Force vs. Vertical Spring Stiffness of the Tyre

The scale of the Compressive Load is exactly the same as Force vs. Deflection, however the scale of the Spring Stiffness is much greater. The values are negative, and with that the smallest negative value is -74,517.7N/m, and the greatest is -145,910.1N/m. The lines do not demonstrate as much linearity as previously, however a general linear relationship can be seen. For all the tyre pressure there is an increasingly negative value to the Vertical Spring Stiffness as the applied Compressive Load is increased.

Each tyre pressure exhibits this increasing negative value as load increases. A general Linear relationship can be observed for the highest 2 lines which are 0.689 bars and 1.034 bars. 1.379 bars shows a very inconsistent line shape, but there is still a negative gradient to the line.

Tyre pressures 1.724 bars and 2.068 bars can be assumed to exhibit a general linear relationship, however the steepness of their lines appears to be decreasing. A linear relationship will be observed, as there is not sufficient curve to assume a quadratic relationship, as well as the linear relationships observed from the other tyre pressures.

It is the order that the tyre pressures are placed on the graph that is important. The highest positioned line, that is the one that has the smallest negative maximum and minimum values for the vertical spring stiffness is that of the lowest tyre inflation pressure (0.689 bars). The position of the other lines is in order, with the lowest position that of the highest negative maximum and minimum values for vertical spring stiffness is that of the highest tyre inflation pressure (2.068 bars).

This causes another observation to be stated which is the higher the tyre inflation pressure the higher the vertical spring stiffness, which is a negative value. This means that the greater the tyre inflation pressure is the stiffer the tyre is in the vertical direction.

5.13 Conclusions

The results of the primary data are relatively simple to define. The more a tyre is compressed, the more it will deflect. This relationship is linear between the compressive load and deflection. It also showed that the greater the inflation pressure, the less the tyre deflected.

When calculating the vertical spring stiffness a similar conclusion is achieved. The greater the inflation pressure the greater the vertical spring stiffness. The inflation pressure was the only parameter that was varied, and shows that the pressure at which a car tyre is inflated to does have a dramatic effect on the vehicle’s handling properties due to the effect it has on vertical spring stiffness.

It is important to state that the vertical spring stiffness of the tyre does not directly represent the linearity of the vehicle handling. This instron testing is just one of a number of testing methods that is needed to build an accurate model to characterise the properties of the tyre. More can be done to evaluate the performance of the tyre, with respect to the tyre inflation pressure.

6.0 Conclusions

The work completed in this project is now assessed for conclusions to this study into Linearity and Bandwidth for vehicle handling. This project has altered and changed as it has progressed, and so these modifications will also be assessed, as well as recommend future work into this subject.

6.1 Original Project Aim

The original aim of the project was to assess 2 vehicle handling characteristics, Linearity and Bandwidth. This would be done by changing the tyre pressures on a car, and having test drivers evaluate the handling of the vehicle in relation to Linearity and Bandwidth, which both centre around Steering feel. This study began with the hypothesis that "Bandwidth is good, and Linearity is good."

6.2 Research Objectives

The objectives for this investigation were:

- To research information concerning vehicle handling and contain this in a literary review.
- To examine the effects of Linearity on Vehicle Handling.
- To examine the effects of Bandwidth on Vehicle Handling.
- To examine vehicle parameters that can affect Linearity and Bandwidth.
- To perform an experiment that tests driver preferences in Linearity and Bandwidth.

Due to changes in the project a number of these objectives required changing. For the project these objectives were restated as:

- To research information concerning vehicle handling and contain this in a literary review.
- To examine Linearity in Vehicle Handling.
- To examine the difference in Bandwidth between Vehicle Handling and the Driver's input.
- To examine vehicle parameters that can affect Linearity and Bandwidth.
- To perform an experiment that tests Tyre performance under load conditions.

6.3 Modifications to Project

The organizing of a Test Track, a Car and a number of Test Drivers for a vehicle handling study was not a possible course of action for this project. Instead Linearity and Bandwidth were assessed separately and by focusing on more quantitative data. The handling study would have generated qualitative data, because the results are calculated from the opinions of the test drivers.

This project cannot link the importance of subjective performance characteristics such as Linearity and Bandwidth in an objective method. This has been a common difficulty with vehicle handling as it is judged on how the driver feels about the performance. The experiments and tests that were conducted were not a part of the original plan, but do appropriately assess Linearity and Bandwidth in objective methods.

Due to the modifications to the project, the experiment cannot assess whether Linearity and Bandwidth are good, but still use this hypothesis as the basis for investigation. The experiments and tests demonstrate the importance and factors that can affect Linearity and Bandwidth, as opposed to whether they are desired or not.

6.4 Conclusions to Project

Bandwidth was shown to be an important vehicle handling characteristic. The simple yet effective experiment showed that human response frequency is significantly higher than the response frequency of a car, as assessed in the Excel mathematical models. The effects of this difference can cause complications in sudden driving manoeuvres, which may lead to a dangerous accident.

Bandwidth was assessed with an Excel model that showed the results graphically in the form of Natural Frequency. The graph displayed the frequency in Hertz of ideal values, which were lower than the results of the human response test. These are the conclusions of the Bandwidth assessment, but the effects of a difference in Bandwidth could be assessed further. The excel model did display ideal handling characteristics, which showed that a simple mathematical model can assess in an objective manner vehicle handling.

Linearity is a quality that is centred around tyre performance and how the slip angle of the tyre is proportional to the lateral force of the tyre. Tyre Linearity is a generalised view, as tyres do not necessarily respond in a perfectly linear manner. The Excel models used Cornering Stiffness as a single linearized value to evaluate vehicle handling, which provides an approximate evaluation.

A tyre was tested for vertical spring stiffness in relation to varying internal pressures. This provided the conclusion for tyre linearity that the higher internal pressure the tyre is, the greater the vertical spring stiffness, and the results do demonstrate a generalised linear relationship. Only 1 tyre was tested, which was a racing tyre and so this test could easily be repeated for other tyres of differing sizes, widths, rubber compositions, tread patterns and tyre manufacturers.

6.5 Strengths and Limitations

The main strength of the modified project is that the results are all objective, which rely on values as opposed to opinions. Vehicle Handling is a much argued over subject between different vehicle dynamicists, about what is better. This project has not demonstrated which is better, but has assessed 2 of the characteristics that are involved in this dispute. Another strength is that the handling characteristics of Linearity and Bandwidth have been assessed and evaluated. The parameters that influence Linearity and Bandwidth have in part been examined.

The limitations of this project include the absence of testing a real car. The results are all drawn from factors outside the car. Human response was conducted scientifically with clearly stated fixed parameters, but the motion of sliding a phone is different to that of turning a wheel. This could provide differing results. The tyre linearity is limited in the fact that the tyre is static, and a rolling wheel may behave differently. However a rolling tyre rig is not a machine that was available for this project.

6.6 Recommendations for further Research

Assessing human response compared to vehicle response may be better demonstrated with an actual car test. A similar device to record input frequency can be attached to the steering wheel, and another to the dashboard. This would provide primary data for the human response at the steering wheel, and the vehicle response at the dashboard. The driver would need to drive at a constant speed, as varying speed can affect bandwidth as demonstrated in the excel models.

Bandwidth is a factor that has not yet been evaluated as to the causes. A simple hypothesis that has not yet been evaluated is that "High Bandwidth is achieved with low mass and wide tyres." This is a statement that if investigated could provide more insight into how the response of the car to steering input can be affected, should a car need to modify its response frequency.

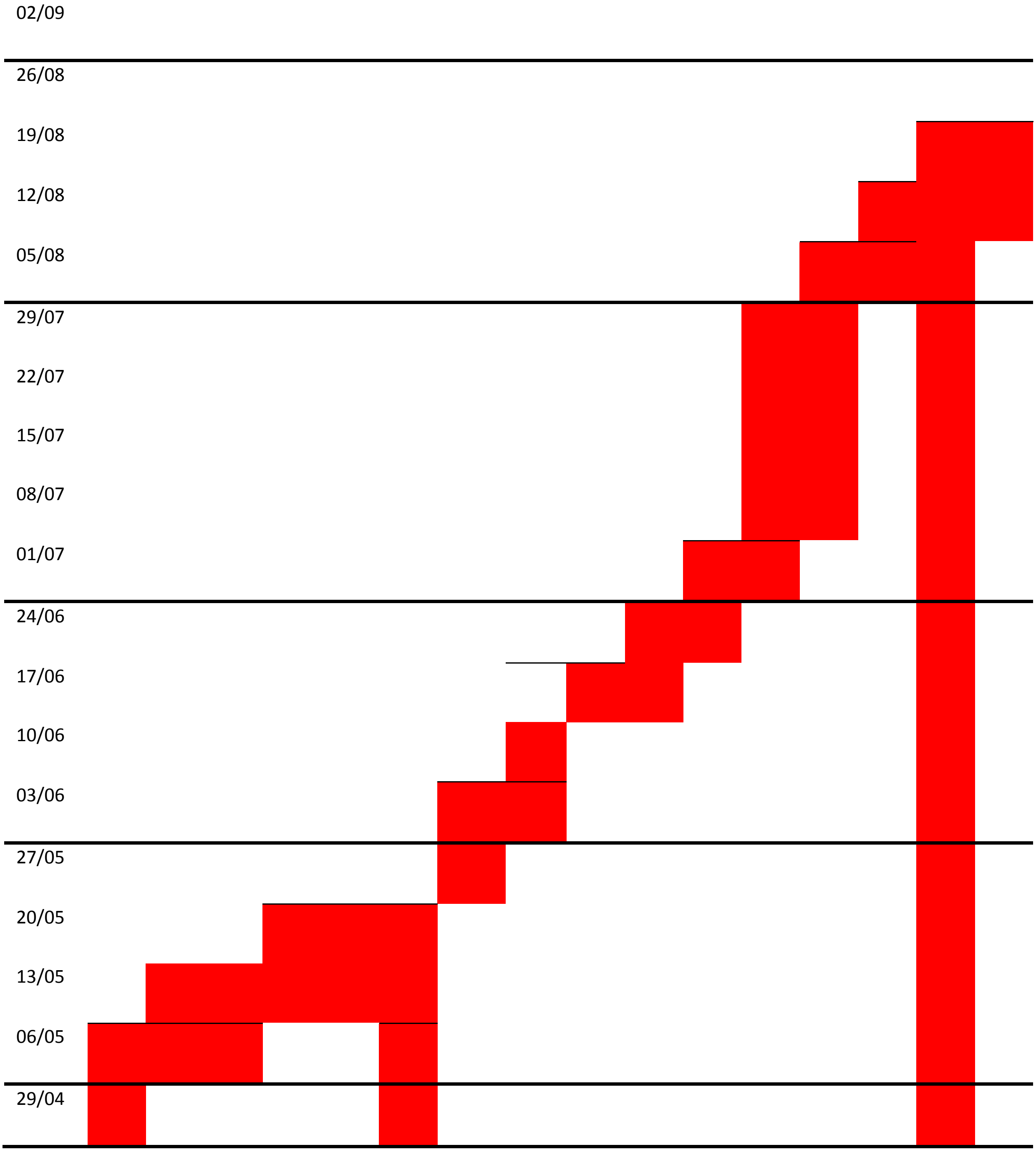
Continuing the tyre instron test can be done with a variety of car tyres, a racing tyre for the formula student car may act differently from other tyres. A full test of car tyres from racing cars, to sports cars, to mass market family cars, to off-road cars would provide a variety of tyres to base conclusions upon.

It would also be valuable to assess the change in damping for the tyre with tyre pressure. The Natural frequency of the tyre will change if the mass and stiffness of the tyre changes. It would be useful to assess if this changes with tyre pressure. Natural frequency can change and assessing which parameters can affect this will show how the frequency response of the tyre changes.

The main recommendation for future work would involve the original plan of testing a real car at a test track and assessing the subjective preferences of the test drivers in an objective manner. This would provide insight into preferred vehicle handling, and so the factors assessed in this project can then be further defined with respect to their purpose. Although this would provide qualitative subjective data, vehicle handling is a driver’s interpretation of vehicle control and a better understanding of vehicle handling preferences would aid development of cars possibly cutting development costs.

Appendices

Appendix Original Project Plan



Section of Investigation	
Literary Review	Literary report on Vehicle Dynamics, Grip and Balance
	Literary report on vehicle models, Suspension and Tyres
	Literary report on Driver-Vehicle Relationship
	Literary report on existing research in handling
	Literary report on vehicle handling
	Format all literary review reports and create appendix
Bandwidth test	Experiment displaying importance of bandwidth
Excel Work	Examine vehicle parameters affecting handling in excel
Experimental Vehicle Test	Define intent of vehicle test
	Define manoeuvres and how they test vehicle handling
	Organize the test (drivers, car, track, etc.)
	Test the experimental car
	Collate and interpret results
	Define the conclusions from the results
	Format report with appropriate appendix
	Create PowerPoint presentation for Viva

Appendix Tyres

AT.1 Footsteps

Haney, P (2003) p21 discusses that a tyre is elastic, and elastic materials such a rubber are known to yield when an external force is exerted on them, resist movement to this external force with an opposite force, and recover to its original shape when the external force is removed. It is this elasticity that allows the tyre to point in different directions to the direction of the vehicle. The result of this is that the leading edge of the tread contact the road surface biased to one side of the contact patch. The tyre rolls which bring new tread rubber, called increments around to the contact patch. As each new increment contacts the road surface, it becomes closer to the direction in which the tyre is pointing.

It is the mass of the car which pushes down on these increments, causing them to stick to the road surface. The tread pulls on the rest of the tyre, which generates force to go through the wheel and Suspension, which causes the car to turn. Therefore the actual force which is required to change the vehicle's path is generated by the tyre.

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Figure AT.1 - Footsteps, Analogy of Slip Angle

Haney, P. (2003) The Racing & High-Performance Tire. 1st edn. Warrendale, Pa: TV MOTORSPORTS and SAE. P21.

Haney, P (2003) p21 uses Footsteps to describe the similarity between a person walking and how a car tyre changes direction. *"A person walking on a circular path changes direction in small increments. At each step a foot is turned in a small angle along the path of the arc. The next step also changes the walker's path a small amount. These small changes continue to build up and the walker's path becomes an arc.*

"Each small increment of tread rubber rotating into contact with the road surface latches onto the road surface a small increment toward a new heading." It is because the tyre is made of an elastic material that allows it to deform as it rotates. It deforms in the contact patch area, where the mass of the car is exerted on the road, and then the tyre recovers when the mass is no longer acting on that contact patch.

AT.2 Rubber Friction

Tyres are made of Rubber, which is a Polymer. To examine the usefulness of Rubber is important to investigate its uses from a vehicle handling perspective. The tyre is a complex chemical composition of vulcanized rubber, but the usefulness of a tyre can never be overstated. It is therefore important to investigate how such a material is used to great effect as tyres.

AT.2.1 Simple Friction

Friction is described by Toolingu.com (2012) as "*A force that resists motion between two objects that are in contact with each other*." Friction is important for the world to work, especially for tyres interacting with the road surface.

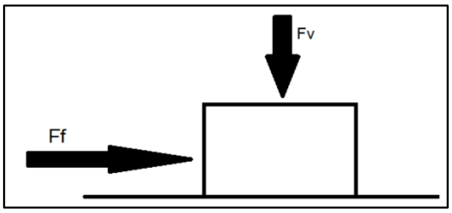

Figure AT.2.1 - Friction Coefficient

There is a general equation which describes Friction.

$$Ff = Cf \ x \ Fv \qquad [41]$$

This shows that the Friction Force (Ff) equals the Coefficient of Friction (Cf) multiplied by the Vertical Force of the object (Fv). It is important to note that the Static Cf is usually higher than the Dynamic Cf, meaning the object requires more force to move it from stationary, than to keep it moving. The Coefficient of Friction is a value which described how 2 material surfaces interact with one another. Therefore it is very important to know the relationship between the tyre and the road surface.

Metal on Metal (dry) can often have a Cf of 0.15 – 0.20, whereas Leather on Metal (dry) is quoted by Haney, P (2003) p38 as being 0.56. The Cf is a unitless value, as it is the product of one force being divided by another. If a Cf greater than 1.0 is achieved by 2 materials, this means that the object requires more force to move than the force pushing it down. Glass is a smooth material and can often have a low Cf with the material it is interacting with. Rubber on Glass (dry) has a Cf quoted as being greater than 2.0 by Haney, P (2003). This shows that Rubber is capable of high friction forces.

AT.2.2 Rubber Friction

The high friction of Rubber can be explained by the 3 ways in which the material generates Friction. These are Adhesion, Deformation and Wear.

AT.2.2.1 Adhesion

Haney, P (2003) p39 says that "*Adhesion is generally thought to be the result of momentary molecular bonding between the two surfaces.*" This is one of the components of friction that a tyre experiences with the road surface. Rubber is a material that changes shape, especially when it is in contact with the road surface. The tyre will press into the irregular road surface increasing the amount of surface area between the tyre and road. The more surface area results in more adhesion, which in turn creates higher friction forces.

AT.2.2.2 Deformation: Mechanical Keying

When the tyre is in contact with the road it deforms and changes shape to generate friction forces. The tyre will shape into the irregular road surface, which can also be called Mechanical Keying. The changing shape of the tyre makes it difficult for the tyre to slide out of the irregular shapes. Friction forces due to deformation are essential because they provide most of the friction force between a tyre and a wet road surface.

The term Hysteresis can be used to describe deformation, as CDXeTextbook.com (DNK) states that "*Hysteresis is the energy lost when a section of vulcanized rubber is deformed in a regular manner.*"

AT.2.2.3 Tearing and Wear

Uneven and rough road surfaces will cause stresses that exceed the tensile strength of the rubber. This causes tearing which is when the tyre deforms the internal structure of the rubber exceeding the point of elasticity. Tearing actually absorbs energy, which adds to the friction forces at the contact patch. Wear is the result of tearing, which Haney, P (2003) p41 describes as "*local stresses increase in strength past initial tearing or remain at high strength for a period of time, that tearing can result is separation of material.*"

AT.2.2.4 Total Friction

A tyre cannot rely on one type of friction. Adhesion is a vital friction force, but it will not work on a wet road surface, as the water prevents adhesive bonds from forming. Therefore the tyre must rely on another friction force. The friction force that connects a tyre to the road is not usually just one of these forces. The Total Friction is defined by Haney, P (2003) p41 as:

$$Ftotal = Fadhesive + Fdeformation + Fwear \quad \textbf{[42]}$$

AT.2.3 Road Surface Effects

The road surface has a big effect on how the tyres work, because the coefficient of friction is a statement of friction between two material surfaces. A road is often an uneven surface with bumps and potholes, even on an apparently flat road surface. These bumps and potholes interact with the tyre and the friction methods in which the tyre contacts the road. A surface with irregularities will benefit the friction force of deformation, but will also increase wear.

Roads are usually constructed using Asphalt (Tarmac), but these aren't the only road surfaces. Concrete is another popular material for road construction, which will interact with a tyre differently to Asphalt. These are 2 materials which are generally fixed surfaces, but modern road cars are expected to drive on gravel, grass, mud, snow and ice. All of these surfaces will interact differently with tyres, but also have another factor which is that they are road surfaces which are not fixed. It is common to see a car on a gravel road pushing the gravel backwards as it travels over it.

AT.3 Rubber Compounding

Haney, P (2003) p55 describes both the importance and difficulty in selecting the Rubber Compound for a tyre. An example given is the Hysteresis of a tyre, "*Low-hysteresis rubber in the tread is desirable for less rolling resistance and low operating temperatures in road-car tires. But high-hysteresis rubber is better for racing applications.*" This example shows the complexity of selecting the rubber compound for a tyre, as it depends on the intended purpose and usage of the vehicle.

AT.3.1 Which Rubber?

There are many different materials which can be used for the rubber of a tyre. Information given by Haney, P (2003) p56-57 explains a number, and the differences between them. "*NBR is acrylonitrile gum rubber, NR is natural rubber, Butyl is polyisobutylene, and SBR is styrene butadiene.*"

Further information is given about the properties of rubbers used to decide on a rubber for the construction of the tyre. Rebound is a test for hysteresis, where a higher hysteresis rubber will rebound less than a lower hysteresis rubber. Hardness is another property which is measured by a stylus penetrating the rubber and providing a durometer reading. The final property listed is stopping distance. Haney, P does state that "*anything that you can do to a rubber compound to raise its hysteresis and lower its hardness will decrease the stopping distance (increase the grip) of a tire using that compound.*" It is also said that compromises are needed because "*a soft, high-hysteresis rubber is highly skid resistant but wears rapidly, so the most difficult qualities to obtain simultaneously are high skid resistance and high wear resistance.*"

AT.3.2 Recipe for a Tyre

A tyre is not just rubber, and will in fact be a mixture of compounds. They can be classified by the following as stated by Haney, P (2003) p57:

1. Rubber – a single polymer or a blend of polymers with a high molecular weight
2. Extending Oil
3. Filler Systems – blends of various carbon blacks, silicas, or newer alternate filler materials
4. Small amounts of processing aids such as softeners, plasticizers, or reclaimed rubber
5. The chemical vulcanization system which can include 2 accelerators, sulphur and zinc oxide
6. Other chemicals such as antioxidants and antizonants

It is part of the challenge of developing the ideal tyre for a car to blend varying amounts of these compounds. They will each produce a rubber compound with varying performance characteristics. The largest compound will be the rubber, but the other compounds are those that change the rubber into the ideal material for the tyre.

AT.4 Lateral Deformation of the Tread

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Figure AT.4 - Lateral Deformation in the Contact Patch

Haney, P. (2003) The Racing & High-Performance Tire. 1st edn. Warrendale, Pa: TV MOTORSPORTS and SAE. P98.

The generation of a slip angle is due to the elastic characteristics of the pneumatic tyre. A car can turn a corner at speed due to tread's grip on the road surface as well as the forces that resist deformation of the tyre. It is important to examine tread deformation in the contact patch of a rolling tyre.

The tyre which is examined in Figure AT.4 is rolling to the left and also has some right hand steering angle which produces a resultant slip angle. Point A is the leading edge of the contact patch, and is called the initial deflection. Point B marks the point at which the tread begins to recover from the maximum lateral deflection. Point C is the final point of the contact patch, when the tread rotates out of the contact patch.

The dotted line with the arrowhead is the direction the vehicle is heading. The X axis is the Wheel heading and also the zero deflection line, the angle between these 2 lines is the slip angle.

The solid red line is the tyre lateral deformation from an unstressed position. It is the tyres resistance to deflection that turns the car. The difference between the zero deflection line and the tyre lateral deformation line is the distance the tyre deflects. Notes are from Haney, P (2003) p97-98.

AT.5 Balance and Control Continued

AT.5.1 Consequences of Imbalance

When a car is balanced both front and rear tyres are operating at the same slip angles which generates maximum grip. When the car understeers or oversteers it is imbalanced, and so one set of tyres is working at less than the maximum slip angle so the car is not generating the maximum possible lateral force.

Tyres that operate at any slip angle generate friction, which increases with slip angle. Understeer causes the front tyres to operate at a higher slip angle, which causes more friction than if it were balanced. This slows the car in a corner, as the power of the engine must overcome tyre friction.

AT.5.2 Control at the Limit of Adhesion

Haney, P (2003) p122-123 describes the conditions of differing front to rear slip angles as discussed in 2.5.1 Oversteer and Understeer. He states that they "*are of no consequence as long as the tyres are operating in the linear portion of the side force vs. slip angle curve. Tyre stiffness, determined by design but adjusted by tyre pressure, determines the slope of the curve in this area.*" The curve is the one described in Figure 2.1.2.1 Lateral Force vs. Slip Angle.

These conditions do affect the vehicle's behaviour when the tyres are operating at their maximum levels of grip, as most of the contact patch is sliding. Haney, P describes an important factor here "*The pair of tyres (front or rear) reaching the limit first give up control. The front tyres of an understeering car at the limit are operating at a high slip angle and more steering earns no extra grip. The rear tyres, however, can still go up the curve, but there is no steering wheel for the rear tyres.*

"*Due to the friction circle phenomenon an increase in driving force at the rear tyres dictates an increase in slip angle for those tyres. So an understeering car at the limit can use the rear tyres better with the careful addition of some throttle. Or the driver can carefully let off the throttle and the car will slow down, regaining front grip and control.*

"*If the rear-tyre pair gets to the top of the curve first, control is also lost at that end. The throttle doesn't help anymore, but the driver can still control the car by letting out steering input to save the spin and letting the car go to a larger-radius turn.*"

These observations by Haney, P link together a number of the sections of this review to explain their importance in real world experiences.

Appendix Suspension

AS.1 Typical Independent Suspension Designs

There are many different Independent Suspension designs which can be explored here. However, there are many components to suspension design which greatly affect the performance of the suspension. The most common types of independent suspensions will be examined here.

AS.1.1 Springs

For the suspension designs investigated here the springs are in the form of helical springs. These are important to the function of suspension, as a coil spring is an elastic component which can compress and expand due to a force exerted on the spring. The motion is in one orientation, which is along the spring axis. The spring is an elastic component, and so has no damping capabilities.

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Figure AS.1.1 - Helical Compression Spring Diagram

Trakar (2013) Design Considerations for Compression Springs[online] available from <http://www.trakar.com/spring-training/compression-springs/> [29 January 2013]

The characteristic of a spring depends on the variables shown in Figure AS.1.1. It is a combination of Spring Rate and Damping Coefficients that create a performance characteristics often categorised as Ride quality. They also influence handling as a stiffer spring will push the wheel onto the road more quickly, and a higher damping coefficient will reduce the number of oscillations the vehicle body will experience after an excitation.

AS.1.1.1 Spring Equations

L	Free Length (Base Length) of Unloaded Spring	N	Number of Active Coils
d	Wire Diameter	f	Maximum Shear

D Mean Diameter

W Load

c Coil

t Torsion Bar

S Spring Rate

X Deflection

$$f = \frac{8DW}{\pi d^3} = 2.55DW/d^3 \qquad [43]$$

$$D = 1.99(\frac{dc}{dt})^3 R \qquad [44]$$

$$S = \frac{Gd^4}{8D^3N} \qquad [45]$$

If a spring is loaded along its centreline $X = \frac{W}{S}$ **[46]**

2 springs in series $S = \frac{S_1 S_2}{S_1 + S_2}$ Multiple springs in series **[47]**

$$\frac{1}{K_t} = \frac{1}{K_1} + \frac{1}{K_2} + \frac{1}{K_3} \dots. \qquad [48]$$

2 springs in parallel $S = S_1 + S_2$ **[49]**

$$X = \frac{F}{S} = \frac{F}{S_1 + S_2} \qquad [50]$$

AS.1.2 Dampers

How Stuff Works.com (2005) is a detailed source to explain the uses of dampers, and their definition of this critical device is "*a device that controls unwanted spring motion through a process known as dampening. Shock absorbers slow down and reduce the magnitude of vibratory motions by turning the kinetic energy of suspension movement into heat energy that can be dissipated through hydraulic fluid.*"

It is again this source that explains that a damper is in effect an oil pump, placed between the chassis and the wheel. The upper mount of the damper is connected to the chassis (the sprung weight of the vehicle) and the lower mount is connected to the axle (the unsprung weight). When the vehicle encounters a bump, this causes the spring to coil and uncoil. The Hydraulic Oil inside the damper must pass through the holes in the Working Piston causing friction. This is how the damper dissipates this kinetic energy as heat energy.

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Figure AS.1.2 - Twin-Tube Damper

How Stuff Works.com (2005) Dampers: Shock Absorbers [online] available from <http://auto.howstuffworks.com/car-suspension2.htm> [29 January 2013]

How Stuff Works.com (2005) again provides an explanation for the motion of the damper "*Shock absorbers work in two cycles -- the compression cycle and the extension cycle. The compression cycle occurs as the piston moves downward, compressing the hydraulic fluid in the chamber below the piston. The extension cycle occurs as the piston moves toward the top of the pressure tube, compressing the fluid in the chamber above the piston.*"

AS.1.2.1 Damper Equations

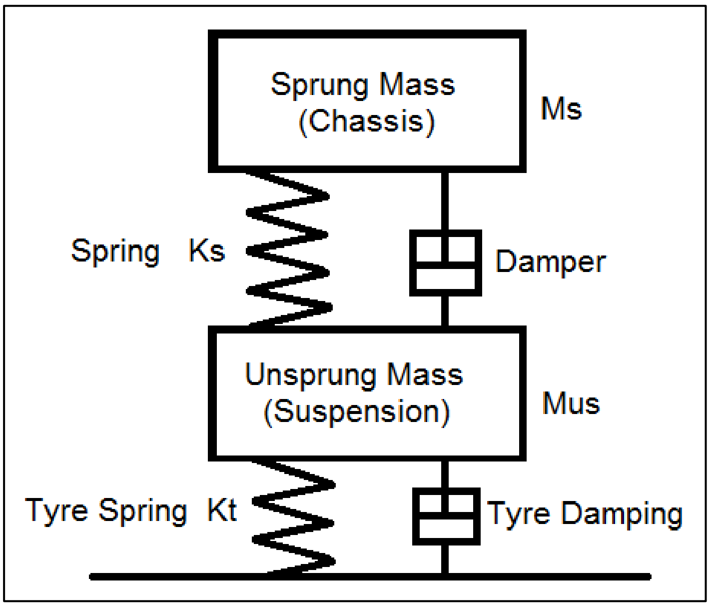

Figure AS.1.2.1 - Mass-Spring-Damper Diagram

Sprung Mass

$$fn\ (S) = \frac{1}{2\pi}\sqrt{\frac{(Ks\ x\ Kt)/(Ks+Kt)}{Ms}} \qquad [51]$$

Unsprung Mass

$$fn\ (US) = \frac{1}{2\pi}\sqrt{\frac{Ks+Kt}{Mus}} \qquad [52]$$

Cr = Critical Damping Coefficient

$$Cr = 2\sqrt{Ks\ x\ M} \qquad [53]$$

Ks = Spring Rate M = Mass

Cs = Suspension Damping Coefficient

$$\text{Damping Ratio} = \frac{Suspension\ Damping\ Coefficient}{Critical\ Damping\ Coefficient} = \frac{Cs}{Cr} \qquad [54]$$

AS.1.3 Bushes

Car Bibles.com (2012) explains the importance of bushes. Suspension bushes are grommets which prevent parts of the suspension rubbing against one another (friction). They are usually made of Rubber, but can also be Polyurethane or Polygraphite. These bushes have an effect on ride and handling, as a harder compound will cause a more uncomfortable ride experience in the cabin. Bushes are exerted to the environment and the stresses of suspension components, and so will wear out over time. It is important to replace bushes, which can provide a dramatic change in the vehicle's ride and handling performance.

AS.1.4 McPherson Strut Suspension

Information and images regarding McPherson Strut suspension is obtained from CarBibles.com (2012). McPherson Strut suspension is commonly used on most cars, especially those which are from European origin. The Spring and Damper form the upper strut, and the wheel knuckle forming another load bearing strut. The packaging for this suspension design makes it very suitable for Front wheel drive vehicles, which do not have much space to spare.

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Figure AS.1.4 - McPherson Strut Suspension

CarBibles.com (2012) The Suspension Bible [online] available from <http://www.carbibles.com/suspension_bible.html> [06 February 2013]

Advantages

Standard Independent Advantages

Independent Front Suspension, resulting in good Ride Quality and Road Holding.

Size and Packaging

Relatively Compact, allowing for small packaging Dimensions. Well suited for Small cars

Suited for Front Wheel Drive

Using Strut as Upper Suspension Link, there are no components or structures obstructing the steering knuckle. Providing clearance for Driveshaft.

Disadvantages

Scrub Radius Issues

Difficult to increase tyre width of wheel. This can only be achieved by increasing scrub radius of tyre which moves through range of suspension travel. This increases Side Loading on suspension, and may result in components bending.

Lack of Camber Gain

Little to No Camber Gain when wheel moves up in Bump Movement. Chassis will roll on the suspension, tyre rolls in Positive Camber, and reduces overall cornering power of tyre.

AS.1.5 Double Wishbone Suspension

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Figure AS.1.5 - Double Wishbone Suspension

CarBibles.com (2012) The Suspension Bible [online] available from <http://www.carbibles.com/suspension_bible.html> [06 February 2013]

Information and images regarding Double Wishbone suspension is obtained from CarBibles.com (2012). Double Wishbone Suspension is a suspension design which is favoured in motorsport. It is also used on more high performance production cars. The basic design consists of 2 arms which take the shape of wishbones. They are joined by the wheel knuckle, to which the wheel and brake assembly are attached. The most common form of wishbone has the spring and Damper connected to the lower wishbone at the bottom, and the chassis at the top. This suspension design is favourable in high performance applications as it allows for adjustments to Camber levels and Roll Centre settings, both of which are important for handling.

<u>Advantages</u>

Kinematics

Easy to work out effects of Moving Joints. Can easily adjust the Kinematics of the system to Optimize wheel motion.

Handling

Increasing Levels of Negative Camber, throughout Suspension Movement.

Performance

Relatively Low Unsprung Mass, lends itself to High Performance Vehicles.

<u>Disadvantages</u>

Complexity

It is a complex system, and as a result it is quite expensive to Manufacture.

Packaging

It is difficult to package in cars with limited space for suspension.

AS.1.6 Pushrod Suspension

Pushrod and Bellcrank Suspension is an evolution of Double Wishbone Suspension. Haney, P (2003) p247-249 explains that the Double Wishbone is maintained, but the Spring and Damper have been relocated inside the body of the vehicle. For the motion of the wishbone to be transmitted to the spring and damper, a Pushrod and Bellcrank are used.

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Figure AS.1.6a - Pushrod and Bellcrank Suspension

Haney, P.W (2003). *Racing & High Performance Tire: Using Tires to Tune for Grip and Balance*. Warrendale, Pa: SAE International. P247-249.

This suspension design has a number of benefits over the regular Double Wishbone designs which are:

- This system is compact, easily adjustable and easy to maintain.
- The Anti-Roll bar can be operated by a Torsion spring.
- The relocation of the Spring and Damper brings the mass inboard, reducing the unspring mass of the suspension.
- The angle of the pushrod can be optimized as it determines a large part of the motion ratio.

The Bellcrank is an adjustable component, and as the diagram shows the geometry of the r lengths results in changing the positions of the h linkages. Haney, P states that "*Changing the pushrod mounting from hole "h1" to "h2" increases the motion ratio, causing more coilover motion for a given pushrod movement.*"

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Figure AS.1.6b - Adjustable Motion Ratios with Bellcrank

Haney, P.W (2003). *Racing & High Performance Tire: Using Tires to Tune for Grip and Balance*. Warrendale, Pa: SAE International. P247-249.

The Anti-Roll bar linkages can have separately adjustable motion ratios as well, as the Anti-Roll bar is connected to the Bellcrank.

Pushrod Suspension was developed for open wheel racing, and a third spring attached to the anti-roll bar can keep the ride height of the vehicle constant at high speed. Aerodynamic forces deflect the main springs, where the solution would be to fit stiffer springs. This would help with the high aerodynamic loads at high speeds, but will keep the ride very stiff at lower speeds. Having a third spring allows the main springs to be the correct stiffness, as the third spring does not engage at low speeds, so softer springs can provide a better ride in slow corners.

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Figure AS.1.6c - Third Spring added for Aerodynamic Forces

Haney, P.W (2003). *Racing & High Performance Tire: Using Tires to Tune for Grip and Balance*. Warrendale, Pa: SAE International. P247-249.

Pushrod suspension is favoured in motorsport for its adjustability and ease of use. It has not been applied to production vehicles with great popularity. However, as racing companies expand their understanding of the design, this system has begun to appear in high performance production cars.

AS.1.7 Multilink Suspension

Information and images regarding Multilink suspension is obtained from AutoEvolution.com (2013). Multilink suspension is another evolution of Double Wishbone suspension. It uses 3 or more lateral arms and 1 or more longitudinal arms. It can be used for either front or rear suspension. Multilink suspension includes a number of different designs, and so here is a diagram of differing designs from AutoEvolution.com (2013).

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Figure AS.1.7 - Multilink Suspension Designs

AutoEvolution.com (2013) Possible multi-link layouts [online] available from <http://www.autoevolution.com/news-image/how-multi-link-suspension-works-7804-3.html> [07 February 2013]

Multilink suspension provides the best compromises between Handling and packaging, and Comfort and Handling. This is why it is considered the best independent system for a production car. It is also very simple to adjust one parameter in the suspension, without the need to adjust the entire suspension assembly. This is a preferably characteristic, as the same is not true of Double Wishbone Suspension.

Multilink suspension does have a number of disadvantages, such as it is expensive to produce, which is only made more expensive due to the complexity of the design. It is however becoming more and more accessible to mainstream cars, and not just reserved for luxury cars.

AS.2 Camber Angle

Blundell, M and Harty, D (2004) p163-164 describe Camber Angle (γ) as "*the angle measured in the front elevation between the wheel plane and the vertical. Camber angle is measured in degrees and taken as positive if the top of the wheel leans outwards relative to the vehicle body.*"

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Figure AS.2a - Camber Angle

BenzWorld.org (2009) Rear Tire wear due to negative camber [online] available from <http://www.benzworld.org/forums/w126-s-se-sec-sel-sd/1678465-rear-tire-wear-due-negative-camber.html> [10 January 2013]

Camber Angle is a Suspension setting which effects on the way the vehicle handles, and can provide Camber Thrust to increase Lateral Forces. The point of Camber Angle is to maximise the contact patch between the tyre and the road surface, and having more of the tyre in contact with the road surface increases the grip between the two. This results in higher speeds being achieved when cornering. Having a Camber angle does reduce the contact area between the tyre and the road surface, which can provide poorer performance when travelling in a straight line, accelerating or braking. However, the benefits of Camber are noticed when the car turns a corner.

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Figure AS.2b - Camber Thrust

Wood, G. (2011) *Tyre Forces and Moments 2.* Lecture delivered for module 306MED on 28 October 2011 at Coventry University.

Camber Thrust is a lateral force which can be used to help the wheel turn a corner. Figure AS.2b shows how the leaning tyre generates a reaction of Camber Thrust. It does not provide as much Lateral force as a Slip Angle would, however equal negative camber on both sides of the vehicle will counteract one another, so the lateral force provided by a Camber angle will not affect the car in motion. Negative Camber adds to the lateral force of the slip angle, to increase the lateral force causing a wheel to turn. It is this that can show that Positive Camber can cause negative camber thrust, and so reduce the lateral force of the turning wheel, causing the effect of understeer.

As the car turns it is the outside wheel which affects how the car handles. Terry Crew from Reality Racing stated on Wannarace.co.uk (DNK) that “*As the body rolls during cornering the wheel leans out too but as it had negative camber to start with the wheel will sit near vertical allowing maximum surface contact of the tyres to the track. This in turn generates more grip in the corners and allows us to corner more quickly. It also reduces rolling resistance and allows higher straight-line speeds to be reached*.”

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Figure AS.2c - Effects of Camber Angle Change

Wannarace.co.uk (DNK) All You Need To Know About – Camber Angle [online] available from <http://www.wannarace.co.uk/page_2275336.html> [24 January 2013]

It is this reasoning that negative camber is favoured in many motorsport and high performance applications as it provides increased grip in heavy cornering as stated by Yospeed.com (2010). Suspension travel does affect the Camber Angle of the wheel, and so for motorsport the designers must maintain negative camber throughout the suspension movement.

Ozebiz.com (DNK) explain that “*While maintaining the ideal camber angle throughout the suspension travel assures that the tire is operating at peak efficiency, designers often configure the front suspensions of passenger cars so that the wheels gain positive camber as they are deflected upward. The purpose of such a design is to reduce the cornering power of the front end relative to the rear end, so that the car will understeer in steadily greater amounts up to the limit of adhesion. Understeer is inherently a much safer and more stable condition than oversteer, and thus is preferable for cars intended for the public*.”

AS.3 Castor Angle

Blundell, M and Harty, D (2004) p164-164 describe Castor Angle (Φ) as “*the angle measured in the side elevation between the steering (kingpin) axis and the vertical. Castor angle is measured in degrees and taken as positive if the top of the steering axis leans towards the rear.*”

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Figure AS.3 - Castor Angle

Team TWF8 (DNK) Caster Set-up [online] available from <http://www.twf8.ws/new/tech/tip/setup/caster.html> [10 January 2013]

Yospeed.com (2010) explains that often when a car has positive Castor this will make it more stable at high speeds. When the car turns a corner positive Castor will increase Tyre Lean, but will also increase the amount of Steering Effort.

Most road vehicles will have a setup which is called Cross-Castor. Cross-Castor has different Castor and Camber angles, which has the effect of causing the vehicle to drift to one side of the road if un-manned. It is a safety feature which is used when the vehicle is un-manned or the driver loses steering input the vehicle will drift to the side of the road, instead of into oncoming traffic.

AS.4 Steer Angle

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Figure AS.4 - Steer Angle

Wheels-InMotion (2013) Wheel Toe-In and Tow-Out Theory [online] available from <http://www.wheels-inmotion.co.uk/tech-wheeltoeintoeout.php> [10 January 2013]

Blundell, M and Harty, D (2004) p163-164 describe Steer Angle or Toe Angle (δ) as "*the angle measured in the top elevation between the longitudinal axis of the vehicle and the line of intersection of the wheel plane and the road surface. Steer angle is taken here as positive if the front of the wheel toes towards the vehicle.*" This is also referred to as "Toe In" or "Positive Toe", and the reverse is called "Toe Out".

Yospeed.com (2010) explains that Toe In causes both wheels to generate forces acting against one another, which in turn reduces the ability of the car to turn a corner. However, it does also provide the vehicle with straighter driving characteristics. The type of car is important for determining the Steer Angle. For example, a Rear wheel drive car will usually have slightly positive toe on the rear wheels as a result of rolling resistance. This causes outward drag on the suspension arms, which at speed will straighten out the wheels and prevent tyre wear.

The opposite is true of Front wheel drive vehicles, which use Negative Toe. This is because typically their suspension arms will pull inward, and so Negative Toe will level out the wheels at speed. Yospeed.com (2010) describes in detail the effects of Negative Toe, "*Negative toe increases a cars cornering ability. When the vehicle begins to turn inward towards a corner, the inner wheel will be angled more aggressively. Since its turning radius is smaller than the outer wheel due to the angle, it will pull the car in that direction. Negative toe decreases straight line stability as a result. Any slight change in direction will cause the car to hint towards one direction or the other.*" Even though the cornering ability may be desirable in some motorsport applications, generally the stability of a vehicle due to positive toe is what is applied to most production vehicles.

AS.5 Bump Movement, Wheel Recession, Half Track Change and Roll Steer

Bump Movement, Wheel Recession and Half Track Change are all movements the wheel can travel relative to the vehicle body. Bump Movement refers to the Z vertical direction, and occurs when the wheel encounters a bump, which moves the wheel vertically upwards. Wheel Recession and Half Track Change are horizontal movements in the X and Y directions respectively. Blundell, M and Harty, D (2004) p163 give these definitions. It is important to note, as they can affect the wheels influence on the road, which will result in an effect on vehicle handling.

Another factor which can affect handling is called Roll Steer. Gillespie, T (1992) states that "*When a vehicle rolls in cornering, the suspension kinematics may be such that the wheels steer. Roll Steer is defined as the steering motion of the front or rear wheels with respect to the sprung mass that is due to the rolling motion of the sprung mass. Consequently, roll steer effects on handling lag the steer input, awaiting roll of the sprung mass.*"

The importance of these behaviours is that they can affect how a vehicle performs. They influence the wheels when ideally the inputs to the wheels whether they are front or rear come from the driver. It is therefore the job of the suspension to keep the driver in control of the wheels, even when there are other inputs to the wheels.

AS.6 Suspension 'Anti' Geometry

The term anti-geometry is defined by Milliken and Milliken (1995) p617 as an "*effect in suspensions that actually describes the longitudinal to vertical force coupling between the sprung and unsprung masses. It results purely from the angle or slope of the side view swing arm*." The side view swing arm (svsa) is a parameter which is defined by the Instant Centre (IC), which is the point at which the pitching motion of Dive, Lift or Squat can act.

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Figure AS.6 - Car Free Body

Milliken,W and Milliken,D (1995). *Race Car Vehicle Dynamics*. Warrendale, Pa: SAE International. P617-619.

The longitudinal load transfer can be described by the diagram shown in Figure AS.6 and the equation:

$$\Delta Load = W\ x \frac{a_x}{g} x \frac{h}{l} \qquad [55]$$

Where Weight (W), CG height (h), Wheelbase (l), Gravitational Constant (g) and forward acceleration (a_x) are utilised. It can be noted that Braking force = Weight x (a_x/g).

AS.6.1 Anti-Dive

Dive is the event when the front of the car drops under braking. Anti-Dive reduces the bump deflection of the front suspension in forward braking. The following Figure AS.6.1a from Milliken and Milliken (1995) p617 displays another freebody diagram for a vehicle with Outboard brakes, which describes the opposing forces from Anti-dive and anti-lift geometry. They state that the percentage *"(%) brake distribution (or brake balance) determines the actual force as a fraction of the total longitudinal force; the % anti-dive on the front is given by:*

$$\%\ anti - dive\ front = \frac{W(\frac{a_x}{g})(\%\ front\ braking)(\frac{svsa - height}{svsa - length})}{W\ x\ \left(\frac{a_x}{g}\right) x\ (\frac{h}{l})} \qquad [56]$$

$$\%\ anti - dive\ front = (\%\ front\ braking)(tan\Phi_F)(\frac{l}{h}) \qquad [57]$$

For rear anti-lift calculation, substitute tanΦ_R and % rear braking."

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Figure AS.6.1a - Anti-dive Free Body

Milliken,W and Milliken,D (1995). *Race Car Vehicle Dynamics*. Warrendale, Pa: SAE International. P617-619.

Milliken and Milliken (1995) p618 describe that when "*all the longitudinal load transfer is carried by the control arms and none by the suspension springs, so the suspension does not deflect when braking or accelerating*" the suspension has 100% anti. When "*all the load transfer is reacted by the springs and the suspension will deflect proportional to the wheel rate, none of the transferred load is carried by the suspension arms*" then the suspension has 0% anti. It is important to note that when θ or Φ equals zero, 0% anti occurs.

The previous Figure AS.6.1a describes a vehicle whereby the control arms react torque from either the brakes or drive torque. This means that the anti-geometries are calculated from the instant centre location relative to the tyre-ground contact patch. If the suspension only reacts from

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Figure AS.6.1b - % anti calculation for Instant Centre Relative to Wheel Centre

Milliken,W and Milliken,D (1995). *Race Car Vehicle Dynamics*. Warrendale, Pa: SAE International. P617-619.

forward or rearward force, not from brakes or drive torque, then the instant centre location is taken to be relative to the wheel centre.

AS.6.2 Anti-Lift

Lift is the event when the vehicle body lifts from the wheels, and can be referred to as wheel droop. This occurs with front suspensions for front wheel drive cars only, and in rear suspensions for forward braking. Anti-Lift reduces the droop of the wheel during these events.

The following Figure AS.6.2 displays the calculation for Front anti-lift.

Figure AS.6.2 – Calculation for Anti-Lift

Milliken,W and Milliken,D (1995). *Race Car Vehicle Dynamics*. Warrendale, Pa: SAE International. P617-619.

AS.6.3 Anti-Squat

Squat is the event when the rear of the car drops under acceleration. Anti-Squat reduces the bump deflection of the rear suspension in forward acceleration. This is only required for rear wheel drive cars. The following diagram displays the calculation for Rear anti-squat.

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Figure AS.6.3 - Rear Anti-Squat for Independent Rear Suspension

Milliken,W and Milliken,D (1995). *Race Car Vehicle Dynamics*. Warrendale, Pa: SAE International. P617-619.

There are differing calculations for differing suspension types, but for this report only independent systems will be assessed.

AS.7 Active Suspension Systems

Edmonds.com (2009) describes a typical event for suspension, and how an Active system will work. The event is a car turning a left corner, with a series of potholes of increasing size. A car with conventional suspension (Passive suspension), will be challenged by the potholes. "*Their ever-increasing size could even max out the system, setting up an oscillation loop — a situation wherein the car begins to bob up and down higher and higher and gets a little out of control.*"

For an Active Suspension System the corner is not such a challenge. Yaw and Body Motion is monitored by sensors, which send the information to the ECU. The wheel sensors also monitor excessive vertical travel, particularly in the front outside wheel of the car which in this scenario is the front right wheel. Rotary-position wheel sensors and steering angle sensors confirm the data.

The ECU collects, evaluates and interprets the data which for an ECU may take only 10 milliseconds. It transmits the interpreted data to the servo atop the right-front coil spring instructing it to "stiffen up." This is accomplished by an engine-driven oil pump sending additional fluid to the servo, this increases spring tension, thereby reducing body roll, yaw, and spring oscillation. A similar event occurs for the right rear servo.

Whilst the springs are being instructed to "stiffen up" the dampers are also receiving similar instructions. To increase the rigidity of the suspension dampers an actuator varies the hydraulic oil inside the damper. To increase the rigidity more oil is pumped in, whilst the reverse is true to "soften" the ride. The damper can be controlled by a number of ways. Magnetorheological fluid is hydraulic oil containing ferrous particles, which when changing the magnetic field strength has the effect of changing the viscosity of the fluid.

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Figure AS.7 - Hydraulic Lines Connect the 4 Wheel Cylinders to 2 Accumulators

CarAndDriver.com (2012) Inside the MP4-12C [online] available from <http://www.caranddriver.com/reviews/2012-mclaren-mp4-12c-first-drive-review-tech-trickledown-page-2> [11 February 2013]

The holes in the working piston can also change diameter to allow the fluid to pass through either more easily with larger diameter holes (softer ride), or reducing the diameter to make it more difficult for fluid to pass through (stiffer ride).

An example of an Active Suspension system in production today is that of the McLaren MP4-12C, as shown in Figure AS.7, which a technical review from CarAndDriver.com (2012) explains how this system works. "*What looks like an ordinary shock absorber at each wheel is instead a hydraulic cylinder. In relation to wheel motion, a piston inside each cylinder pumps hydraulic fluid into and out of the chambers above and below the piston. All eight chambers are connected to two accumulators, each of which contains fluid and nitrogen separated by a bladder.*

"*Unlike conventional shock absorbers, these pistons have no orifices or valves. Instead, the flow restrictors are located where the hydraulic lines attach to each cylinder. The size of the restriction, which is varied by an electronic controller, determines the amount of damping provided.*

"*The pressurized nitrogen contained within the two accumulators acts as a spring to resist roll motion; each accumulator handles one cornering direction. Individual wheel motion is resisted by the coil springs.*"

Appendix Vehicle Dynamics

AV.1 Newton's Laws of Motion

Sir Isaac Newton described 3 laws which explain motion. These are 3 laws of motion that influence vehicle dynamics.

Newton's first law is "Every object in a state of uniform motion tends to remain in that state of motion unless an external force is applied to it."

Newton's second law is "The relationship between an object's mass m, its acceleration a, and the applied force F is F = ma."

Newton's third law is "For every action there is an equal and opposite reaction."

AV.2 Inertia

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Figure AV.2 - Mass on String

EngineeringExpert.net (2012) Mechanical Power Transmission [online] available from <http://www.engineeringexpert.net/Engineering-Expert-Witness-Blog/?p=4256> [10 March 2013]

Inertia is the resistance that an object has to change is state of motion. This is described by Newton's second law. Inertia is important when looking at an object travelling on a circular path, such as a car on a constant radius turn. A simple model of a mass on a string can describe the effect of inertia, such as shown in Figure AV.2.

Figure AV.2 displays Fc, which is Centrifugal Force or Inertial Force. This can be shown to be

$$F=MA \text{ (Newton's second law)} \tag{58}$$

but can also be described as

$$F=MxV^2/R. \tag{59}$$

This shows the effect that Mass, Velocity and Radius of the turn has on the inertia of the object.

For a car instead of a string the tyres hold it on its course, but a lightweight car travelling slower with a larger radius will require less force to hold it on its radius.

AV.3 Inertial Forces and Lateral Weight Transfer

When a car is turning the tyres generate force that accelerates the car toward the centre of the turn. However, inertial forces are generated by the mass of the car, which resists this acceleration. The inertial force distributes an uneven load on the wheels and their contact patches with the ground.

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Figure AV.3 - Forces on a Car (Left Turn)

Haney, P. (2003) The Racing & High-Performance Tire. 1st edn. Warrendale, Pa: TV MOTORSPORTS and SAE. P210.

The Lateral Weight Transfer is calculated using moments (a Torque) which on Figure AV.3 is selected as point Z. There are 3 moments that need to be added to solve for W_R.

$$W_R \times t = W \times t/2 + W \times A \times h \quad [60]$$

A is acceleration caused by tyre forces and is in the units of G, Gravity or 9.81 m/s^2.

Solve for W_R.

$$W_L = \text{Static Weight Distribution} - W_R \quad [61]$$

This is calculating the forces about 1 axle, and so the static weight distribution is the weight of the vehicle that is acting on this 1 axle.

This can also be calculated by Fractional Weight Transfer, and so going back to calculating moments about Z.

$$W_R \times t = W \times t/2 + W \times A \times h \quad [62]$$

$$W_R = W/2 + W \times A \times h/t \qquad \text{(divide by t)} \quad [63]$$

$$W_R - W/2 = W \times A \times h/t \qquad \text{(subtract W/2)} \quad [64]$$

The Weight Transferred

$$W_R - W/2 = W \times A \times h/t \quad [65]$$

Fractional Weight Transfer

$$FWT = A \times h/t \qquad [66]$$

This shows that weight transfer is proportional to acceleration, and that weight transfer increases with vehicle weight and the height of the CG. Weight transfer decreases with a wider track.

To calculate the weight gained on W_R

$$W_R = \text{Static Weight Distribution} \times A \times h/t. \qquad [67]$$

This value is added to the static weight on W_R, and to calculate W_L is the value subtracted from the static W_L value.

AV.4 Tyre Roll

The tyres have spring rates, so the chassis of the car will roll laterally due to the deflection of the tyres. This roll is contained by the tyres, it cannot be controlled by the suspension springs or by anti-roll bars.

AV.5 Longitudinal Weight Transfer

Longitudinal Weight Transfer is experienced during Acceleration and Braking. Changing weight distribution due to longitudinal weight transfer has the same effect on the springs and tyres as the lateral weight transfer, and is calculated in a much similar way.

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Figure AV.5 - Longitudinal Weight Transfer (Braking)

Haney, P. (2003) The Racing & High-Performance Tire. 1st edn. Warrendale, Pa: TV MOTORSPORTS and SAE. P212.

Calculate using moments about point Z, which is now at the centre of the rear contact patches.

Wbrake is the weight transfer due to braking, and A is the acceleration in G cause by braking.

$$Wbrake \times wb = A \times W \times h \qquad [68]$$

$$Wbrake = A \times W \times h/wb \qquad [69]$$

This shows that weight transfer due to braking is proportional to the height of the CG, the vehicle weight and the acceleration. It is inversely proportional to the wheelbase. To calculate longitudinal weight transfer in acceleration the calculation is exactly the same, except in the other direction. Point Z would be at the centre of the front contact patches.

AV.6 Centre of Gravity

The Centre of Gravity or Centre of Mass is a very important point on vehicle models. It is a point on vehicle models by which forces can act. As is shown by the Weight Transfer calculations it has a proportional effect.

AV.7 Roll Centres

Haney, P (2003) p218 states that a Roll Centre "*can be thought of as the instantaneous centre of the rotation of a set of linkages.*" Haney, P also states the Society of Automotive Engineers (SAE) definition "*the point at which lateral forces may be applied to the sprung mass without producing suspension roll.*" The Roll centre for Double Wishbone design is displayed by Figure AV.7a.

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Figure AV.7a - Roll Centre Construction (Static Conditions)

Haney, P. (2003) The Racing & High-Performance Tire. 1st edn. Warrendale, Pa: TV MOTORSPORTS and SAE. P218.

Imaginary lines are drawn from the upper and lower suspension wishbones until those 4 lines intersect at points 1 and 2. From these points lines are drawn to the centres of the contact patches from which the lines are created. These points are labelled points 3 and 4. The point of intersection of the lines from 1 to 3, and 2 to 4 is the Roll Centre (RC). The Roll Centre changes as the car leans when turning a corner.

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Figure AV.7b - Roll Centre as Car Corners

Haney, P. (2003) The Racing & High-Performance Tire. 1st edn. Warrendale, Pa: TV MOTORSPORTS and SAE. P219.

AV.8 Cornering Forces

The cornering forces acting on a car are best described by the Figure AV.8a.

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Figure AV.8a - Forces in a turn (Left)

Haney, P. (2003) The Racing & High-Performance Tire. 1st edn. Warrendale, Pa: TV MOTORSPORTS and SAE. P220.

The Tyre forces cause the car to accelerate towards the centre of the arc of the corner. This acceleration causes a resisting force at the CG which is inertia. The inertial force tries to roll the car away from the centre of the arc. Weight transfer from the inside tyre contact patch to the contact patches on the outside of the turn is called the overturning force. It is calculated as follows:

$$\text{Magnitude of force x distance of CG from ground = Overturning Force} \quad \textbf{[70]}$$

The weight transfer causes the tyre loads to be unequal, so the total weight of the vehicle must be supported by the sum of the contact patch forces.

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Figure AV.8b - Equivalent Forces (Left Turn)

Haney, P. (2003) The Racing & High-Performance Tire. 1st edn. Warrendale, Pa: TV MOTORSPORTS and SAE. P220.

Figure AV.8b uses the Centre of Gravity and Roll Centre to display the tyre forces acting on the chassis. The Forces generated by the tyres are replaced by their equivalents (F_R from the right and F_L from the left) in directions determined by suspension linkages. This diagram displays that F_R is larger than F_L which is due to the weight transfer that has transferred the load to the right tyre, so it must generate more grip.

There are 2 new features which are M_1 which is a moment created by inertial force acting on the CG, and F_1 which is an internal reaction to F_R and F_L.

$$M_1 = F_1 \text{ x distance from CG to RC} \quad \textbf{[71]}$$

The distance from RC to CG is very important as it determines the magnitude of the moments causing the chassis to roll. If the RC is high, or the CG low then the moment will decrease in magnitude.

AV.9 Unsprung Weight Transfer

Due to most vehicles using a form of spring in their suspension design it separates parts of the vehicle into 1 of 2 groups. Sprung and Unsprung Mass. The Unsprung Mass includes the wheels, brakes, tyres, axles and parts of the suspension links. Figure AV.9 displays how the unsprung masses are calculated due to their weight transfer.

The unsprung CGs of both front and rear axles are located at the centre of the tyres. Lateral weight transfer is calculated independently for both axles using the same formula for the Lateral Weight Transfer used previously.

Fraction of total weight transferred = Lateral Acceleration x height of CG of unsprung weight/ track of that axle.

$$FWT = A \times h/t \qquad [72]$$

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Figure AV.9 - Unsprung Weight Transfer (Left Turn)

Haney, P. (2003) The Racing & High-Performance Tire. 1st edn. Warrendale, Pa: TV MOTORSPORTS and SAE. P227.

AV.10 Sprung Weight Transfer

The sprung mass includes the body, chassis and engine. When calculating the Sprung Weight Transfer there are 2 forces to calculate. These have already been discussed in Figure AV.8b, where an internal reaction to the tyre forces was labelled as F_1 which is the Direct Force, and a moment around the roll centre was labelled M_1 is the Roll Force.

AV.10.1 Direct-Force Weight Transfer

F_1 is now F_D, which has the effect of F_D x height of RC = moment that takes weight from inside tyre to outside. As tyre forces increase with slip angle through the suspension linkages at each axle the Direct Forces act instantly. The forces must be balanced front to rear otherwise the car will spin on the road. The direct force at each axle cannot be calculated, but the sum of the forces using the suspended weight of the vehicle and lateral acceleration can be calculated. The Direct forces on each axle are then calculated based on the longitudinal positioning of the sprung mass CG inside the car's wheelbase.

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Figure AV.10.1 - Direct Force Weight Transfer (Left Turn)

Haney, P. (2003) The Racing & High-Performance Tire. 1st edn. Warrendale, Pa: TV MOTORSPORTS and SAE. P228.

When A is lateral acceleration the forces are calculated as follows.

Fraction of Front Direct Force Transferred = A (b/WB) x front height of RC/ front track **[73]**

Fraction of Rear Direct Force Transferred = A (a/WB) x rear height of RC/ rear track **[74]**

AV.10.2 Roll-Force Weight Transfer

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Figure AV.10.2 - Roll Moment Weight Transfer (Left Turn)

Haney, P. (2003) The Racing & High-Performance Tire. 1st edn. Warrendale, Pa: TV MOTORSPORTS and SAE. P230.

Springs provide stiffness to roll that opposes roll forces. Anti-roll bars also increase roll stiffness. Roll forces reach the tyres only when there is resistance to roll. Springs on outside wheels of a turn compress whilst the inside springs expand. Softer springs allow for more roll than stiffer springs.

The front and rear roll forces can be calculated using the diagram of Figure AV.10.2.

A is lateral acceleration. M_R is total body roll moment proportional to car's unsprung weight. The distance for the force to act over is the distance between the Roll Centre (RC) and the Sprung Mass Centre of Gravity (SMCG). There is a multiplier used in this calculation, which is (RM/TM) for the Rear, and (FM/TM) for the front. TM is the Total Roll Resistance. RM is the Rear Roll Resistance portion, and FM is the Front Roll Resistance Portion. FM + RM = 1.

Rear Roll Force Weight Transfer = A x (SMCG – RC) x (RM/TM) **[75]**

Front Roll Force Weight Transfer = A x (SMCG – RC) x (FM/TM) **[76]**

Appendix Grip and Balance

AG.1 Ride Height

The ride height of a vehicle is decided by factors including the suspension travel requirements and the spring preload values. A lower ride height will lower the CG, but will prove more costly for driving over bumps. The ride height is measured from a level surface between the tyres and a specific mark on the chassis. It is therefore different for all cars.

AG.2 Static Weight Distribution

A lower CG will have the effect of less weight transfer, which causes the tyres to grip more and grip more evenly. Race cars will have weight minimum limits, and so some cars require ballast to meet the specific requirements. Packaging for production vehicles will sometimes be optimised for weight distribution. This is why some cars have the battery in the boot, as opposed to the engine bay.

AG.3 Moment of Inertia

When a car turns to change direction it requires a rotation about a vertical axis. A heavier vehicle is more difficult to get turning, and as inertia is proportional to mass times the distance between the axis and mass squared, the magnitude of the mass and its positioning are important to a car's ability to turn. The tyres of a car provide the turning force and need to work less if the moment of inertia is lower. It is therefore important to place the mass closer to the centreline of the car, and not towards the outer dimensions.

AG.4 Spring Rate, Wheel Rate, Tyre Rate

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Figure AG.4 - Motion Ratio

MiraCerros.com (DNK) Spring Rate vs. Wheel Rate [online] available from <http://www.miracerros.com/mustang/t_wheel_rate.htm> [30 April 2013]

The spring rate of a spring is defined as the force required in order to deflect the spring by a certain unit of length. The Motion Ratio is a suspension parameter that is defined by Figure AG.4.

It is a ratio of dimensions between the chassis and the spring and the wheel. It is defined as the amount of spring movement relative to wheel movement. It determines the mechanical advantage of the spring.

MiraCerros.com (DNK) lists the equation to calculate Wheel Rate (Kw).

$$Wheel\ Rate = (\,(Motion\ Ratio^2)\ x\ (Spring\ Rate) x\ sine(Spring\ Angle) \qquad [77]$$

The Tyre Rate or static spring rate of a tyre is a factor of tyre design and tyre pressure. The tyre is a pneumatic component, and so deflections cannot be easily measured as they are highly dependent on speed. The most reliable source of deflections vertical, lateral or longitudinal will need to come from the tyre manufacturer.

AG.5 Basic Setup

Tuning is often a long and complex process, one that requires testing and re-testing as various different setups are tested. Basic setups require the softest possible dampers, and toe setting for both front and rear to have the tyres pointing directly forwards. When changing characteristics of the setup there will often be trade-off, as one parameter is improved another will reduce in efficiency.

AG.5.1 Springs

The static weight of each corner of the car is an important measurement, as this informs engineers as to the static force of that corner. Stiffer springs will provide a harsher ride experience, but will keep the wheel in contact with the ground more. It will also translate the wheel’s movements to the suspension better which will inform more experienced drivers about the car’s behaviour.

AG.5.2 Anti-Roll Bars

Choosing anti-roll bar sizes can be simplified by defining a percentage of roll stiffness that needs to be added to the selected springs. Figure AG.5.2 allows the calculation of the distance the springs move, which will provide the spring force. Then that force multiplied by the moment arm will equate the roll-resisting moment.

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Figure AG.5.2 - Roll Stiffness Calculation

Haney, P. (2003) The Racing & High-Performance Tire. 1st edn. Warrendale, Pa: TV MOTORSPORTS and SAE. P251.

Spring movement is described as the sin of 1 degree multiplied by the distance from the point of rotation to the spring. This calculation can be done using Spring spacing S, and the distance S/2, but for wheel rates, the distance is T/2 (half of the track). Kw is the Wheel Rate, and so the calculation is as follows.

$$Roll\ Resistance\ per\ degree\ of\ Roll = \frac{T}{2} x \frac{T}{2} x \sin(1 degree)\ x\ Kw \qquad [78]$$

An Anti-Roll Bar will be added with a percentage of that Roll Resistance per degree.

AG.6 Diagonal Weight Transfer

Cars can be balanced using Diagonal Weight Transfer. The Front Left and Rear Right corners will transfer weight, as will the Front Right and Rear Left. To visualise this a wedge can be placed under one tyre, and Figure AG.6 displays how the weight is transferred diagonally.

This image has been removed

Figure AG.6 - Diagonal Weight Transfer Jacking

Haney, P. (2003) The Racing & High-Performance Tire. 1st edn. Warrendale, Pa: TV MOTORSPORTS and SAE. P253.

Diagonal Weight Transfer adjusts the weight loaded on each tyre for a corner. If there is too much load on the front left, it can be transferred to the rear right. This is an adjustment which needs fine-tuning, but can allow all 4 tyres to grip and wear evenly. It can even reduce oversteer or understeer.

The principles of Diagonal Weight Transfer is used with Active Suspension systems that link the diagonal dampers, providing a suspension system that allows the tyres to best grip the road surface. This is system put in use by McLaren. Diagonal Weight Transfer is most often used in motor Racing.

Haney, P (2003) p256 provides a summary of Diagonal Weight Transfer which he calls wedge, and it is used in reference to NASCAR, where the cars all race around an oval track turning left. "*Adding wedge is defined as adding more static weight on the inside-rear tyre. This adjustment is an adjustment away from oversteer and toward understeer. If the front suspension has more roll resistance than the rear, the car wedges itself more as it corners harder, and it will tend to understeer more (or oversteer less) as corner speed increases.*

"*De-wedging is defined as more static weight on the outside-rear tyre, causing more oversteer and less understeer. If the rear has more roll resistance than the front, the car de-wedges itself more as it corners harder, and it will tend to oversteer more (or understeer less) with increased corner speeds."*

AG.7 Roll Resistance

Stiffer springs will cause roll-resisting force to increase. As the springs are stiffer they need more force to deflect, which causes the tyres to deflect more. As the car turns a corner it will roll, which exerts large forces on the outer tyre patches. Stiffer springs or stiffer anti-roll bars may actually decrease grip across the axle as tyre contact patch forces increase, this actually reduces grip.

Roll resistance is important to know the distribution from front to rear. Haney, P (2003) p259 describes "*if the chassis is rigid, it rolls the same amount front and rear.*" Haney, P states the importance of chassis rigidity as a lack of torsional rigidity can affect the vehicle handling. Roll resistance adjustments are delicate much like Diagonal Weight Transfer. Roll resistance can be affected by Stiffer Springs, Stiffer Anti-Roll Bars, a higher roll centre or increasing tyre pressure. The distribution affects balance, Increasing roll resistance at the front will increase understeer tendencies, and at the rear will increase oversteer tendencies.

AG.8 Spring Preload

Haney, P (2003) p263 describes Preload as "*the suspension doesn't move until the force on the tyre contact patch exceeds the wheel rate dictated by the preload distance times the spring rate modified by the motion ratio. Spring preload is exactly the same as static friction in the suspension components.*"

AG.9 Springs, Anti-Roll Bars and Dampers

Haney, P (2003) p264 summarises the importance of these components. "*The springs support the car, keep it from hitting the ground, and resist body roll. Anti-roll bars resist body roll in addition to the springs, allowing for softer spring rates, and they are a sensitive balance adjuster. The dampers control the springs and prevent cyclic oscillations, helping the tyres follow road irregularities. Dampers also control the rate of body roll, contributing to how the car feels to the driver.*" When both the front and rear tyres have the maximum grip when weight transfer occurs this is balanced. Changing the parameters of the components can greatly affect this driver feel.

Appendix Bandwidth

For the testing there is a need to evaluate graphs from excel, which are located here. In the main report this will just be tabulated.

AB.1 Person 1

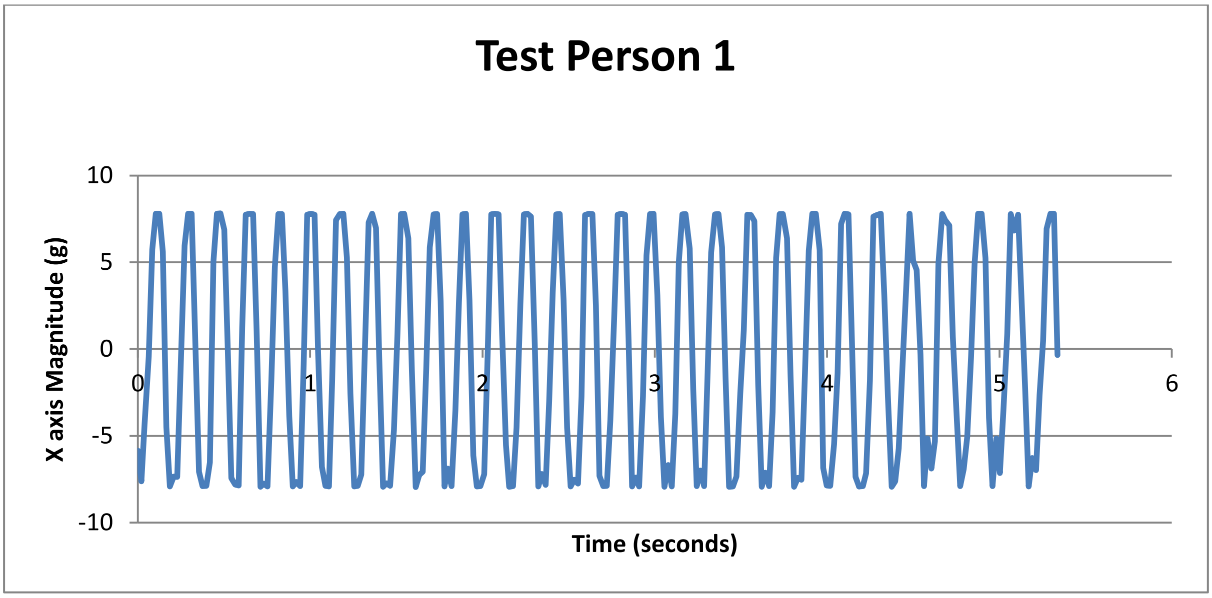

Figure AB.1 - Test Person 1

The number of oscillations is counted to be 28.75. The final recording time is 5.3369 seconds. Dividing the number of oscillations by the time provides a value for frequency response of the test person which in this test is 5.39Hz.

AB.2 Person 2

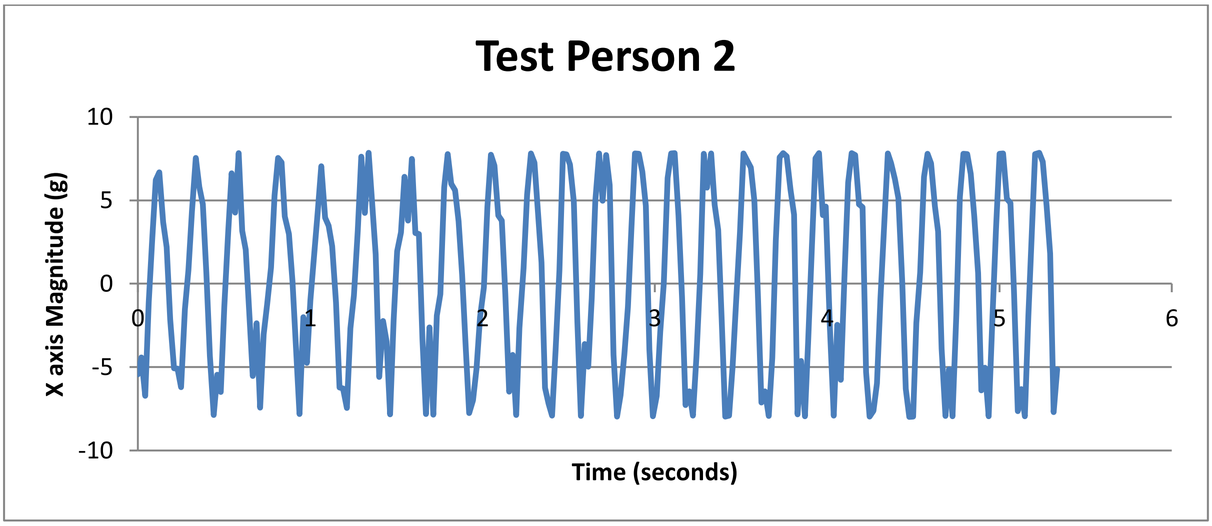

Figure AB.2 - Test Person 2

The number of oscillations is counted to be 24.00. The final recording time is 5.3358 seconds. Dividing the number of oscillations by the time provides a value for frequency response of the test person which in this test is 4.50Hz.

AB.3 Person 3

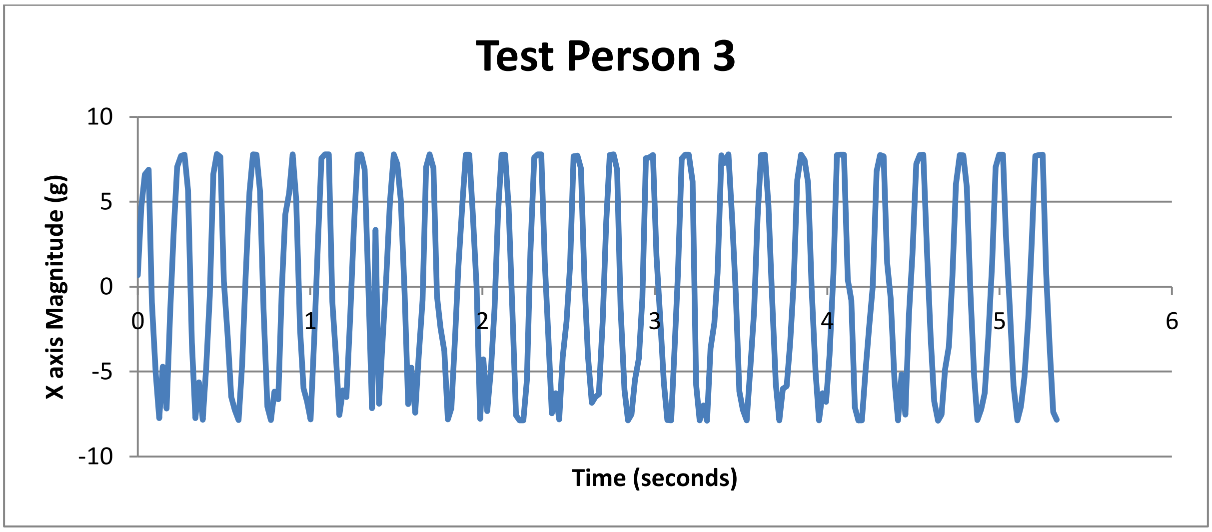

Figure AB.3 - Test Person 3

The number of oscillations is counted to be 24.75. The final recording time is 5.3322 seconds. Dividing the number of oscillations by the time provides a value for frequency response of the test person which in this test is 4.64Hz.

AB.4 Person 4

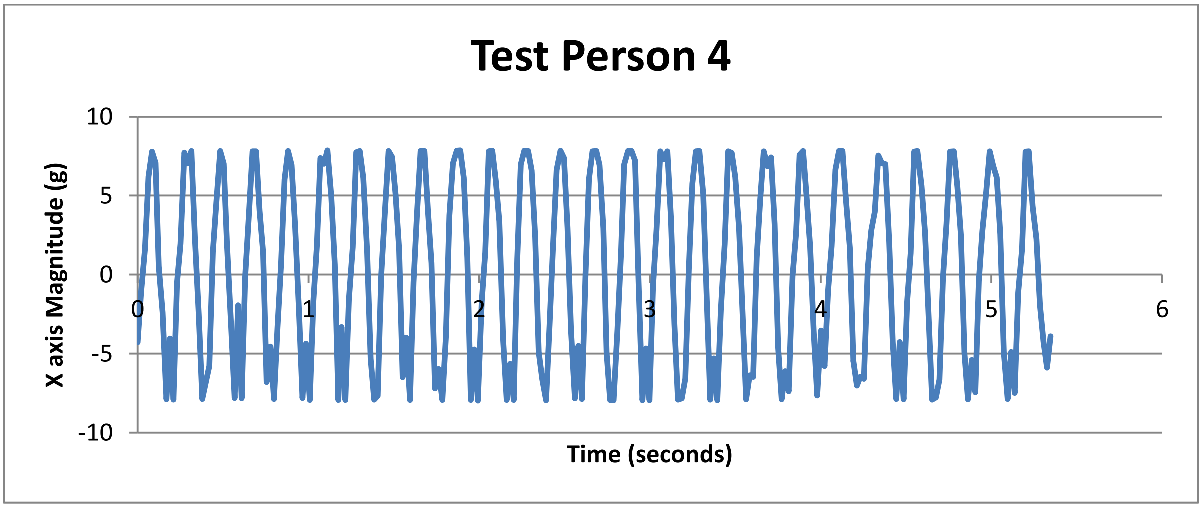

Figure AB.4 - Test Person 4

The number of oscillations is counted to be 26.00. The final recording time is 5.3474 seconds. Dividing the number of oscillations by the time provides a value for frequency response of the test person which in this test is 4.86Hz.

AB.5 Person 5

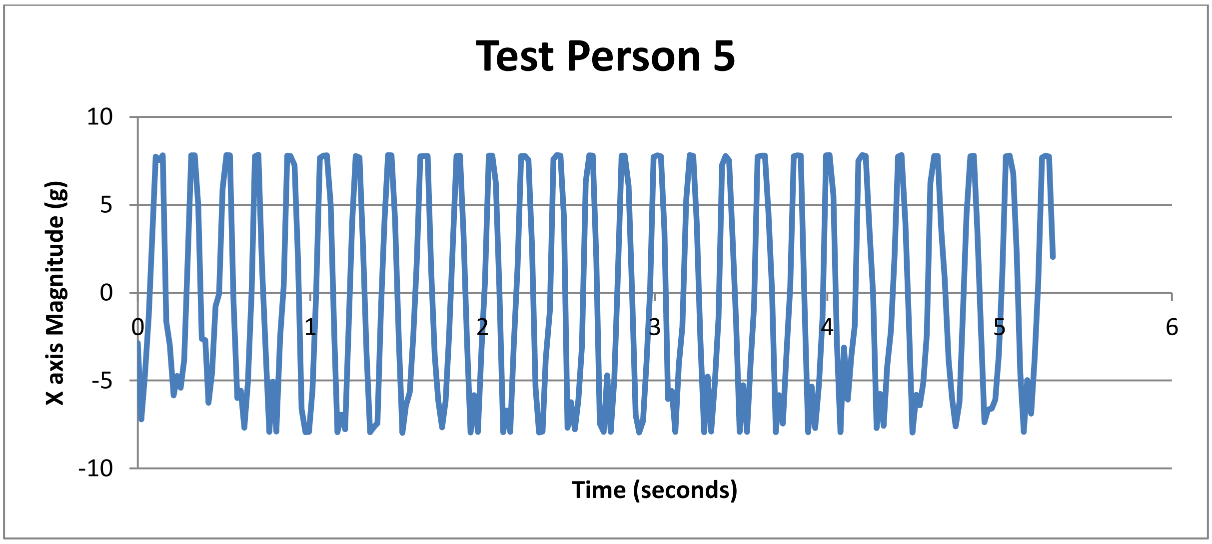

Figure AB.5 - Test Person 5

The number of oscillations is counted to be 26.75. The final recording time is 5.3092 seconds. Dividing the number of oscillations by the time provides a value for frequency response of the test person which in this test is 5.04Hz.

AB.6 Person 6

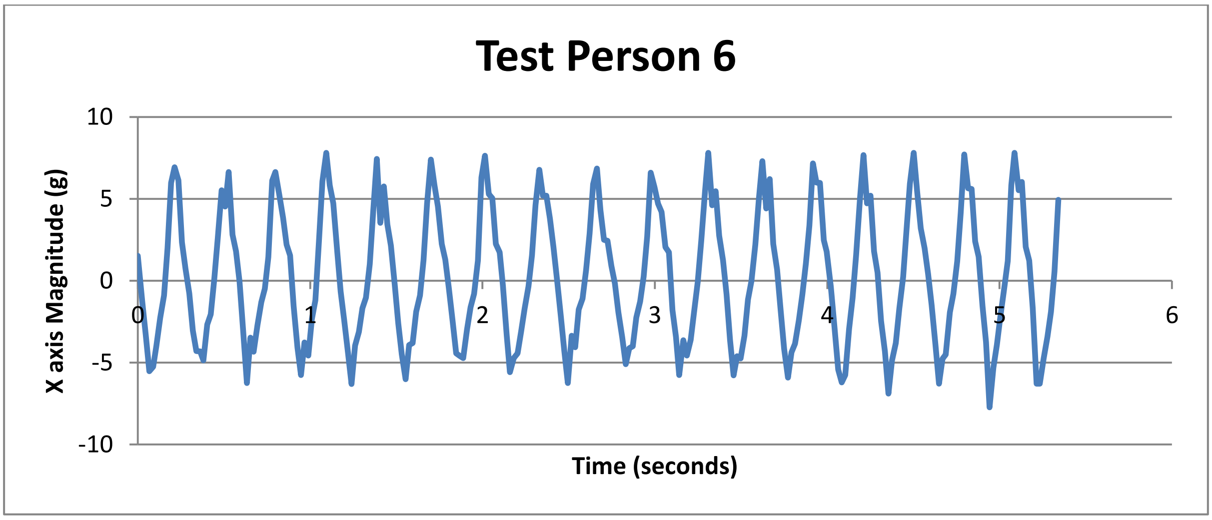

Figure AB.6 - Test Person 6

The number of oscillations is counted to be 18.75. The final recording time is 5.3406 seconds. Dividing the number of oscillations by the time provides a value for frequency response of the test person which in this test is 3.51Hz.

AB.7 Person 7

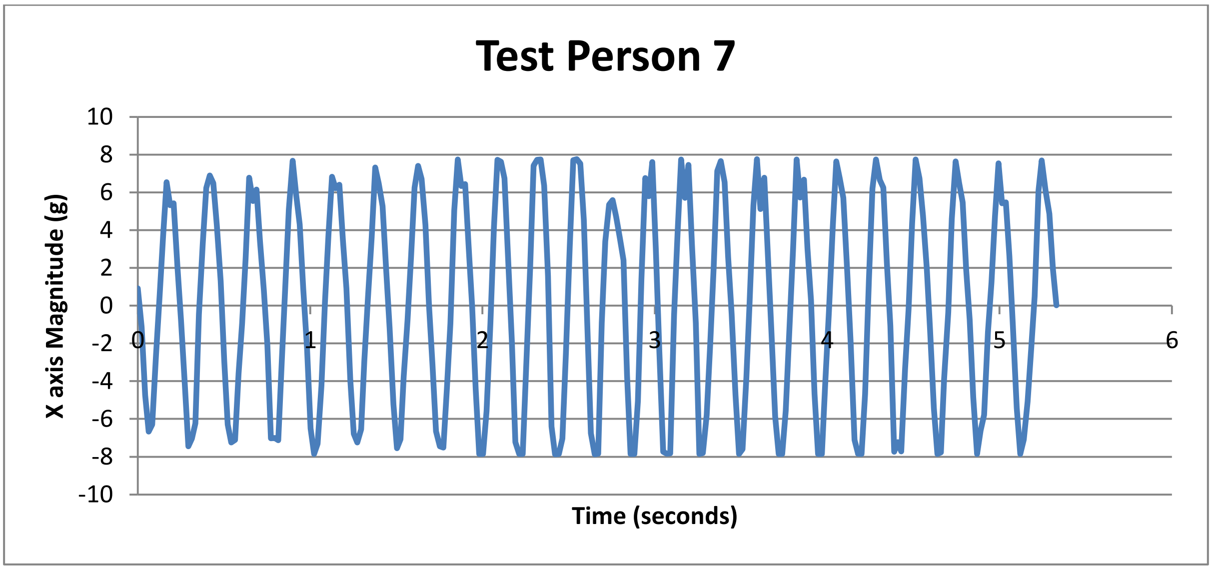

Figure AB.7 - Test Person 7

The number of oscillations is counted to be 24.00. The final recording time is 5.3306 seconds. Dividing the number of oscillations by the time provides a value for frequency response of the test person which in this test is 4.50Hz.

AB.8 Person 8

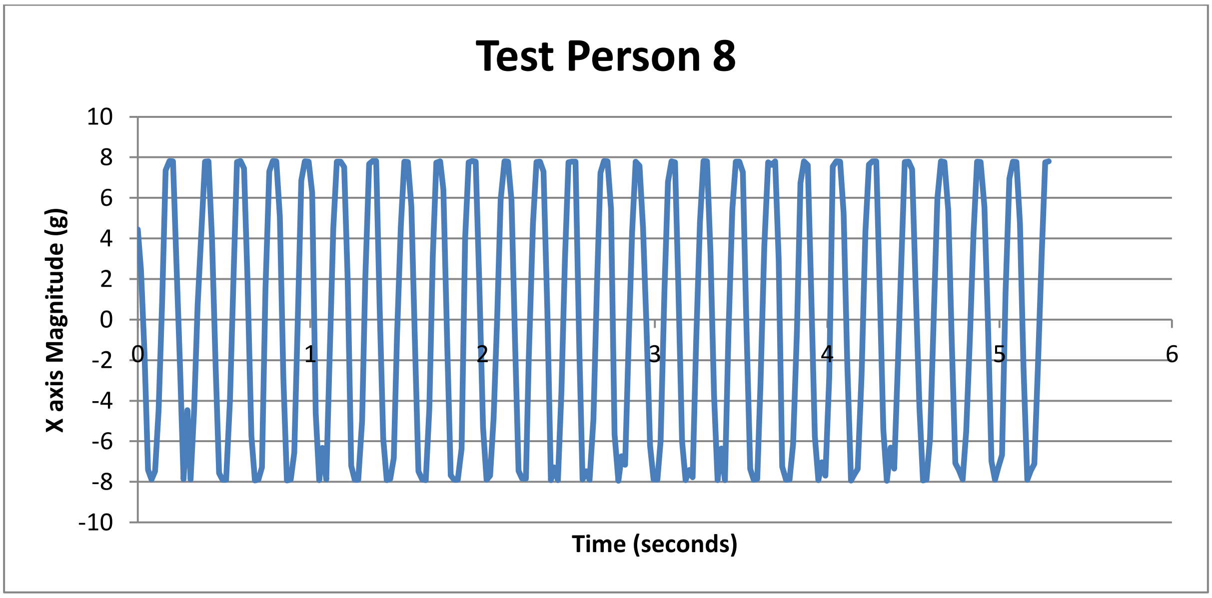

Figure AB.8 - Test Person 8

The number of oscillations is counted to be 27.00. The final recording time is 5.2860 seconds. Dividing the number of oscillations by the time provides a value for frequency response of the test person which in this test is 5.11Hz.

AB.9 Person 9

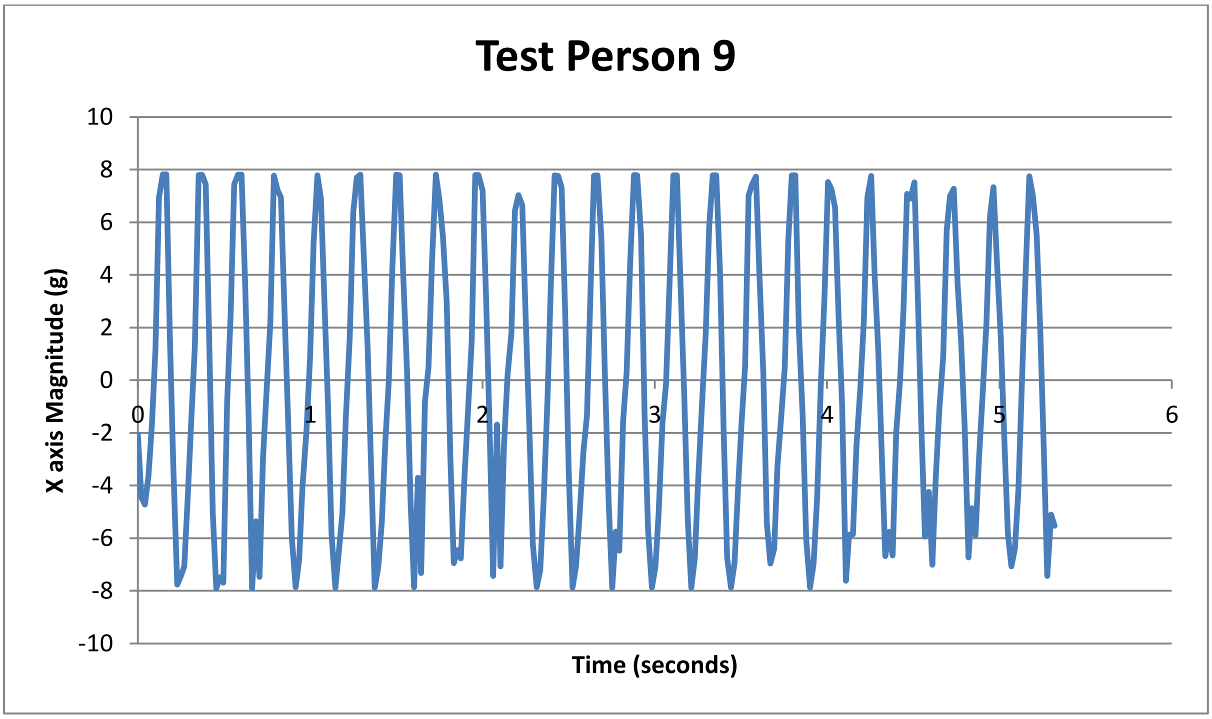

Figure AB.9 - Test Person 9

The number of oscillations is counted to be 23.00. The final recording time is 5.3193 seconds. Dividing the number of oscillations by the time provides a value for frequency response of the test person which in this test is 4.32Hz.

AB.10 Person 10

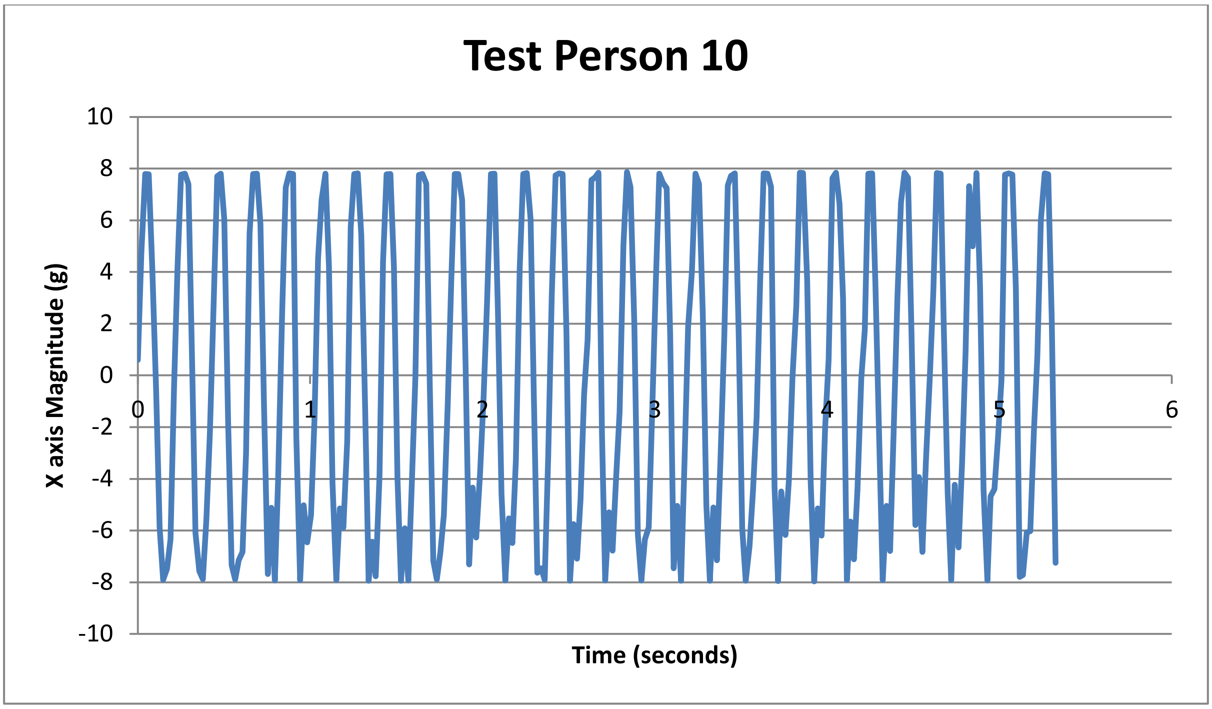

Figure AB.10 - Test Person 10

The number of oscillations is counted to be 26.75. The final recording time is 5.3249 seconds. Dividing the number of oscillations by the time provides a value for frequency response of the test person which in this test is 5.02Hz.

Appendix Instron

AI.1 Tabulated Tyre Instron Testing Results

Here are the Tabulated results for the 30 psi (2.068 bars) tyre test.

Extension (mm)	Compressive Load (N)	Equivalent Stiffness (N/m)	Vertical Spring Stiffness (N/m)
-1.701	93.4	-54908.87713	-109817.7543
-3.229	190.7	-59058.53205	-118117.0641
-4.656	294	-63144.3299	-126288.6598
-5.991	391.7	-65381.40544	-130762.8109
-7.246	490.1	-67637.31714	-135274.6343
-8.587	591.9	-68929.77757	-137859.5551
-9.878	696.6	-70520.34825	-141040.6965
-11.16	791	-70878.1362	-141756.2724
-12.38	891	-71970.92084	-143941.8417
-13.57	990	-72955.0479	-145910.0958

Here are the Tabulated results for the 25 psi (1.724 bars) tyre test.

Extension (mm)	Compressive Load (N)	Equivalent Stiffness (N/m)	Vertical Spring Stiffness (N/m)
-1.986	92	-46324.26989	-92648.53978
-3.826	195.3	-51045.47831	-102090.9566
-5.369	296	-55131.30937	-110262.6187
-6.796	395.4	-58181.28311	-116362.5662

-8.205	493.4	-60134.06459	-120268.1292
-9.502	594.2	-62534.20333	-125068.4067
-10.75	688.5	-64046.51163	-128093.0233
-12.07	796.2	-65965.20298	-131930.406
-13.31	894.2	-67182.5695	-134365.139
-14.56	993	-68200.54945	-136401.0989

Here are the Tabulated results for the 20 psi (1.379 bars) tyre test.

Extension (mm)	Compressive Load (N)	Equivalent Stiffness (N/m)	Vertical Spring Stiffness (N/m)
-2.173	95.21	-43815.0023	-87630.0046
-3.971	198.6	-50012.59129	-100025.1826
-5.644	296	-52445.07442	-104890.1488
-7.395	396.2	-53576.74104	-107153.4821
-9.059	498.1	-54983.99382	-109967.9876
-10.61	594.6	-56041.47031	-112082.9406
-12.02	693.5	-57695.50749	-115391.015
-13.36	793.8	-59416.16766	-118832.3353
-15.15	899.6	-59379.53795	-118759.0759
-15.96	994.7	-62324.5614	-124649.1228

Here are the Tabulated results for the 15 psi (1.034 bars) tyre test

Extension (mm)	Compressive Load (N)	Equivalent Stiffness (N/m)	Vertical Spring Stiffness (N/m)
-2.478	95.55	-38559.32203	-77118.64407
-4.741	201.2	-42438.30416	-84876.60831
-6.691	297	-44387.98386	-88775.96772
-8.666	394.1	-45476.57512	-90953.15024
-10.55	496.6	-47071.09005	-94142.18009
-12.22	590.8	-48346.97218	-96693.94435
-13.85	690.8	-49877.25632	-99754.51264
-15.5	796.1	-51361.29032	-102722.5806
-16.97	890.2	-52457.27755	-104914.5551
-18.5	993	-53675.67568	-107351.3514

Here are the Tabulated results for the 10 psi (0.689 bars) tyre test.

Extension (mm)	Compressive Load (N)	Equivalent Stiffness (N/m)	Vertical Spring Stiffness (N/m)
-2.623	97.73	-37258.8639	-74517.72779
-5.077	199.8	-39353.94918	-78707.89837
-7.36	294.4	-40000	-80000
-9.62	394.5	-41008.31601	-82016.63202

-11.92	495.1	-41535.2349	-83070.4698
-13.89	589.3	-42426.2059	-84852.41181
-15.86	698.1	-44016.39344	-88032.78689
-17.56	790.1	-44994.30524	-89988.61048
-19.41	893.6	-46038.12468	-92076.24936
-21.18	995.7	-47011.33144	-94022.66289

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Electronic Copy of Project on CD

Vibration iOSApp file: VibrationData 2013-06-26 at 11:23-email.csv

Source Internal Accelerometer

3 Channels

256 Points

50 Sample Rate (Hz)

Time	X	Y	Z
0	-5.84456	1.439246	0.882615
0.02069	-7.62175	1.473115	0.940759
0.038976	-4.31482	1.517148	0.891981
0.062469	-0.43358	1.264011	1.066169
0.0835	5.732079	0.55046	1.043194
0.103552	7.808294	-0.52532	0.938767
0.123719	7.811058	-0.85709	0.950551
0.144755	5.618317	1.364934	1.051481
0.165788	-4.49094	2.782056	1.099939
0.184776	-7.90937	2.902545	1.023215
0.207819	-7.34073	1.69573	1.047969
0.227986	-7.37172	1.602201	1.041704
0.249019	-0.92344	1.28729	1.039576
0.270053	5.954303	0.933444	1.013073
0.291089	7.803942	-0.34333	0.962289
0.312147	7.795162	0.078984	0.831526
0.330557	1.37228	4.099091	1.099802
0.354223	-7.07134	4.129339	1.015126
0.375256	-7.8969	2.345742	1.068207
0.396288	-7.88474	1.798539	1.129224
0.41727	-6.53455	2.438236	0.80513
0.437578	5.029185	2.041375	1.022394
0.458612	7.795712	0.031208	0.907399
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0.521717	-0.0622	3.118542	1.047482
0.542761	-7.43768	3.721737	0.948787
0.563813	-7.80227	1.41589	1.037188
0.584863	-7.86256	2.600963	0.916598
0.605408	1.253174	2.303291	1.063584
0.626445	7.748955	1.370503	0.972643
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0.752667	-7.91122	3.030886	0.864855
0.7737	-1.82309	2.056256	1.080538
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0.836182	7.787313	0.363099	1.01987
0.856811	3.336185	2.917746	1.152062
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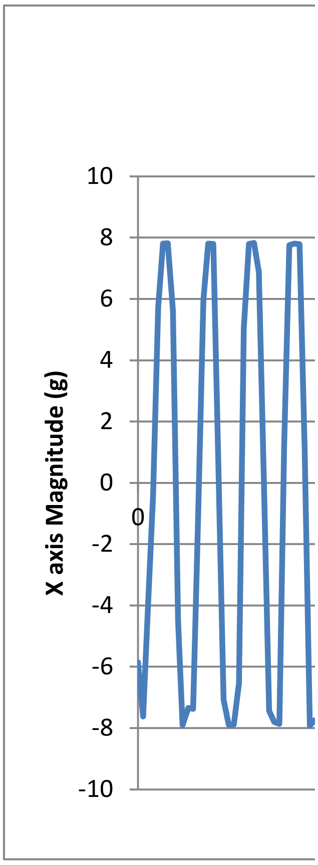

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0.982912	7.752039	1.831922	1.234214
1.003945	7.805591	-0.38339	0.858469
1.024979	7.744603	1.327291	0.94976
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1.088101	-7.88748	1.948714	1.026545
1.109152	-7.90907	2.890997	1.018608
1.127604	-1.80777	3.250473	1.140096
1.149936	7.428361	2.485327	1.275085
1.170971	7.789176	0.272263	1.048836
1.192005	7.81034	-0.56169	0.766373
1.213039	5.274101	3.881178	0.981295
1.23388	-2.55788	4.241415	1.084385
1.25492	-7.92461	3.55096	1.071339
1.275962	-7.88551	1.848948	1.073772
1.296745	-7.23204	2.282538	0.847583
1.317783	0.433985	2.831034	1.10923
1.33882	7.299299	2.707881	1.013758
1.35986	7.809348	-0.61077	1.066717
1.380896	6.980278	1.912806	1.118307
1.399799	-0.44035	3.543946	1.129695
1.422266	-7.94127	4.306019	0.972765
1.4432	-7.72812	0.876965	1.078409
1.464237	-7.88036	1.663245	0.946658
1.48521	-4.66626	0.58302	1.008512
1.506243	0.880464	2.684952	1.054629
1.527277	7.787099	0.37877	0.997002
1.54562	7.811058	-0.66485	1.001822
1.56936	6.392964	3.290946	1.187033
1.590394	-1.21363	3.390911	1.149067
1.611433	-7.94555	4.485879	0.991406
1.632465	-7.2467	0.533038	1.080979
1.652588	-7.05893	1.481575	0.91041
1.673625	-1.09663	2.201258	1.227919
1.694661	5.861492	3.715498	1.013165
1.715697	7.76679	0.887007	2.226566
1.736729	7.777861	1.098621	-0.04484
1.757763	2.757804	3.194633	2.364916
1.778812	-7.91847	3.327706	0.92528
1.798387	-6.89106	0.357317	1.044289
1.820887	-7.90062	2.550616	0.929264
1.841919	-3.53154	1.705026	1.104425
1.862953	2.662259	3.463503	1.047345
1.883988	7.763034	1.377411	1.157566
1.904065	7.804996	-0.34505	0.817112
1.925098	2.816334	3.198665	1.117197
1.946131	-6.12204	3.800902	1.128525

1.967165	-7.91791	3.273372	1.024264
1.988201	-7.89656	2.349439	1.009363
2.009247	-7.2197	3.389009	1.044806
2.030281	-0.17167	1.841233	1.038435
2.051313	7.768516	1.204824	0.940728
2.070521	7.808615	-0.74374	1.607618
2.093483	7.770607	1.555856	-0.50782
2.114517	0.868035	4.285311	0.781471
2.13533	-5.54685	3.560637	0.999602
2.155448	-7.93497	4.015057	1.026393
2.176583	-7.90211	2.609347	0.948924
2.197624	-4.51927	1.452939	0.955918
2.218658	2.596736	2.998097	1.12781
2.239265	7.770119	1.122646	0.981128
2.260407	7.794688	0.035574	1.037994
2.281449	7.636461	1.237628	0.464934
2.302487	0.279407	3.75413	1.236434
2.323526	-7.92179	3.436131	1.043666
2.344582	-7.20364	1.833185	0.960738
2.365618	-7.82504	2.302257	0.936121
2.38665	-2.99447	0.957971	1.030103
2.406758	3.249345	3.653542	1.114369
2.427796	7.76053	1.523021	1.036884
2.448832	7.78745	0.412731	0.835038
2.469864	2.854539	3.399036	1.206374
2.490483	-4.51956	3.007318	1.007037
2.511524	-7.91104	2.974301	1.025374
2.532566	-7.52052	2.224309	0.856766
2.553603	-7.75079	2.762732	0.820183
2.57461	-2.73932	1.556951	1.175721
2.595652	7.732097	1.996916	0.947327
2.616695	7.804003	-0.40404	1.152001
2.63773	7.785145	0.791409	-0.07731
2.657836	2.514064	4.377622	1.145645
2.67888	-7.30705	4.617095	0.964889
2.699914	-7.90072	2.523015	1.031882
2.720951	-7.88746	1.940498	1.051101
2.741237	-4.12243	1.431836	1.00018
2.763148	1.786143	2.760206	1.198285
2.784195	7.743213	2.229299	1.192218
2.805234	7.799544	-0.17172	1.026165
2.826299	7.742862	0.948689	-0.11117
2.84735	0.564345	3.319201	1.102844
2.868397	-7.91962	3.322624	1.108165
2.889439	-7.40826	0.841559	1.018137
2.909609	-7.90705	2.79826	1.033463
2.930668	-2.74196	1.909048	1.079048
2.951709	5.407224	2.343901	0.885276
2.972752	7.775616	0.855952	1.071689
2.993194	7.8064	-0.48654	1.080294

3.014243	3.091911	4.597346	1.109716
3.035242	-3.90784	3.565552	0.983652
3.056322	-7.93611	4.062711	1.033433
3.077369	-6.6809	1.16674	1.064329
3.097924	-7.91522	3.16046	1.010945
3.118969	-3.72463	1.682934	1.043179
3.140033	5.026986	3.964557	1.056119
3.16014	7.774731	0.817047	1.325094
3.178729	7.783786	0.646666	0.592717
3.201561	5.789127	2.778221	2.011066
3.222576	-2.28843	2.953197	1.121682
3.243058	-7.89427	3.268154	1.004726
3.264109	-6.9902	0.14202	1.048379
3.285157	-7.88963	2.069006	0.940895
3.306198	-1.32843	1.790125	1.050067
3.32724	5.568628	3.510427	1.240524
3.348305	7.768882	0.561536	2.996622
3.369353	7.782488	0.986591	-0.33687
3.390398	5.86453	3.349692	3.377628
3.410914	-1.65727	3.986361	1.331237
3.431483	-7.93037	3.870847	0.842109
3.45305	-7.91557	3.277739	0.67677
3.474102	-7.34093	3.421189	0.52875
3.495146	-2.54649	1.017067	1.043772
3.516196	1.092107	3.167078	1.015658
3.536271	7.742236	2.360988	0.898884
3.557038	7.729088	0.23243	1.069894
3.578099	7.38617	1.581159	-0.29569
3.599149	-2.05503	3.2792	1.077786
3.620198	-7.93152	3.840111	1.108408
3.641243	-7.12407	0.623508	1.030392
3.662183	-7.90056	2.584759	0.808141
3.683233	-3.64141	1.792818	1.066762
3.704279	5.265091	2.893751	0.973997
3.724333	7.779342	0.496932	1.716288
3.742492	7.790398	0.49004	0.161139
3.766438	6.390749	2.407653	0.856295
3.787482	-1.499	3.533371	1.14484
3.808522	-7.93619	4.097296	0.929811
3.829571	-7.41212	1.114308	1.051344
3.850619	-7.53369	3.394973	0.938311
3.871684	-1.43175	1.644713	1.046068
3.892743	5.686253	2.529406	1.02434
3.913626	7.793849	0.062992	1.070077
3.934676	7.797529	-0.25006	1.571415
3.955726	5.707203	2.871202	0.797467
3.976787	-6.85322	2.557006	0.964144
3.997631	-7.8666	1.021768	1.090163
4.018681	-7.88749	1.975569	0.940439
4.039723	-5.48186	2.005863	1.046159

4.060238	-1.39864	1.824512	1.115296
4.081291	7.207419	2.331379	1.051238
4.102167	7.79733	-0.27286	1.672832
4.123386	7.757964	1.994056	-0.14103
4.144428	0.334318	4.905471	1.918362
4.16483	-7.35608	4.255306	0.940865
4.185879	-7.92067	3.402489	0.995284
4.206357	-7.89665	2.37071	0.952679
4.226433	-7.15956	3.142689	1.000757
4.247458	-1.81727	2.062342	1.118261
4.268512	7.643439	1.667338	0.954641
4.289574	7.723194	-0.02526	1.224103
4.310629	7.806248	-0.49696	1.138408
4.331673	3.060791	3.824394	2.428367
4.35272	-2.64996	2.36995	1.254589
4.373767	-7.92617	3.606055	1.111434
4.394907	-7.61156	1.515915	1.016206
4.415949	-5.72132	1.530142	1.016373
4.436114	-1.29595	0.586642	1.111176
4.45716	3.379323	1.013917	1.036641
4.478046	7.799895	-0.16898	0.967565
4.499109	5.103245	-0.47831	1.100411
4.520155	4.558243	2.286935	1.005562
4.541106	-0.33455	1.743871	1.030894
4.562149	-7.90521	2.713237	1.048836
4.583191	-5.15807	-0.06136	0.995238
4.604253	-6.88428	0.728342	1.038876
4.625305	-5.31767	1.429173	1.105215
4.646354	4.920692	0.460279	1.017316
4.66722	7.79052	0.20527	1.078789
4.685593	7.430591	0.217169	0.968568
4.709342	7.124152	0.939667	0.946567
4.729855	0.711853	2.092042	1.074912
4.750896	-3.84113	1.9417	1.01613
4.77194	-7.90153	2.566166	1.005121
4.792991	-6.92643	0.933276	1.036626
4.813209	-5.06535	1.14877	1.030954
4.834251	-0.4396	0.712046	1.012055
4.855304	4.906322	1.004773	1.008071
4.876346	7.801392	-0.4866	1.795977
4.897394	7.809226	-0.43732	0.516571
4.918456	5.248325	1.170239	0.773261
4.939511	-3.95376	1.432916	1.078804
4.960554	-7.90081	2.538976	0.992486
4.981596	-5.1548	1.305336	0.952801
5.002643	-7.13711	2.309682	1.00284
5.023371	-3.54852	1.198661	1.101794
5.044412	0.876876	1.495436	0.938919
5.065445	7.790642	0.195152	1.094602
5.084157	6.820753	-0.25021	1.038663

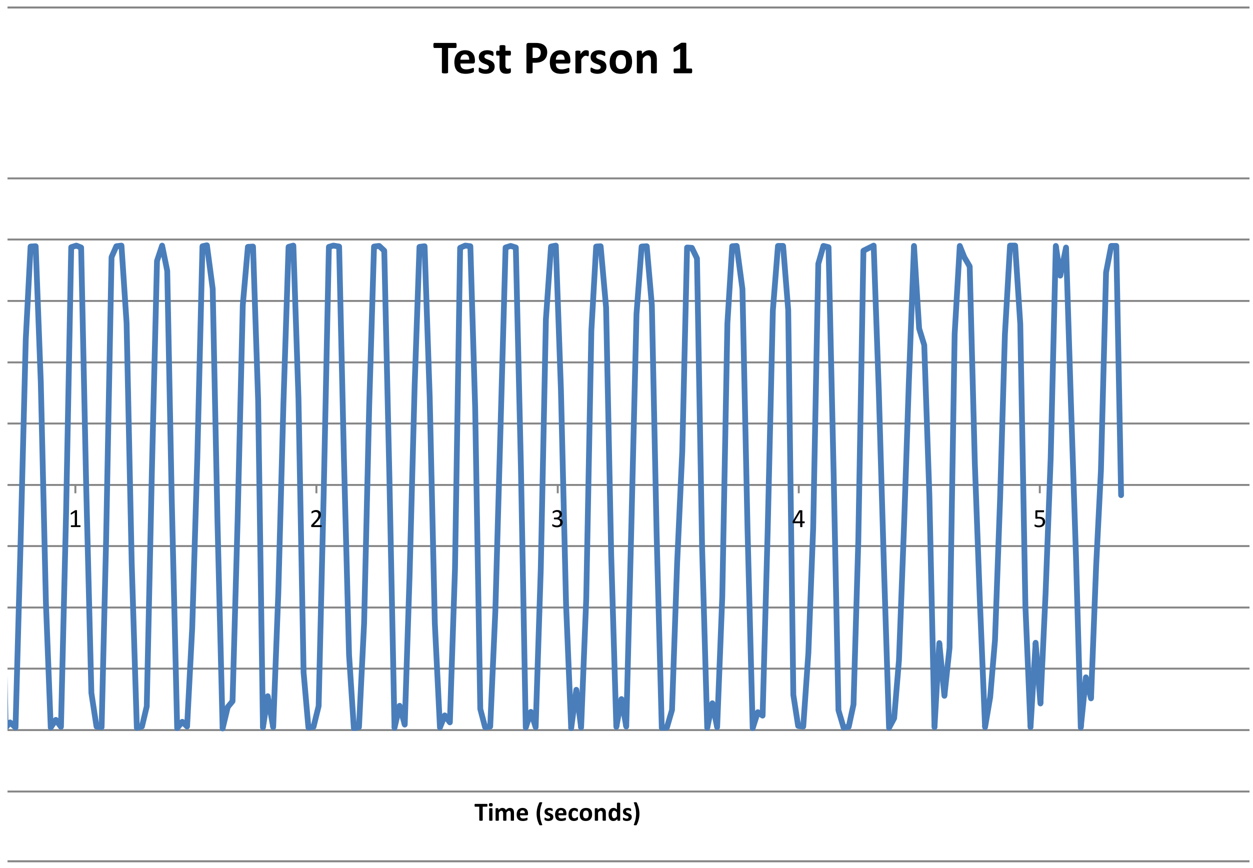
5.107512	7.738861	-0.18458	0.734199
5.127806	2.761026	2.409662	1.139944
5.148841	-2.30654	2.460298	0.997184
5.169719	-7.91877	3.333686	0.947403
5.190753	-6.27907	1.593392	1.010002
5.211688	-6.96702	2.232814	0.897136
5.232339	-2.64637	0.963144	0.999161
5.253377	0.462341	1.561622	1.055769
5.274415	6.93317	1.113608	1.403035
5.29545	7.793879	-0.00668	1.293848
5.316488	7.799697	-0.28469	1.377126
5.336922	-0.33274	3.051777	2.270098

Frequency Data

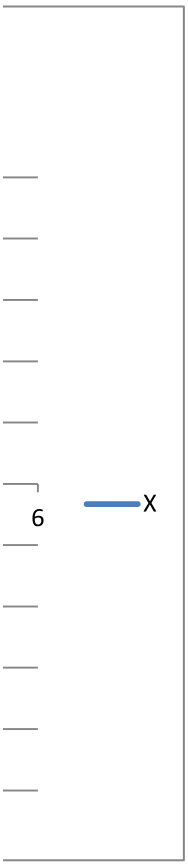
Frequency	X	Y	Z
0	0.301849	2.148766	1.030836
0.186642	0.346572	2.268214	1.011243
0.373284	0.112111	0.11015	0.057256
0.559926	0.06673	0.076814	0.077082
0.746568	0.078249	0.083206	0.082926
0.93321	0.042967	0.128146	0.05537
1.119852	0.117426	0.061999	0.076623
1.306494	0.106954	0.121731	0.091215
1.493136	0.072933	0.050938	0.054492
1.679778	0.282909	0.110591	0.028248
1.86642	0.445396	0.072429	0.070189
2.053062	0.237933	0.080823	0.072898
2.239704	0.056037	0.154065	0.042563
2.426346	0.109535	0.156312	0.031493
2.612988	0.093836	0.175432	0.030308
2.79963	0.119366	0.245401	0.044537
2.986272	0.076607	0.172288	0.065825
3.172914	0.045814	0.10197	0.056405
3.359555	0.11741	0.076824	0.048015
3.546198	0.172598	0.155344	0.05715
3.73284	0.127583	0.115876	0.034133
3.919482	0.243758	0.158595	0.026071
4.106123	0.159458	0.157803	0.070731
4.292766	0.213574	0.075284	0.090691
4.479407	0.605621	0.061236	0.045442
4.666049	0.251061	0.056762	0.027201
4.852691	0.197723	0.084361	0.04749
5.039333	1.514949	0.072068	0.070466
5.225976	3.722967	0.396181	0.055808
5.412617	7.697485	0.780276	0.020118
5.599259	6.10249	0.612276	0.021452
5.785901	2.30296	0.330744	0.046949
5.972543	0.942472	0.143484	0.077175
6.159185	0.373749	0.122305	0.082753

6.345827	0.391563	0.070005	0.052902
6.532469	0.331189	0.081901	0.066176
6.719111	0.212447	0.159406	0.079025
6.905753	0.207679	0.160947	0.054895
7.092395	0.085475	0.136793	0.021349
7.279037	0.14856	0.102557	0.045249
7.465679	0.177	0.154643	0.062259
7.652321	0.104067	0.179919	0.034585
7.838963	0.103055	0.116346	0.014907
8.025605	0.143793	0.080738	0.019278
8.212247	0.219959	0.143633	0.02473
8.398889	0.117539	0.131172	0.026858
8.585531	0.217454	0.141555	0.015471
8.772173	0.240156	0.142235	0.02084
8.958815	0.10233	0.155641	0.018165
9.145457	0.164786	0.132783	0.0337
9.332099	0.3014	0.103782	0.06668
9.518741	0.231372	0.079418	0.093803
9.705382	0.080571	0.088483	0.09592
9.892025	0.121546	0.213123	0.053173
10.07867	0.041098	0.102491	0.023939
10.26531	0.0546	0.069704	0.03238
10.45195	0.157639	0.325623	0.024005
10.63859	0.232989	0.457357	0.061365
10.82523	0.381579	0.662875	0.112653
11.01188	0.304275	0.813364	0.116793
11.19852	0.28382	0.572982	0.069295
11.38516	0.331857	0.381351	0.065214
11.5718	0.102228	0.068699	0.030651
11.75845	0.105717	0.232491	0.014179
11.94509	0.129879	0.166835	0.019073
12.13173	0.141162	0.058602	0.009835
12.31837	0.059394	0.128086	0.01284
12.50501	0.334361	0.093078	0.020862
12.69165	0.327213	0.045451	0.052788
12.8783	0.176822	0.159517	0.086856
13.06494	0.236032	0.201004	0.047221
13.25158	0.244867	0.14534	0.051921
13.43822	0.095224	0.072443	0.072868
13.62487	0.030504	0.096816	0.042377
13.81151	0.0519	0.100618	0.040311
13.99815	0.031111	0.08037	0.070583
14.18479	0.093386	0.053385	0.051871
14.37143	0.141723	0.066169	0.033697
14.55807	0.12576	0.117464	0.070716
14.74472	0.082075	0.083269	0.117427
14.93136	0.086984	0.069528	0.11413
15.118	0.094898	0.121804	0.078659
15.30464	0.073995	0.08726	0.057097
15.49128	0.171442	0.06958	0.028433

15.67793	0.28944	0.04019	0.06065
15.86457	0.374554	0.137163	0.082668
16.05121	0.649867	0.235531	0.048514
16.23785	0.620342	0.287243	0.083808
16.42449	0.572085	0.251539	0.12212
16.61114	0.565635	0.282446	0.119943
16.79778	0.624163	0.292133	0.09657
16.98442	0.209426	0.062413	0.033205
17.17106	0.2466	0.081183	0.07016
17.3577	0.115569	0.043534	0.067233
17.54435	0.082153	0.054719	0.026264
17.73099	0.154242	0.084737	0.036615
17.91763	0.185091	0.057931	0.072766
18.10427	0.109558	0.095096	0.072836
18.29092	0.113706	0.152048	0.110492
18.47756	0.148103	0.087452	0.097154
18.6642	0.14945	0.112716	0.062027
18.85084	0.047295	0.062411	0.116871
19.03748	0.134312	0.036381	0.092659
19.22412	0.084513	0.090531	0.033328
19.41077	0.029932	0.027105	0.070988
19.59741	0.109922	0.072983	0.087997
19.78405	0.234175	0.131408	0.055719
19.97069	0.318217	0.244119	0.072968
20.15733	0.238462	0.213507	0.175256
20.34398	0.14903	0.21946	0.161654
20.53062	0.114311	0.115405	0.079723
20.71726	0.105638	0.093303	0.071089
20.9039	0.079394	0.208521	0.085525
21.09054	0.084574	0.23605	0.067844
21.27719	0.16999	0.334074	0.103255
21.46383	0.216649	0.321462	0.095074
21.65047	0.144739	0.229921	0.064524
21.83711	0.181676	0.223939	0.111273
22.02375	0.085068	0.25814	0.171331
22.2104	0.170722	0.219805	0.174621
22.39704	0.184705	0.15821	0.056365
22.58368	0.078067	0.12969	0.0832
22.77032	0.095863	0.227791	0.09734
22.95696	0.119461	0.049547	0.044003
23.1436	0.168025	0.083444	0.052442
23.33025	0.065128	0.111715	0.120222
23.51689	0.2318	0.083625	0.091777
23.70353	0.156218	0.05379	0.085203



Test Person 1
1
2
3
4
5
Time (seconds)


6
X

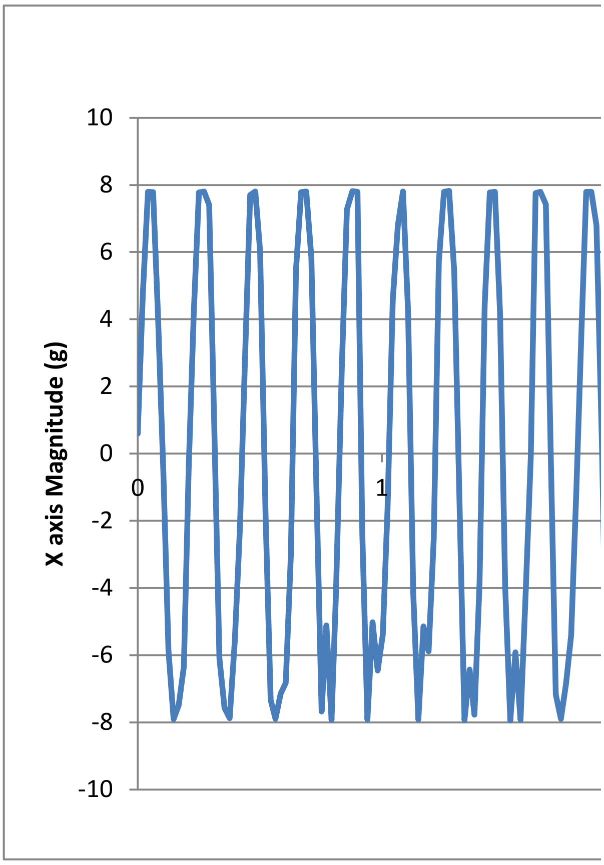
Vibration iOSApp file: VibrationData 2013-06-29 at 16:35-email.csv

Source Internal Accelerometer

3 Channels

256 Points

50 Sample Rate (Hz)



Time	X	Y	Z
0	0.595832	1.806482	0.823802
0.021031	4.763442	1.326211	0.485948
0.042061	7.797055	-0.09847	1.14262
0.062782	7.783648	0.481611	1.152837
0.082794	4.180387	1.478608	0.730139
0.104855	-0.55075	2.12086	1.251974
0.125888	-5.87062	2.843967	1.185558
0.14692	-7.91082	2.924501	1.159391
0.16797	-7.48707	1.110763	0.653491
0.189005	-6.34586	2.348329	0.674504
0.209051	-0.47976	1.395	0.519885
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0.272167	7.806232	-0.35324	0.667784
0.293203	7.400539	1.460167	0.398489
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1.693895	-0.35931	1.320749	2.0681
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Frequency Data

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2.244771	0.247024	0.120846	0.042323
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2.993028	0.06692	0.07324	0.056713
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3.554221	0.189288	0.041669	0.159347
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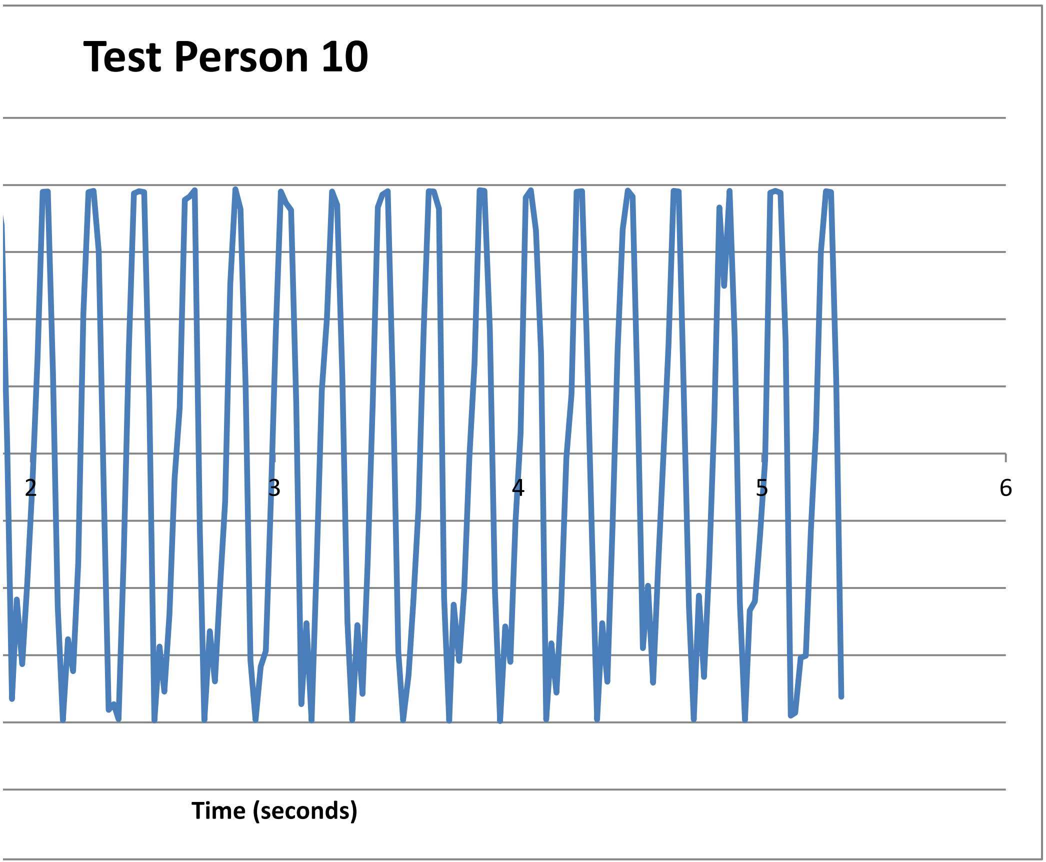
18.89349	0.148404	0.085677	0.085328
19.08055	0.378239	0.119539	0.107248
19.26762	0.285938	0.137724	0.098087
19.45468	0.178265	0.237296	0.060016
19.64175	0.246634	0.260384	0.060517
19.82881	0.492943	0.267632	0.135846
20.01588	0.567158	0.331612	0.221266
20.20294	0.348037	0.280463	0.204965
20.39	0.243489	0.33037	0.188557
20.57707	0.177594	0.228749	0.160613
20.76413	0.036503	0.158893	0.117958
20.9512	0.165737	0.157511	0.12575
21.13826	0.226396	0.084386	0.055645
21.32532	0.167051	0.20989	0.08274
21.51239	0.082569	0.250223	0.070156
21.69945	0.03851	0.171554	0.064845
21.88652	0.133425	0.080663	0.139253
22.07358	0.204266	0.105533	0.133266
22.26065	0.075057	0.070994	0.113057
22.44771	0.175168	0.14734	0.100348
22.63477	0.146874	0.141819	0.106495
22.82184	0.242089	0.156193	0.150877
23.0089	0.137937	0.0934	0.16457
23.19597	0.060024	0.107477	0.062891
23.38303	0.138425	0.127613	0.073904
23.5701	0.11423	0.100764	0.117515
23.75716	0.104705	0.081887	0.165426


Test Person 10
2
3
4
5
6
Time (seconds)

Vibration iOSApp file: VibrationData 2013-06-26 at 11:24-email.csv

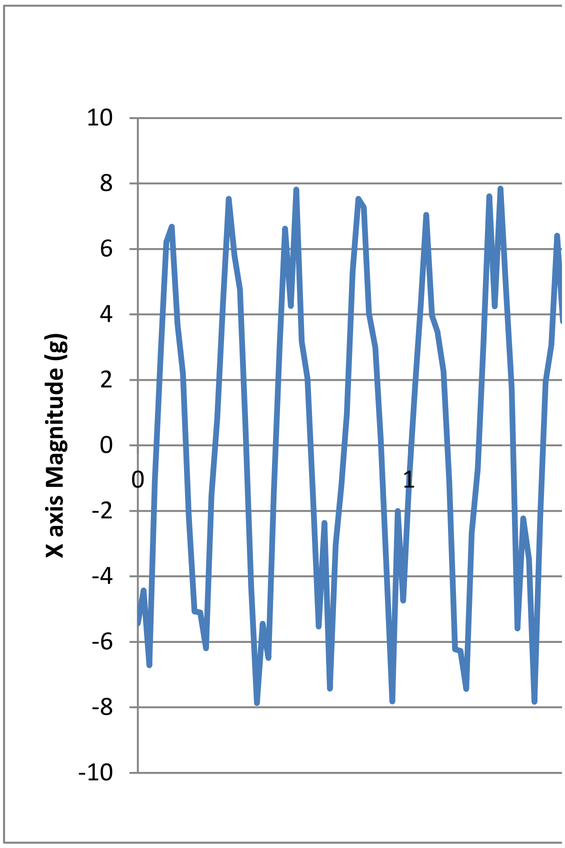
Source Internal Accelerometer

3 Channels

256 Points

50 Sample Rate (Hz)

Time	X	Y	Z
0	-5.43733	1.017478	1.036018
0.02103	-4.42644	-0.67419	0.988457
0.042061	-6.71789	1.742897	1.081435
0.062406	-1.0994	0.721647	0.959856
0.083439	2.710299	0.765087	1.034543
0.104468	6.210548	0.074343	0.948239
0.124778	6.680345	0.533342	0.964144
0.145815	3.694984	0.701806	0.951098
0.166853	2.184308	0.333794	1.043103
0.187887	-2.13348	0.730198	1.084096
0.208927	-5.07108	0.79748	1.024705
0.229831	-5.09919	0.787362	1.05104
0.250868	-6.20332	1.9742	1.040503
0.271906	-1.53485	0.827211	1.072418
0.292942	0.808772	1.364082	1.074015
0.313979	4.338768	0.678131	0.950687
0.335016	7.533892	-0.62978	0.928853
0.356051	5.792532	0.361668	1.006383
0.376258	4.767977	-0.43137	1.040457
0.397295	0.637626	0.487118	0.991239
0.418331	-4.31636	1.710717	1.024948
0.439371	-7.87031	2.39828	1.016783
0.46041	-5.45063	0.887341	0.974438
0.481447	-6.49563	2.262164	1.038891
0.501616	-1.39426	1.083619	1.080507
0.522666	3.022707	0.787788	0.998264
0.543699	6.623434	-0.47412	1.116802
0.564043	4.256264	-0.46472	1.00839
0.5847	7.820266	-1.88174	0.986404
0.605111	3.169559	0.726166	0.954185
0.625835	2.04836	0.503353	1.054142
0.646872	-1.7239	1.883289	1.083366
0.667105	-5.53648	2.339473	0.937748
0.688071	-2.36643	1.261014	1.012708
0.708835	-7.42997	2.622402	1.036215
0.729589	-3.03661	0.847569	1.002156
0.750699	-1.224	1.641944	1.144855
0.771722	0.968297	1.845737	1.016723
0.792745	5.287706	0.402415	0.910379
0.813775	7.533068	-0.49008	0.89452
0.834239	7.27108	-0.2025	0.788724
0.853176	4.039369	0.896942	0.929081
0.876294	2.983555	0.4604	1.017103
0.8965	0.155796	1.201841	1.089281



0.917518	-3.8164	1.686357	1.013666
0.938541	-7.82046	2.263534	1.020296
0.95956	-2.00101	0.023554	1.019216
0.979633	-4.73821	1.586408	1.002202
1.001637	-0.99877	1.064721	1.107025
1.022675	1.785487	1.011924	1.099574
1.043695	4.313725	0.280906	0.991741
1.064728	7.044687	-0.31625	0.772288
1.085767	3.964042	1.236806	1.058886
1.106017	3.47221	0.712107	0.996424
1.127876	2.257849	0.15433	1.049459
1.148913	-1.12409	1.032526	1.010428
1.170029	-6.22653	2.222316	1.020843
1.191064	-6.27924	1.24309	1.058263
1.212102	-7.43976	1.621677	1.081663
1.232378	-2.68154	0.98799	0.927196
1.254399	-0.70933	2.021215	1.11557
1.275447	3.174262	1.431562	0.96498
1.296494	7.612059	-0.5631	0.929537
1.317536	4.248705	-0.21508	1.236875
1.338599	7.841552	-1.99337	1.00725
1.358725	4.817787	-0.01235	0.936547
1.379856	1.756015	1.101451	0.992836
1.400777	-5.5933	5.462366	1.115752
1.42185	-2.22745	-0.13592	0.851764
1.442894	-3.46817	1.132414	0.958579
1.463952	-7.83344	2.273378	1.036018
1.484857	-2.21956	1.921159	0.878966
1.505104	1.946952	0.519207	1.031137
1.526146	3.071816	0.588331	0.98207
1.547192	6.412082	-0.41576	0.907064
1.568251	3.784986	-0.11533	1.108287
1.589327	7.486968	-1.10369	1.001396
1.610374	3.03923	1.301638	1.143167
1.630505	2.985143	0.609023	1.08735
1.650693	-3.28046	1.198235	0.996165
1.671831	-7.81956	2.111442	0.980945
1.692874	-2.62092	-0.34081	1.059525
1.713915	-7.84553	3.316888	0.978026
1.734965	-1.91627	0.481976	1.008907
1.756036	-0.63072	2.193117	1.082454
1.777093	5.785951	0.727703	1.119827
1.798133	7.775433	-0.22436	0.963049
1.819183	5.993653	2.522194	0.949136
1.840231	5.598939	0.235473	1.01619
1.861281	3.735572	-0.01234	1.077786
1.881398	0.537454	0.570635	0.942963
1.902207	-3.71955	1.042416	0.98502
1.923255	-7.76165	2.761013	0.976749
1.944305	-6.99055	0.836477	1.032855

1.965346	-5.09873	1.065071	0.926436
1.986412	-2.0074	1.35792	0.994219
2.007468	-0.21404	2.386641	1.104166
2.028517	4.603305	1.354588	1.004163
2.049564	7.730967	-0.6307	1.040716
2.068229	7.086298	0.445474	0.953774
2.091698	4.098494	1.14874	0.998203
2.112744	3.784879	0.242563	1.106949
2.132872	-0.64232	0.871883	1.081283
2.153916	-6.4692	1.867495	0.982253
2.174969	-4.26249	0.163444	1.035683
2.196026	-7.86286	3.206593	1.052378
2.214028	-2.65011	1.706867	1.066306
2.237921	0.922793	2.558619	1.149021
2.258968	5.335593	1.770635	1.065698
2.280017	7.800705	-0.23222	1.05805
2.301076	7.243029	1.710123	0.938083
2.322131	4.282238	1.028631	1.126061
2.342252	1.263589	1.125902	1.021178
2.363298	-6.24294	3.029243	1.019551
2.383394	-7.18382	3.059263	1.058034
2.40379	-7.90765	2.793787	1.133907
2.424841	-3.99155	1.701725	0.954702
2.44589	0.79341	2.282157	1.07146
2.466956	7.794261	0.036685	1.097567
2.487997	7.752223	-0.20291	0.761036
2.508145	7.134719	-0.22627	1.115494
2.529192	4.914584	-0.03235	1.185695
2.550238	-2.2545	2.160937	0.958913
2.571279	-7.93164	3.883156	0.982922
2.592256	-3.6237	0.371163	1.054385
2.613318	-4.9847	2.286311	1.013864
2.634205	-0.85158	1.887884	0.939649
2.654848	4.928403	1.447401	0.936592
2.6759	7.800003	-0.15567	0.909695
2.696874	4.970701	1.715799	1.035273
2.717264	7.703404	-1.08774	1.02656
2.738426	5.916967	-0.13634	0.925843
2.759479	-4.25864	3.204036	1.106341
2.780521	-7.96949	5.514296	1.034756
2.801571	-6.68903	1.418431	1.057639
2.822414	-4.2179	2.654384	0.877901
2.843489	-1.3866	2.669949	0.911322
2.864533	3.363916	2.108977	1.14081
2.88539	7.807668	-0.44248	0.756839
2.906442	7.783267	0.206381	1.39341
2.926996	6.72504	-0.19664	1.170825
2.947307	4.662568	-0.10193	1.102707
2.96835	-3.93149	2.59754	1.064253
2.989392	-7.94559	4.472307	1.042966

3.010444	-6.71757	1.012685	1.040792
3.031511	-2.87209	2.149419	0.978482
3.052558	0.000928	2.518679	1.09109
3.073605	6.338435	1.018132	1.436364
3.09465	7.801682	-0.44372	1.614551
3.115696	7.825381	-0.94447	-0.12569
3.136758	4.096387	1.568073	0.842671
3.157807	-0.79881	1.872516	1.054507
3.178857	-7.2843	2.864386	1.116315
3.199902	-6.44362	3.243414	1.0922
3.22095	-7.90943	2.884881	1.089615
3.242007	-4.37683	2.25687	1.119022
3.263057	0.583707	1.824968	0.993216
3.284104	7.787511	0.004261	1.146421
3.302591	5.750952	-0.73878	1.014001
3.326192	7.810935	-0.66101	1.005957
3.34725	4.726763	0.493996	0.991802
3.368306	3.220683	0.065594	1.032292
3.388404	-2.20334	1.361876	1.082743
3.409407	-7.97039	5.553308	1.036915
3.430456	-7.91023	2.915676	1.101277
3.451517	-4.97152	2.772577	0.978543
3.472566	-1.05977	2.852731	1.020281
3.493611	3.052927	2.719597	1.147972
3.514658	7.800812	-0.25204	1.108165
3.535706	7.406021	0.819801	1.001837
3.55677	6.968704	-0.97595	1.006703
3.577808	4.963982	-0.08746	1.063691
3.598864	-0.64284	1.859903	0.978391
3.619037	-7.12263	3.878348	0.980839
3.639181	-6.45503	3.935405	1.099468
3.660239	-7.93213	3.869021	1.098921
3.681285	-4.44105	2.254663	0.991437
3.702337	2.588322	1.903981	1.150952
3.723381	7.580969	0.469286	1.126518
3.744432	7.832757	-1.49072	0.613806
3.765497	7.639606	-0.48386	1.031106
3.786556	5.622088	0.139343	1.262952
3.807592	4.139906	1.308698	1.033205
3.828641	-7.83394	4.921264	0.93898
3.849112	-4.63856	3.177577	1.11522
3.870174	-7.94553	4.460698	1.072175
3.890324	-3.48234	2.859988	1.093447
3.91137	2.34698	1.776219	1.062429
3.932416	7.520775	0.220836	2.458944
3.953462	7.824495	-0.87499	-0.22493
3.974519	4.118467	-0.62548	2.909862
3.992653	4.62337	-0.45195	1.134896
4.016618	-2.62928	1.940787	1.009455
4.037667	-7.90837	3.445518	1.039135

4.058708	-2.47077	0.509439	1.066032
4.079785	-5.75588	2.745448	1.110172
4.10084	0.69782	2.032033	0.992881
4.121883	6.060673	1.053066	1.006155
4.142091	7.822037	-1.08164	0.801846
4.16314	7.718308	0.154345	0.956511
4.184199	4.757288	0.431081	0.993216
4.205247	4.59173	-0.31062	1.168483
4.225705	-5.30637	2.327514	0.939405
4.246751	-7.96308	5.218023	1.092033
4.267803	-7.61562	2.39612	1.093249
4.288899	-5.97405	3.255784	1.042054
4.309937	-0.85934	2.346685	1.018015
4.330979	3.665956	1.702531	1.06033
4.352032	7.815547	-0.86523	1.017209
4.371648	7.228843	1.847822	0.945974
4.393299	6.278744	-0.08012	1.023854
4.414343	5.130776	-0.46685	0.985309
4.435392	0.074483	0.95012	1.085905
4.456043	-6.30479	2.921352	1.00243
4.477088	-7.9843	6.142474	1.088718
4.498147	-7.96525	5.393228	0.826889
4.517433	-2.34639	2.755581	1.051588
4.540319	0.677862	3.256347	1.152199
4.561365	6.411761	2.09437	0.997792
4.582411	7.798368	-0.08294	0.902366
4.60337	7.218368	1.293361	0.988122
4.624421	4.647176	0.117463	1.049307
4.644682	3.123291	0.028149	1.193435
4.664928	-3.91002	1.70921	1.050554
4.686002	-7.92948	3.785367	0.997564
4.707055	-5.12254	-0.26709	0.992334
4.728097	-7.9384	4.181528	0.969177
4.74915	-1.82396	2.305528	1.304416
4.770201	5.182206	2.382061	1.162112
4.791177	7.7809	0.660831	0.9587
4.812238	7.774639	0.660238	1.852646
4.83321	6.579288	-0.07311	1.162143
4.854256	4.030634	-0.37137	1.092337
4.875303	0.637106	0.324847	1.017802
4.895455	-6.40027	2.19085	0.880425
4.915961	-5.02412	-0.29848	1.118687
4.93758	-7.94123	4.290789	1.015339
4.958623	-2.43363	3.008961	1.190302
4.979667	3.331177	2.608632	0.938128
5.000725	7.791711	0.033033	1.472552
5.02186	7.813455	-0.52983	0.217002
5.042894	5.085119	0.863043	1.194514
5.063926	4.843991	-0.30539	1.154221
5.084959	-0.42665	0.641919	1.061775

5.105999	-7.63741	3.335344	1.187444
5.127037	-6.32136	4.503163	1.244341
5.147311	-7.94692	4.481953	1.200794
5.168344	-1.92237	3.055657	1.173988
5.189379	3.614908	2.977252	0.760747
5.207564	7.775753	0.831775	1.130076
5.230633	7.83917	-1.96629	1.258694
5.25167	7.312935	-1.01382	1.155711
5.272704	4.672249	-0.25572	0.976095
5.293737	1.806193	0.001705	0.844861
5.314768	-7.69023	3.837723	1.01578
5.335806	-5.12374	3.357407	1.132356

Frequency Data

Frequency	X	Y	Z
0	0.520338	1.365517	1.038227
0.186681	0.549282	1.485167	1.032288
0.373362	0.067026	0.177005	0.018864
0.560043	0.098442	0.09144	0.021684
0.746724	0.207084	0.092276	0.017116
0.933405	0.22715	0.108299	0.021184
1.120086	0.086384	0.077489	0.034041
1.306767	0.069061	0.129972	0.023898
1.493448	0.146497	0.118877	0.01506
1.680129	0.081443	0.08395	0.03282
1.86681	0.050945	0.163052	0.03476
2.053491	0.071692	0.138059	0.030349
2.240172	0.199495	0.124832	0.030787
2.426853	0.355775	0.175076	0.014473
2.613534	0.341538	0.177792	0.024085
2.800215	0.162405	0.193978	0.02719
2.986897	0.123601	0.147138	0.036165
3.173578	0.140078	0.06976	0.026636
3.360259	0.438872	0.085931	0.022582
3.54694	0.904372	0.26591	0.010667
3.733621	0.724151	0.175231	0.018088
3.920302	2.22965	0.264106	0.027764
4.106983	2.325326	0.296869	0.031437
4.293664	1.700646	0.073196	0.030452
4.480345	2.98579	0.673295	0.015587
4.667026	5.3796	1.087529	0.015324
4.853707	5.06225	1.082792	0.013983
5.040388	2.620817	0.676317	0.011628
5.227069	1.05907	0.212796	0.013818
5.41375	0.970192	0.199407	0.020742
5.600431	0.804041	0.177591	0.029422
5.787112	0.212442	0.138347	0.031156
5.973793	0.331209	0.041322	0.027184
6.160474	0.461215	0.15783	0.029951

6.347155	0.281587	0.102088	0.038604
6.533836	0.237291	0.052059	0.036948
6.720517	0.312856	0.095443	0.041848
6.907198	0.218827	0.087957	0.043283
7.093879	0.115973	0.101622	0.025437
7.28056	0.044965	0.030506	0.025664
7.467241	0.10776	0.037366	0.034001
7.653922	0.055015	0.071143	0.036756
7.840603	0.071301	0.08988	0.03518
8.027285	0.14764	0.165919	0.025143
8.213965	0.29387	0.047273	0.031485
8.400646	0.142182	0.167209	0.028927
8.587328	0.085759	0.102074	0.029759
8.774009	0.168438	0.109007	0.028398
8.96069	0.219647	0.040843	0.024642
9.14737	0.278585	0.102834	0.025706
9.334051	0.389361	0.336387	0.026921
9.520733	0.311537	0.366132	0.038442
9.707414	0.156432	0.150524	0.040901
9.894094	0.104284	0.059135	0.029286
10.08078	0.174715	0.123271	0.034834
10.26746	0.158368	0.165365	0.029625
10.45414	0.174437	0.252136	0.022854
10.64082	0.316739	0.299172	0.033302
10.8275	0.327616	0.171652	0.045812
11.01418	0.097759	0.066122	0.037542
11.20086	0.310667	0.168139	0.033456
11.38754	0.394658	0.216427	0.026651
11.57422	0.175936	0.092541	0.01944
11.76091	0.116923	0.046846	0.01652
11.94759	0.259345	0.11481	0.027933
12.13427	0.133545	0.091334	0.043586
12.32095	0.156883	0.070996	0.041431
12.50763	0.198342	0.087616	0.034443
12.69431	0.122975	0.113013	0.032624
12.88099	0.260637	0.261688	0.042795
13.06767	0.399858	0.252421	0.058005
13.25435	0.180686	0.154564	0.038699
13.44103	0.145183	0.145465	0.019315
13.62772	0.272093	0.229677	0.015227
13.8144	0.109988	0.225215	0.022225
14.00108	0.229203	0.238581	0.032191
14.18776	0.520856	0.336856	0.059296
14.37444	0.76384	0.462231	0.068249
14.56112	0.546587	0.325447	0.058312
14.7478	0.301488	0.115232	0.025675
14.93448	0.274375	0.089149	0.031441
15.12116	0.412199	0.161385	0.028001
15.30784	0.353612	0.141424	0.019502
15.49453	0.052256	0.151993	0.039662

15.68121	0.049399	0.179541	0.058586
15.86789	0.054735	0.146912	0.057496
16.05457	0.100869	0.076038	0.017105
16.24125	0.352063	0.157773	0.014417
16.42793	0.445342	0.251978	0.029527
16.61461	0.254778	0.196358	0.042755
16.80129	0.070261	0.066589	0.039388
16.98797	0.105439	0.047324	0.05086
17.17466	0.10978	0.060067	0.029864
17.36134	0.090032	0.049417	0.019825
17.54802	0.080673	0.032635	0.039541
17.7347	0.069257	0.090871	0.061561
17.92138	0.097133	0.12325	0.058483
18.10806	0.172484	0.144372	0.039631
18.29474	0.145644	0.077583	0.027216
18.48142	0.140828	0.12027	0.022251
18.6681	0.206937	0.166252	0.043473
18.85478	0.207549	0.297743	0.043772
19.04147	0.517489	0.375651	0.052133
19.22815	0.21587	0.16977	0.04324
19.41483	0.256069	0.100612	0.035464
19.60151	0.22029	0.100838	0.029511
19.78819	0.364926	0.141681	0.036276
19.97487	0.352106	0.114786	0.027047
20.16155	0.330667	0.173413	0.044455
20.34823	0.338189	0.181591	0.062853
20.53491	0.121051	0.102881	0.06576
20.72159	0.36369	0.115453	0.051452
20.90828	0.169986	0.103997	0.019358
21.09496	0.155023	0.049311	0.032601
21.28164	0.140751	0.091028	0.052857
21.46832	0.192341	0.171074	0.065477
21.655	0.101431	0.071355	0.064008
21.84168	0.151197	0.116723	0.05067
22.02836	0.128349	0.074326	0.01702
22.21504	0.156754	0.120867	0.037913
22.40172	0.127687	0.221003	0.059409
22.58841	0.264914	0.197831	0.056237
22.77509	0.056179	0.067647	0.052225
22.96177	0.392381	0.144263	0.037112
23.14845	0.523996	0.230914	0.028729
23.33513	0.383409	0.135824	0.030281
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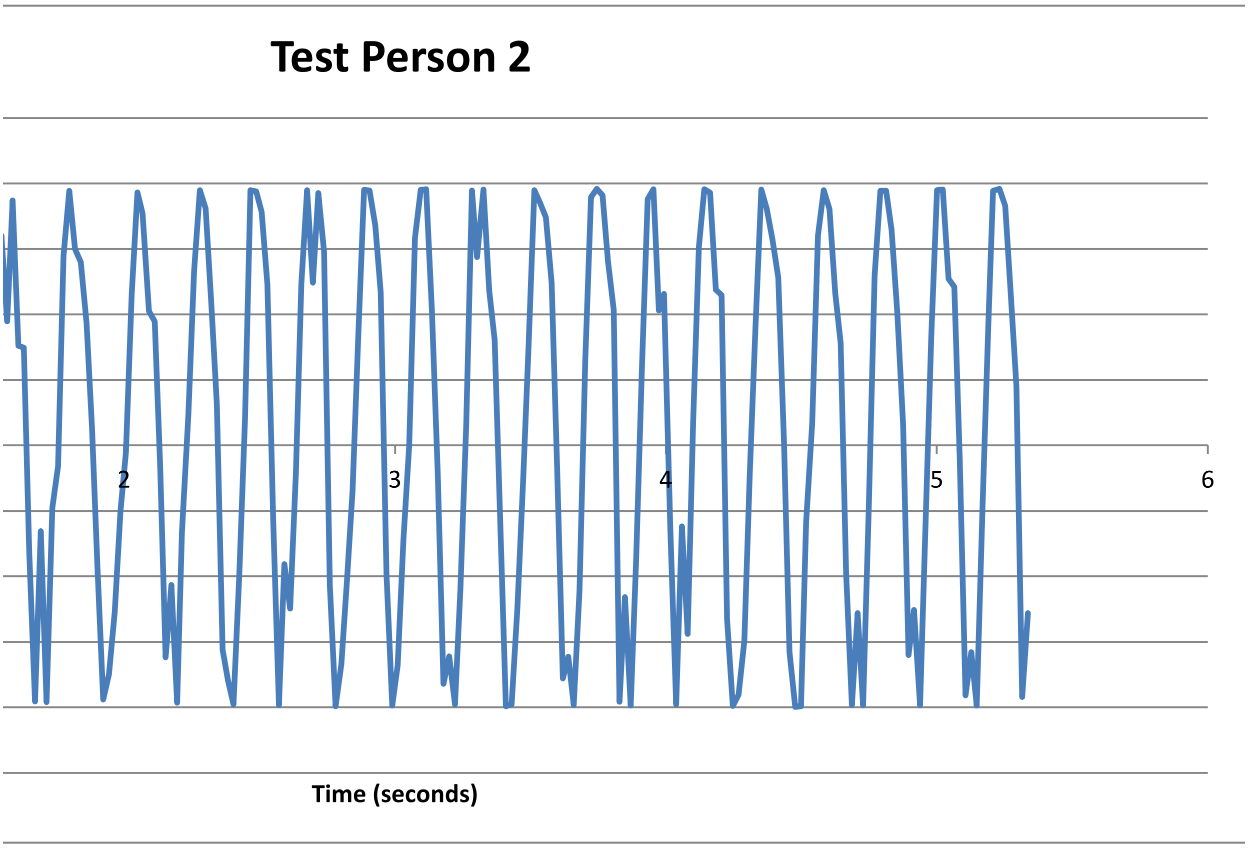
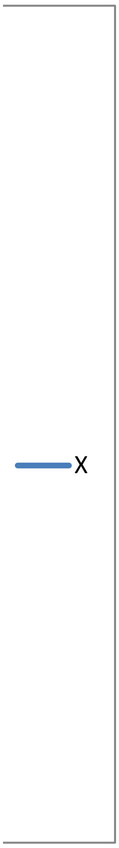


Test Person 2
2
3
4
5
6
Time (seconds)


X

Vibration iOSApp file: VibrationData 2013-06-26 at 11:25-email.csv

Source	Internal Accelerometer			
3	Channels			
256	Points			
50	Sample Rate (Hz)			
Time	X	Y	Z	
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0.020235	4.695749	0.971117	1.024796	
0.041084	6.605827	0.595649	0.937155	
0.061891	6.887422	1.345048	0.939877	
0.080494	-0.92958	2.261662	1.10225	
0.103734	-5.10295	1.402394	1.068359	
0.124124	-7.75209	0.432815	1.08665	
0.145059	-4.70351	-0.06333	1.02136	
0.165973	-7.17819	0.413735	0.99241	
0.187398	-1.58923	0.946757	1.01467	
0.207904	3.155862	1.501583	1.046068	
0.228941	7.051482	1.427804	1.029145	
0.249975	7.704092	0.739434	1.168088	
0.271104	7.772272	0.892515	1.428914	
0.292076	5.656492	3.566282	-0.54521	
0.31311	-3.29871	1.998727	1.248765	
0.333599	-7.73368	0.325821	0.955234	
0.354663	-5.63341	-0.31885	1.00988	
0.375697	-7.84277	0.029001	1.045338	
0.396734	-4.67087	1.712725	1.160409	
0.416868	-0.55681	2.664609	1.015886	
0.437991	6.629939	1.515368	1.258299	
0.45827	7.807652	-0.29997	0.290351	
0.479302	7.634598	0.742644	0.855641	
0.49844	0.321766	1.90319	1.161337	
0.521466	-2.9342	1.485333	1.087471	
0.5425	-6.48102	1.137496	0.938858	
0.563002	-7.2545	0.076838	1.068906	
0.583713	-7.85747	1.276701	0.82143	
0.604746	-4.60881	1.648517	0.999587	
0.625747	0.583967	1.185668	1.282794	
0.646778	5.55458	1.006934	3.042966	
0.667798	7.783587	0.778248	0.189953	
0.688756	7.769233	1.174743	0.935604	
0.709108	5.633801	0.948781	2.216136	
0.730142	-1.33611	1.904286	1.091333	
0.75118	-7.06378	1.18051	0.921904	
0.772212	-7.86045	0.761009	1.065698	
0.793244	-6.18562	0.322656	1.170703	
0.814238	-6.62625	1.145378	0.998522	
0.83543	-0.17987	1.005716	1.166035	
0.856469	4.252584	1.255521	1.068435	
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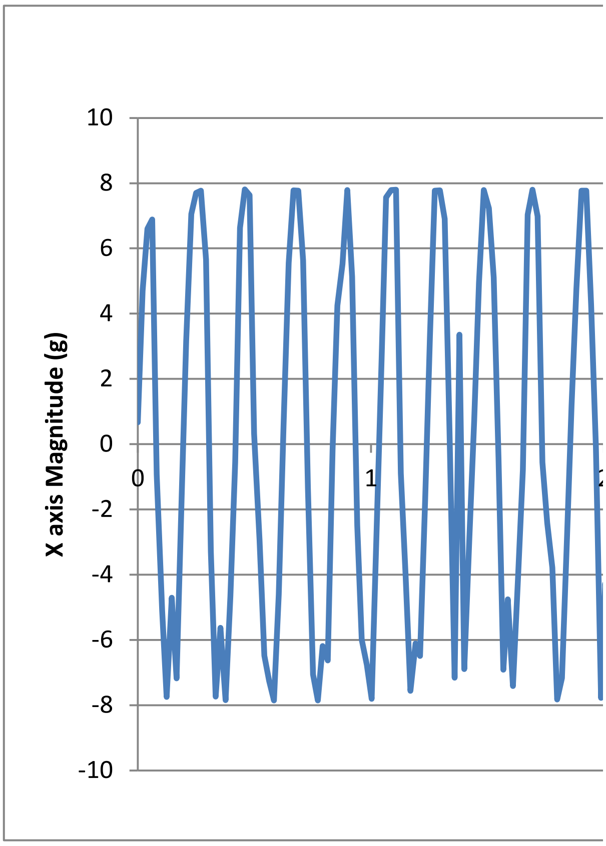

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1.003044	-7.81108	0.886596	1.000332
1.02408	-2.78299	1.274601	1.081161
1.045116	2.586138	1.565091	1.619645
1.065544	7.567348	1.3417	3.037477
1.086576	7.790611	0.536796	-0.02346
1.10752	7.795635	0.424371	-0.67612
1.127757	-0.89519	1.468565	1.452634
1.148795	-4.04188	1.16642	1.072981
1.169713	-7.56197	0.703799	1.027685
1.190746	-6.11196	0.349937	1.024766
1.210907	-6.4912	1.130725	0.916431
1.232244	-1.69584	0.917802	0.925006
1.253281	3.328611	1.460775	1.086057
1.274315	7.773081	0.989953	0.991893
1.295347	7.783083	0.583355	0.899644
1.316378	6.908891	1.654998	1.048151
1.337313	0.401735	2.215058	1.193115
1.358351	-7.15519	1.652944	0.663907
1.379382	3.354677	0.143755	0.423395
1.400414	-6.89771	1.315469	3.447722
1.421553	-2.87302	1.061054	1.239962
1.44259	0.721901	1.308927	1.186577
1.463632	4.95737	1.404798	2.866513
1.484669	7.785756	0.805057	-0.20766
1.505702	7.233363	0.373019	0.607162
1.526734	5.107169	1.470528	2.186486
1.547771	-0.43349	1.492879	1.088247
1.568185	-6.91322	0.129803	1.035227
1.587055	-4.7587	0.103541	1.025116
1.609469	-7.41849	0.347244	0.933551
1.630501	-4.06618	0.441899	1.057974
1.651532	-0.79627	2.029827	1.095119
1.672453	7.038702	1.65687	3.057974
1.693489	7.79733	0.356723	-0.39059
1.714455	6.982538	1.587199	-1.98279
1.735486	-0.55936	1.235741	1.227615
1.756528	-2.41376	0.862982	1.034193
1.777566	-3.78157	0.183056	1.281091
1.798603	-7.8215	1.163727	1.200094
1.819635	-7.16777	0.693727	1.450353
1.840714	-2.80868	0.67874	1.010413
1.860781	1.183879	1.304742	1.043255
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1.902971	7.766683	1.279926	0.954549
1.923288	7.770714	1.270371	0.411033
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2.361624	1.428871	1.95938	3.378038
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2.487051	-2.03989	1.421504	1.029282
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2.571227	6.954136	-0.01938	1.919289
2.592262	0.341235	1.519978	1.102479
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2.675625	-6.32284	0.56041	1.002749
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2.78107	6.891712	1.864771	-0.66092
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2.823248	-6.06511	1.946584	1.058643
2.844288	-7.88306	1.726541	1.126822
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2.927457	-0.65828	1.768946	1.129331
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4.38991	-5.54865	1.288279	0.943085
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4.431994	-5.16548	-0.13097	1.090771
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5.166164	-1.89324	1.394193	1.069803
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5.290871	-3.58993	1.422144	1.067644
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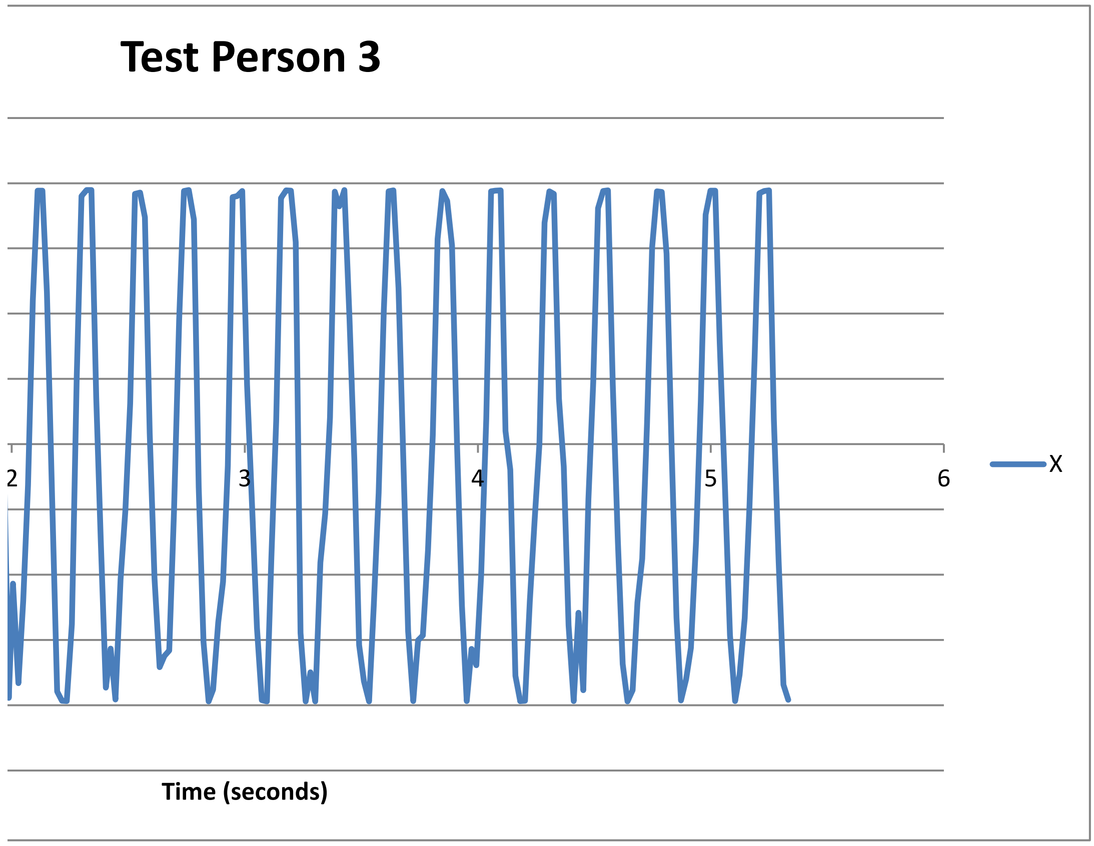
Frequency Data

Frequency	X	Y	Z
0	0.234935	1.33703	1.112233
0.186808	0.375627	1.399737	1.112025
0.373615	0.219345	0.116847	0.04104
0.560423	0.2369	0.067489	0.08724
0.74723	0.092562	0.106135	0.089124
0.934038	0.115272	0.136649	0.035737
1.120845	0.076344	0.078413	0.057575
1.307653	0.094493	0.057114	0.080554
1.49446	0.215353	0.058364	0.065104
1.681268	0.26653	0.068237	0.103876
1.868075	0.147833	0.026507	0.152677
2.054883	0.164173	0.086849	0.091117
2.24169	0.265991	0.067839	0.059056
2.428498	0.527215	0.096142	0.118411
2.615305	0.379882	0.118123	0.140344
2.802113	0.237838	0.127137	0.143891
2.98892	0.13167	0.06039	0.115043
3.175728	0.213326	0.044819	0.064916
3.362535	0.255358	0.037984	0.029985
3.549343	0.173734	0.085779	0.047393
3.736151	0.053991	0.085043	0.076593
3.922958	0.296308	0.030559	0.115059
4.109766	0.870375	0.083464	0.103471
4.296573	2.162033	0.053123	0.047742
4.483381	4.767414	0.240469	0.090558
4.670188	6.702889	0.217138	0.129148
4.856996	4.48406	0.069908	0.098852
5.043803	1.747836	0.089867	0.052259
5.230611	0.279738	0.049363	0.155961
5.417418	0.249107	0.097167	0.110509
5.604226	0.138646	0.126336	0.026932
5.791033	0.32917	0.070825	0.063017
5.977841	0.302388	0.063897	0.069161
6.164649	0.226335	0.09069	0.054221

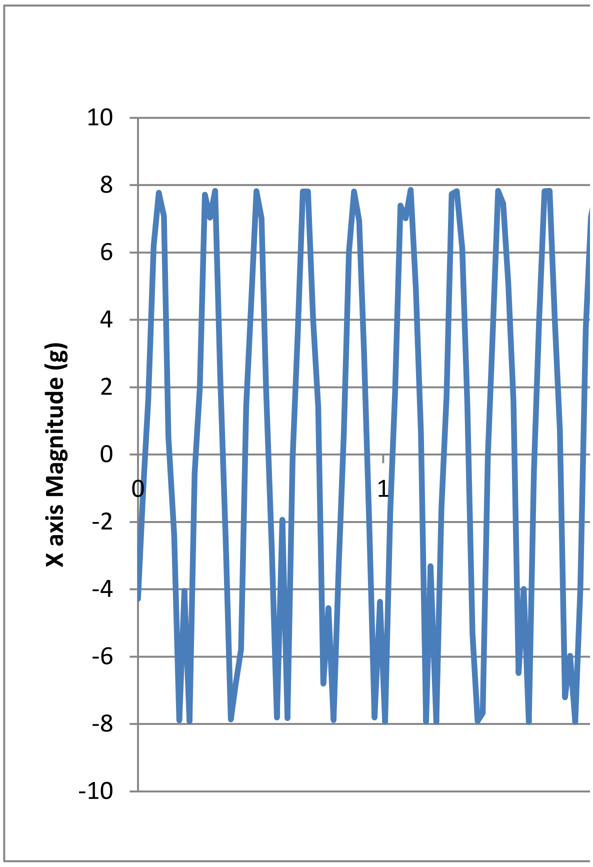
6.351456	0.163439	0.046179	0.099881
6.538263	0.469403	0.07914	0.192234
6.725071	0.773799	0.21469	0.222719
6.911879	0.539455	0.217033	0.152956
7.098686	0.311785	0.15541	0.131894
7.285493	0.195704	0.077406	0.136597
7.472301	0.102642	0.058481	0.151059
7.659109	0.179272	0.053883	0.146175
7.845916	0.223542	0.042887	0.040652
8.032723	0.204127	0.060784	0.161964
8.219531	0.09119	0.035129	0.153235
8.406339	0.048769	0.0853	0.035872
8.593146	0.091891	0.093951	0.093151
8.779954	0.303608	0.11299	0.06848
8.966762	0.444872	0.130149	0.12663
9.153569	0.597894	0.206162	0.221411
9.340377	0.620561	0.23666	0.202332
9.527184	0.48428	0.226041	0.11646
9.713991	0.29074	0.145517	0.133026
9.900799	0.055434	0.042721	0.155425
10.08761	0.193412	0.108232	0.122049
10.27441	0.202022	0.078961	0.063522
10.46122	0.119622	0.064288	0.018693
10.64803	0.088772	0.129388	0.041135
10.83484	0.263201	0.111863	0.045904
11.02165	0.232459	0.048445	0.073831
11.20845	0.11858	0.050363	0.234229
11.39526	0.04172	0.050779	0.289205
11.58207	0.22497	0.028599	0.141038
11.76887	0.387625	0.051303	0.073969
11.95568	0.329251	0.078324	0.086079
12.14249	0.039117	0.102458	0.056566
12.3293	0.125893	0.078783	0.043151
12.51611	0.275093	0.107688	0.075412
12.70291	0.327506	0.12789	0.113527
12.88972	0.092695	0.096518	0.062219
13.07653	0.301599	0.077578	0.113214
13.26333	0.122013	0.097888	0.121826
13.45014	0.171026	0.064645	0.196745
13.63695	0.154145	0.044235	0.214402
13.82376	0.090004	0.113851	0.276318
14.01057	0.144374	0.14951	0.197135
14.19737	0.226958	0.121312	0.155406
14.38418	0.301026	0.04667	0.244941
14.57099	0.119301	0.054643	0.243731
14.75779	0.228481	0.058642	0.19624
14.9446	0.067047	0.094967	0.105663
15.13141	0.210888	0.089331	0.108515
15.31822	0.278051	0.051136	0.137224
15.50503	0.187009	0.043503	0.139598

15.69183	0.19057	0.037838	0.138624
15.87864	0.276588	0.059278	0.161978
16.06545	0.261589	0.12978	0.172038
16.25225	0.188724	0.094685	0.115883
16.43906	0.21472	0.048291	0.074132
16.62587	0.100989	0.049253	0.095946
16.81268	0.06862	0.040918	0.052063
16.99949	0.062459	0.056946	0.063341
17.18629	0.271452	0.066968	0.045697
17.3731	0.424294	0.068846	0.047123
17.55991	0.19449	0.040591	0.148762
17.74672	0.175989	0.048124	0.128508
17.93352	0.368473	0.071505	0.160265
18.12033	0.282818	0.059153	0.187376
18.30714	0.257874	0.068044	0.108028
18.49395	0.298902	0.074229	0.184109
18.68075	0.106469	0.067651	0.113843
18.86756	0.221173	0.098859	0.176588
19.05437	0.393496	0.082999	0.193219
19.24118	0.270986	0.034565	0.166117
19.42798	0.063409	0.086443	0.0531
19.61479	0.076083	0.136039	0.104467
19.8016	0.135224	0.138106	0.106865
19.98841	0.273789	0.138154	0.084754
20.17521	0.117475	0.106177	0.048157
20.36202	0.117844	0.091481	0.06193
20.54883	0.197701	0.062856	0.073212
20.73564	0.255939	0.06633	0.081631
20.92244	0.230674	0.025455	0.065281
21.10925	0.346729	0.067491	0.073231
21.29606	0.230255	0.097757	0.064015
21.48287	0.212892	0.085963	0.100263
21.66967	0.170065	0.039894	0.166367
21.85648	0.13022	0.099916	0.092363
22.04329	0.259644	0.062057	0.060484
22.2301	0.109101	0.046671	0.106091
22.4169	0.246678	0.067756	0.120725
22.60371	0.10768	0.048336	0.124697
22.79052	0.29381	0.043764	0.119861
22.97733	0.166254	0.042772	0.088417
23.16413	0.138613	0.055722	0.068125
23.35094	0.341993	0.069536	0.060186
23.53775	0.399559	0.058934	0.084098
23.72456	0.159244	0.037816	0.104779


Test Person 3
2
3
4
5
6
X
Time (seconds)

Vibration iOSApp file: VibrationData 2013-06-26 at 11:28-email.csv

Source	Internal Accelerometer			
3	Channels			
256	Points			
50	Sample Rate (Hz)			
Time	X	Y	Z	
0	-4.28151	0.76355	0.930085	
0.021033	-1.07819	0.84769	1.063782	
0.042096	1.617471	1.35331	1.036428	
0.063127	6.194637	1.986676	1.306073	
0.084158	7.77809	0.662657	1.350715	
0.105196	7.078862	0.855815	0.156882	
0.124018	0.532797	2.05052	1.418924	
0.146747	-2.38489	1.362895	1.031791	
0.167652	-7.894	2.246645	0.980215	
0.188687	-4.04597	0.51125	1.114262	
0.209723	-7.92023	3.45025	0.774462	
0.230756	-0.55113	0.789096	1.213444	
0.251793	1.960007	2.271004	0.609534	
0.272831	7.714521	0.712533	0.994736	
0.293869	7.034731	-0.91844	0.863122	
0.314907	7.828298	-1.80525	1.225517	
0.335945	2.296604	1.473784	1.104288	
0.356981	-2.52881	2.015799	0.965299	
0.378017	-7.86843	1.100279	1.091349	
0.398702	-6.82843	1.1703	0.986571	
0.419763	-5.78483	2.687614	1.038511	
0.440734	1.431421	0.283675	1.052378	
0.461771	4.575697	0.50419	1.022242	
0.482802	7.818861	-1.02714	1.07736	
0.50394	7.009933	-1.99103	1.008694	
0.522681	1.993159	0.804662	1.130577	
0.546017	-2.80466	0.880997	1.070685	
0.56706	-7.80957	1.440387	1.009181	
0.588102	-1.93911	0.178689	0.974301	
0.609005	-7.82908	3.072363	1.064527	
0.630041	-0.12336	0.239261	0.998826	
0.650827	3.577528	1.084699	0.993079	
0.671882	7.807821	-0.55979	1.117532	
0.692923	7.809836	-0.57438	0.879209	
0.713955	4.029718	0.418178	1.04882	
0.734991	1.414578	0.417843	1.177941	
0.756036	-6.80141	1.612624	1.028202	
0.77707	-4.55807	0.998656	1.000073	
0.798108	-7.88444	1.804428	1.067705	
0.819144	-3.33286	0.822631	1.057989	
0.839375	0.605604	1.394041	1.086863	
0.860413	6.01607	1.117762	1.096077	
0.881442	7.815761	-1.80318	0.826828	
0.902266	6.936301	-0.06287	1.000408	



0.921239	3.090094	0.762865	1.204428
0.944344	-2.24573	1.85333	0.989232
0.965377	-7.80584	2.878232	1.041872
0.986424	-4.37402	1.482244	0.975046
1.007459	-7.93323	3.943074	1.012556
1.028498	-1.70603	1.677958	1.045338
1.04888	1.799107	1.376969	1.161565
1.069924	7.389545	-0.24637	0.955082
1.090962	7.011658	-1.63829	1.067461
1.111995	7.863556	-2.90267	0.849559
1.133028	4.946452	1.330274	1.127886
1.153995	0.631884	1.813085	1.102965
1.175035	-7.92941	3.78272	0.996333
1.193571	-3.31378	0.177137	1.098404
1.216817	-7.93978	6.000987	0.987377
1.237852	-1.59709	1.272288	1.032779
1.258889	1.731171	1.38759	1.009151
1.279926	7.735303	-0.43496	1.110476
1.30053	7.819609	-1.4841	0.699091
1.322102	6.116226	-0.51244	1.107116
1.343154	1.461457	1.194036	1.135443
1.364213	-5.32393	2.996622	1.012541
1.385262	-7.91702	3.203154	1.126928
1.406307	-7.67101	1.505645	1.051588
1.426864	-0.03787	0.887204	1.080386
1.447908	3.796545	0.553731	1.008938
1.468968	7.833917	-1.6717	1.042617
1.490017	7.449617	-1.41065	0.867988
1.511067	5.052945	-0.09531	1.029708
1.531259	1.589695	1.026318	1.130942
1.552299	-6.48797	3.200598	0.98832
1.573385	-3.99028	0.831273	0.973449
1.594432	-7.93713	4.2089	1.003707
1.615474	-0.47566	0.759746	1.100091
1.636533	3.945244	0.868977	0.999039
1.657579	7.823274	-1.20067	1.015187
1.678639	7.829947	-1.6579	0.881596
1.699677	4.039521	1.727393	1.215345
1.720723	0.728696	2.260917	1.113639
1.74176	-7.21175	4.500364	0.927348
1.762815	-5.97456	3.387518	0.85111
1.78388	-7.94329	4.337773	1.156593
1.804928	-3.96778	4.934197	0.926709
1.825974	3.750796	1.070397	1.007524
1.847021	7.038656	-0.45352	1.19643
1.868073	7.848805	-2.3168	1.033661
1.889168	7.858059	-2.66741	0.862119
1.910209	6.130335	0.982939	1.00246
1.930866	1.050419	1.805812	1.107709
1.951908	-7.93182	3.881908	1.01283

1.971236	-4.74453	1.119481	1.053853
1.993408	-7.97577	5.820016	0.929081
2.014461	-1.71534	2.324212	1.004239
2.035509	1.396254	1.991028	1.117319
2.056556	7.799865	-0.3709	1.259713
2.077602	7.849493	-2.31983	0.943921
2.097879	5.941308	0.26846	2.936608
2.118766	3.359426	1.238404	1.162417
2.139808	-4.17659	4.026027	0.937109
2.16085	-7.93729	4.124911	0.997412
2.181905	-5.65413	1.249983	1.134074
2.202964	-7.93579	5.861372	0.944165
2.224011	0.980941	1.714718	1.07108
2.244099	6.972949	0.447361	1.079033
2.265145	7.837048	-1.80971	1.048516
2.286194	7.833978	-1.61848	0.858728
2.307253	6.593138	0.023509	1.084598
2.3283	2.382513	1.44877	1.153689
2.349353	-4.89181	3.809346	0.918179
2.370395	-6.61935	2.699452	1.149386
2.391441	-7.95037	4.687877	1.017833
2.412498	-3.17906	3.067114	0.970986
2.433555	1.917068	0.887524	1.057593
2.454601	6.636917	0.032531	1.108469
2.47565	7.839582	-1.92362	1.060483
2.496691	7.380597	-1.38383	1.162067
2.517756	2.971263	1.19148	1.123325
2.53881	-3.57491	2.798929	1.050827
2.559855	-7.8438	3.32865	1.133421
2.580903	-4.50742	0.437501	1.061091
2.601218	-7.87361	5.043413	1.021619
2.622283	-0.12415	1.677608	1.06065
2.643326	6.040013	0.313892	1.066047
2.664389	7.814906	-0.85714	1.083366
2.685436	7.822862	-1.15406	0.920551
2.705675	6.924558	0.308339	1.118429
2.726727	2.914718	1.294716	1.188143
2.746973	-4.91728	3.666444	0.86554
2.767041	-7.93181	3.823603	1.204732
2.788084	-7.95531	4.934136	0.91488
2.809134	-3.48785	3.298478	0.883436
2.830191	1.265131	1.818274	1.083503
2.850284	6.974766	0.737638	1.060498
2.871329	7.829061	-1.45931	1.037417
2.892368	7.829458	-1.41811	0.847963
2.913412	7.217544	0.363692	1.053078
2.933704	-0.47805	3.122802	1.217124
2.955457	-7.95036	4.679828	1.380699
2.976123	-4.66612	0.069535	0.904328
2.997169	-7.94921	7.095833	-0.0631

3.01822	-0.75857	3.365912	1.142376
3.039312	2.84217	1.63213	1.000088
3.060357	7.81115	-0.6479	0.932016
3.081404	7.303972	-0.99338	1.107998
3.102149	7.811226	-2.15938	1.007356
3.123197	3.656122	1.650236	1.205462
3.144253	-3.15005	2.98664	1.148945
3.165299	-7.91592	3.20145	0.975912
3.186349	-7.84387	1.51768	1.087988
3.20739	-6.58162	3.825657	0.892255
3.228438	0.325293	0.90598	1.100608
3.248785	5.765917	0.697257	0.979638
3.269862	7.805637	-0.47799	1.162493
3.290911	7.830435	-1.44935	0.810285
3.311952	5.111139	1.101344	2.561136
3.333003	-1.5119	2.370162	1.080142
3.354065	-7.92141	3.455743	0.958047
3.375117	-5.30909	1.10489	1.04286
3.395483	-7.95028	4.695135	0.980383
3.416531	-2.27329	2.5375	1.110948
3.437585	1.920657	1.788939	1.026955
3.45864	7.809714	-0.6223	1.053838
3.479693	7.705237	0.146053	0.873264
3.500735	6.182253	-0.34598	1.019931
3.521782	2.910336	1.098667	1.163831
3.541918	-1.99391	2.353745	1.118778
3.56298	-7.89313	2.978865	0.971731
3.58403	-6.36616	1.08546	1.135595
3.604443	-6.48247	3.929349	0.982572
3.625464	1.068026	1.184526	1.077847
3.646507	4.740705	1.428975	1.077223
3.667604	7.7962	-0.095	1.251077
3.688653	6.84691	-0.23473	1.001609
3.709284	7.414298	-1.88243	0.98464
3.73033	3.21372	1.128641	1.199015
3.750823	-4.61577	2.547329	0.918073
3.771923	-7.90033	2.515362	1.00246
3.792679	-6.11662	0.227546	1.003844
3.813721	-7.38795	3.946527	0.984777
3.834766	-0.10477	0.728737	0.997823
3.855429	2.592017	1.324416	1.092991
3.875911	7.580435	-0.15876	1.017772
3.896932	7.816433	-0.86505	0.890765
3.917683	4.914095	0.389619	1.029206
3.938729	1.78599	1.033347	1.093721
3.959774	-3.56656	1.850941	1.026575
3.980839	-7.65424	1.742471	1.015871
4.001887	-3.53902	0.134961	1.023337
4.022939	-5.7821	2.905832	1.055982
4.043984	-1.03236	1.073287	0.967945

4.065034	1.778722	1.262216	1.042054
4.086092	6.655318	0.365959	0.999298
4.107143	7.82274	-1.49046	1.01914
4.128191	7.829901	-1.42286	0.798349
4.149257	4.697292	1.253284	1.103999
4.17031	1.703746	1.818532	1.128266
4.19137	-5.46376	3.348551	1.110826
4.212417	-7.02228	4.889586	2.655559
4.233459	-6.45446	0.052828	0.537812
4.25431	-6.59687	6.047013	0.823422
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4.296413	2.793734	0.146524	1.101384
4.316938	3.972562	0.687473	0.999495
4.337995	7.540412	-0.96354	0.955477
4.359042	7.052811	0.405519	0.88669
4.380088	6.98573	-1.38217	1.066245
4.40105	2.069356	1.324477	1.052576
4.422142	-4.26988	2.067378	0.987909
4.443185	-7.88151	1.822458	1.032916
4.464237	-4.27423	0.194513	1.007387
4.485278	-7.8942	3.782704	1.042039
4.506366	-1.73723	1.094574	1.042647
4.527403	1.351467	1.801217	1.113943
4.548445	7.787771	0.20664	1.46495
4.567377	7.818907	-0.86719	0.544213
4.590538	5.621875	0.123336	2.709734
4.611589	2.644134	0.884177	1.093933
4.632634	-2.58314	2.175392	0.973921
4.653572	-7.90754	2.819211	1.036641
4.67462	-7.76944	1.012715	1.111176
4.695665	-6.64065	4.058983	1.059373
4.716722	-0.1901	1.119633	1.09518
4.737772	3.216881	1.75586	1.175021
4.758819	7.787267	0.295908	1.039819
4.779862	7.814081	-1.10035	1.624541
4.800908	5.56223	1.221043	2.273489
4.821983	2.490059	1.15405	1.178503
4.842483	-4.95316	3.756458	0.990068
4.863614	-7.8868	4.844579	1.480504
4.884657	-5.39783	-0.76215	0.959415
4.905707	-7.4426	7.118991	0.556985
4.926764	-0.3964	1.159467	0.97573
4.947807	2.768493	0.077797	1.015157
4.96889	4.990308	0.064696	1.029023
4.989939	7.811989	-1.02035	0.977372
5.010993	6.865845	0.302207	0.967018
5.032031	6.152141	-0.96914	1.059068
5.052854	2.552941	0.816925	1.146406
5.073892	-4.88859	2.12544	1.008907
5.094934	-7.87627	1.732109	1.021573

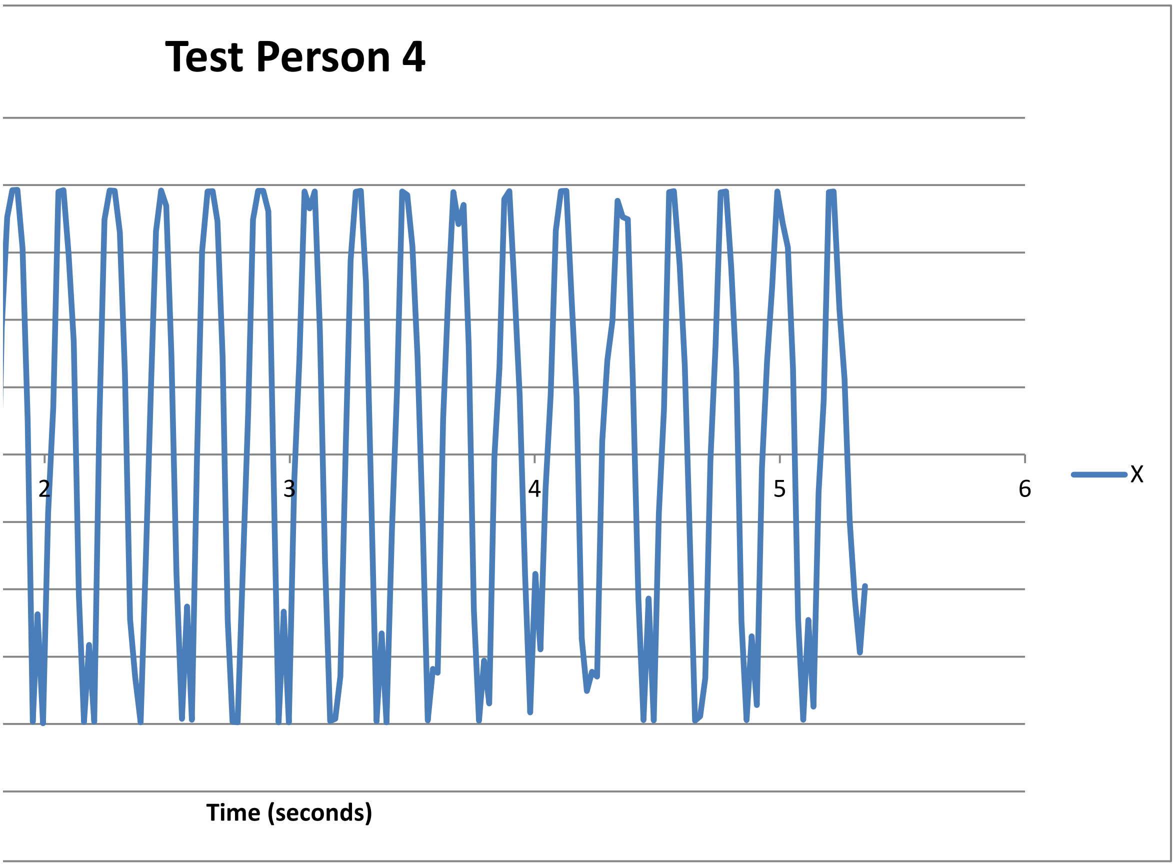
5.11597	-4.90635	0.130868	0.989673
5.137083	-7.48107	3.520088	0.956374
5.158123	-1.12079	0.441533	1.015734
5.179157	1.606919	1.358148	0.991361
5.200193	7.792933	0.074632	1.16079
5.219036	7.812524	-0.60067	0.582058
5.242271	4.332767	0.271396	2.051694
5.26331	2.25397	0.4971	1.091394
5.284343	-1.94957	1.313704	1.027412
5.305376	-4.25189	1.094239	1.06734
5.326411	-5.88196	0.955156	1.029175
5.347448	-3.90746	-0.26243	1.359975

Frequency Data

Frequency	X	Y	Z
0	0.51595	1.37408	1.062937
0.186275	0.61713	1.560376	1.060928
0.372549	0.123095	0.239141	0.028713
0.558824	0.077686	0.060489	0.032948
0.745098	0.132631	0.136811	0.056201
0.931373	0.090775	0.129005	0.046524
1.117648	0.097847	0.128586	0.01877
1.303922	0.137174	0.126335	0.030394
1.490197	0.148841	0.139103	0.05571
1.676471	0.182459	0.195909	0.048681
1.862746	0.103083	0.136819	0.048318
2.049021	0.041556	0.105046	0.026514
2.235295	0.218481	0.124035	0.035792
2.42157	0.312931	0.195736	0.057881
2.607844	0.250104	0.07912	0.048148
2.794119	0.380634	0.220755	0.039079
2.980394	0.187107	0.120443	0.024486
3.166668	0.097996	0.205745	0.040839
3.352943	0.149907	0.23479	0.041305
3.539217	0.138994	0.032189	0.016179
3.725492	0.139373	0.135388	0.037572
3.911767	0.638094	0.251563	0.044085
4.098041	0.451739	0.207775	0.048129
4.284316	1.101395	0.165942	0.028434
4.470591	0.663133	0.097729	0.023063
4.656865	2.246731	0.686434	0.067972
4.84314	5.973572	1.763128	0.075908
5.029414	6.825406	1.932157	0.053202
5.215689	3.404019	1.063125	0.052981
5.401964	0.129225	0.1362	0.031822
5.588238	0.624538	0.185104	0.055271
5.774513	0.230363	0.13315	0.051157
5.960787	0.266838	0.069398	0.032701
6.147062	0.471069	0.101784	0.022075

6.333336	0.213219	0.10189	0.016048
6.519611	0.143607	0.086649	0.02427
6.705886	0.250773	0.07555	0.032764
6.89216	0.06818	0.030721	0.024237
7.078435	0.151119	0.077814	0.047164
7.264709	0.077174	0.040806	0.049346
7.450984	0.104428	0.066022	0.047068
7.637259	0.253025	0.113376	0.040047
7.823534	0.242072	0.160439	0.028799
8.009808	0.06261	0.12873	0.070099
8.196082	0.127887	0.064287	0.067105
8.382358	0.059799	0.064911	0.053984
8.568632	0.109477	0.066789	0.038791
8.754907	0.182965	0.106943	0.030458
8.941181	0.197257	0.146536	0.044115
9.127456	0.022452	0.154163	0.035248
9.31373	0.043135	0.191107	0.023503
9.500005	0.115461	0.158147	0.040435
9.686279	0.096588	0.392728	0.037908
9.872554	0.245907	0.510149	0.032588
10.05883	0.302881	0.47613	0.0457
10.2451	0.260049	0.21295	0.041725
10.43138	0.059761	0.087328	0.071595
10.61765	0.039493	0.131219	0.061525
10.80393	0.179878	0.111441	0.065802
10.9902	0.210217	0.061229	0.047354
11.17648	0.123451	0.099929	0.040437
11.36275	0.090808	0.087323	0.044672
11.54903	0.124413	0.054626	0.047442
11.7353	0.121704	0.07233	0.047508
11.92158	0.163392	0.049817	0.044768
12.10785	0.373861	0.200578	0.01944
12.29412	0.34431	0.2156	0.039213
12.4804	0.240573	0.184806	0.027589
12.66667	0.065712	0.208561	0.047558
12.85295	0.116392	0.246759	0.057021
13.03922	0.065185	0.181746	0.054389
13.2255	0.170222	0.088195	0.059212
13.41177	0.037941	0.123179	0.026007
13.59805	0.107456	0.073476	0.032838
13.78432	0.209963	0.127999	0.037242
13.9706	0.128274	0.081509	0.059321
14.15687	0.156147	0.165627	0.06845
14.34314	0.131922	0.057647	0.03503
14.52942	0.299188	0.184217	0.037105
14.71569	0.584703	0.36576	0.07009
14.90197	0.664525	0.461382	0.0601
15.08824	0.585695	0.364922	0.050204
15.27452	0.287527	0.118636	0.056162
15.46079	0.02647	0.03072	0.028443

15.64707	0.061556	0.071571	0.047959
15.83334	0.020007	0.062887	0.019524
16.01962	0.056357	0.102686	0.047338
16.20589	0.175212	0.130194	0.039376
16.39216	0.120437	0.095068	0.053391
16.57844	0.051288	0.138924	0.058737
16.76472	0.051348	0.11241	0.034704
16.95099	0.11911	0.097218	0.052241
17.13726	0.068822	0.093199	0.061921
17.32354	0.233891	0.125275	0.055538
17.50981	0.373417	0.246604	0.051172
17.69609	0.257452	0.209195	0.026157
17.88236	0.143598	0.10064	0.047234
18.06864	0.296214	0.235661	0.05827
18.25491	0.199009	0.140051	0.040831
18.44119	0.174574	0.264768	0.053003
18.62746	0.116676	0.082808	0.026675
18.81373	0.055253	0.038815	0.041692
19.00001	0.052275	0.1138	0.030075
19.18629	0.300626	0.179862	0.025371
19.37256	0.248583	0.139732	0.04315
19.55883	0.20011	0.278682	0.057906
19.74511	0.418629	0.484956	0.058212
19.93138	0.554674	0.592312	0.040684
20.11766	0.489222	0.400001	0.045105
20.30393	0.24309	0.26344	0.06019
20.49021	0.111048	0.066095	0.052129
20.67648	0.23375	0.156804	0.045057
20.86276	0.175263	0.071762	0.046176
21.04903	0.21958	0.145018	0.038369
21.2353	0.091589	0.070354	0.060131
21.42158	0.22096	0.183418	0.033889
21.60786	0.13325	0.119431	0.02788
21.79413	0.120085	0.080945	0.025294
21.9804	0.122409	0.15826	0.049498
22.16668	0.186618	0.141986	0.070718
22.35295	0.083982	0.119467	0.042386
22.53923	0.318637	0.208456	0.021621
22.7255	0.386355	0.309735	0.052804
22.91178	0.525049	0.516701	0.059054
23.09805	0.497552	0.411379	0.049706
23.28433	0.102476	0.074164	0.032663
23.4706	0.387254	0.29572	0.041965
23.65687	0.214302	0.148773	0.05997



Test Person 4
2
3
4
5
6
X
Time (seconds)

Vibration iOSApp file: VibrationData 2013-06-29 at 16:14-email.csv

Source	Internal Accelerometer		
3	Channels		
256	Points		
50	Sample Rate (Hz)		
Time	X	Y	Z
0	-2.86884	1.488847	1.147957
0.020433	-7.21248	2.753877	0.905453
0.04133	-4.7567	2.21947	0.748735
0.061955	-1.41564	0.734534	0.915838
0.082857	3.134438	1.510194	1.178716
0.103747	7.741014	0.364088	1.999161
0.123995	7.535205	-0.39029	0.4672
0.144758	7.813333	-0.5949	0.274888
0.165489	-1.64845	2.430826	1.155179
0.186205	-2.97788	2.14134	1.696232
0.206992	-5.84058	3.407967	1.726931
0.227508	-4.73001	1.628052	1.501761
0.247932	-5.40247	1.824938	0.22421
0.268521	-3.82004	1.859187	-0.02243
0.289052	1.90896	0.801755	0.281289
0.309159	7.809683	-1.25068	3.118748
0.329603	7.819487	-1.40544	2.227767
0.349974	4.93726	1.600801	-0.28496
0.370262	-2.62053	3.982892	-0.60515
0.390522	-2.70034	1.560085	0.405513
0.410727	-6.26635	3.482096	-0.15655
0.43093	-4.57682	4.001926	1.044821
0.451035	-0.77848	-0.36144	2.041902
0.471434	-0.09059	1.047056	0.927758
0.492477	5.906584	0.448532	0.457226
0.513531	7.835001	-1.49461	0.306909
0.534384	7.804889	-0.87593	0.598388
0.554642	-0.41171	1.150246	1.828272
0.576492	-5.98312	1.261911	1.381566
0.59752	-5.56948	1.050723	0.572874
0.618578	-7.6839	1.77173	-0.53856
0.638697	-5.14466	2.184901	1.249784
0.659738	0.179984	2.372034	2.687611
0.679834	7.75549	1.264544	2.600426
0.699933	7.851004	-1.50508	-1.9401
0.720196	1.601178	3.478657	0.340664
0.741844	-3.4278	2.261389	1.505212
0.762885	-7.91148	2.440442	2.839265
0.783116	-5.06868	0.701715	2.32365
0.804162	-7.90653	3.398868	0.218371
0.825136	-2.48911	1.681488	0.483393
0.846186	0.35791	1.838784	0.982344
0.86723	7.790764	0.071787	1.48131
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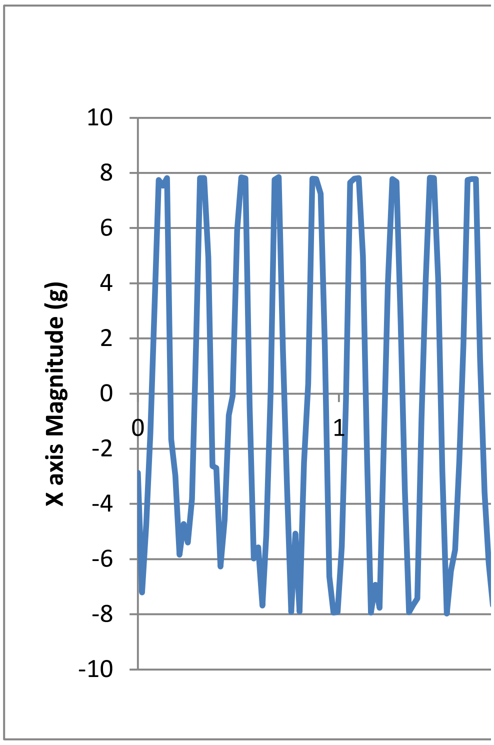


0.908807	7.244755	0.937506	0.297741
0.929858	1.735416	2.455475	0.581085
0.950913	-6.62691	3.673778	0.496819
0.971959	-7.93434	3.741045	1.835099
0.992898	-7.91108	2.950337	1.110263
1.013315	-5.54356	2.968306	1.551846
1.034374	-0.25113	2.88234	0.414348
1.055429	7.657839	2.647416	-0.0886
1.07647	7.796796	-0.3816	2.107207
1.097524	7.812356	-0.38584	-0.09966
1.118564	4.980627	2.984906	-0.21845
1.138836	-2.34344	2.571324	1.539971
1.158756	-7.93732	3.809864	2.033995
1.180939	-6.93203	1.437207	1.306377
1.201983	-7.76807	3.823618	0.793042
1.22303	-1.93143	2.042501	1.462638
1.243609	3.995986	3.677552	1.133542
1.264661	7.77948	0.88868	0.412173
1.285706	7.678377	0.463291	-0.93368
1.306753	2.576885	3.003971	1.286991
1.327072	-3.49095	2.691038	1.481569
1.348034	-7.93216	3.850123	1.167525
1.36862	-7.66287	0.427231	1.006459
1.389659	-7.43293	3.720809	1.02323
1.410709	-0.92535	2.320515	1.429841
1.430846	4.055921	3.201952	1.464554
1.451906	7.824572	-1.32113	1.22608
1.472956	7.81912	-0.63026	-0.26347
1.493116	4.159635	3.300532	0.033463
1.514166	-2.78708	3.339346	0.820092
1.535205	-7.97838	5.737215	1.57257
1.556302	-6.43513	1.082812	2.403917
1.577422	-5.66	2.831125	1.521238
1.597907	-2.46049	2.798716	1.283098
1.618948	1.783043	4.310143	1.804598
1.6391	7.749733	2.616848	-1.01142
1.660177	7.778762	0.586581	1.50541
1.681224	7.782564	1.192012	-1.02152
1.701981	1.249189	2.859243	2.056119
1.723024	-3.5719	2.163843	1.545931
1.743903	-6.13914	2.020622	1.673212
1.764965	-7.67414	1.972222	0.274416
1.786013	-6.16354	3.036531	1.243064
1.807069	-2.39371	2.281473	0.945381
1.828111	2.934447	3.356463	1.318769
1.848187	7.766836	1.224558	1.114338
1.869247	7.796994	0.241711	0.035273
1.889539	3.340843	3.43292	-0.00904
1.910442	-2.84758	2.962113	1.559144
1.93145	-7.94915	4.408175	1.762587

1.951689	-5.82403	0.437562	2.225958
1.97283	-7.9253	3.685342	0.729607
1.993873	-3.30448	2.067835	1.606447
2.014788	0.613988	3.053938	0.68007
2.035837	7.797407	0.067587	0.547467
2.056394	7.799361	0.18511	-0.11644
2.077449	6.250632	2.356591	0.68714
2.098496	0.244041	2.475696	1.379087
2.119544	-7.93446	4.263796	0.647668
2.140589	-6.70401	1.951636	1.649325
2.161594	-7.92185	3.589029	0.553093
2.181856	-3.01386	2.433549	1.509637
2.20373	1.520583	4.667914	1.161352
2.22478	7.768332	1.392306	0.350669
2.24569	7.774486	0.931207	0.985324
2.266743	7.531067	1.525836	-0.79991
2.286957	2.687455	3.187117	0.336954
2.307136	-5.37715	3.190434	1.907855
2.327528	-7.95667	4.777054	1.624054
2.348572	-7.90864	3.138367	0.144976
2.366956	-3.76336	1.648243	1.812413
2.390688	-1.01677	3.154526	1.760276
2.411083	7.593094	2.254542	1.139244
2.431355	7.820755	-0.71439	-0.21892
2.452406	7.7993	0.27873	-0.41486
2.473457	4.251148	2.62088	0.885641
2.493676	-7.68567	3.412106	0.704397
2.51314	-6.22092	2.159796	1.684099
2.535358	-7.77833	2.686747	0.333168
2.556078	-6.09939	2.070117	1.42563
2.577128	-3.07593	4.408692	1.200566
2.598184	6.304993	3.437348	2.020113
2.619106	7.814692	-0.50609	-0.03639
2.639341	7.793116	0.532475	-0.36343
2.660339	1.91661	2.328762	-0.40511
2.681417	-7.44207	3.40961	3.379817
2.702475	-7.91602	2.766156	2.416963
2.723511	-4.70128	0.704301	1.590725
2.744552	-7.91461	3.30359	0.455948
2.764743	-5.02243	2.270442	1.136218
2.785445	0.793945	4.516614	1.197069
2.806531	7.794749	0.244161	0.34775
2.824919	7.785832	0.869935	-0.43119
2.848099	6.067117	2.117802	-0.51164
2.868551	-0.11471	2.847299	2.244995
2.889605	-6.94721	3.248206	1.959962
2.910042	-7.95532	4.731834	1.580553
2.93109	-7.30731	2.256717	-0.34888
2.952141	-3.93951	2.027727	1.349407
2.972424	0.092578	3.507855	1.763803

2.993258	7.726676	2.559045	2.468796
3.014216	7.815868	-0.25493	-1.02868
3.03478	7.75943	1.281509	-0.70577
3.055831	3.455749	2.843525	-0.33866
3.076884	-6.05149	3.704833	0.946841
3.097734	-5.59547	0.467582	2.651454
3.118655	-7.92704	3.527224	1.49425
3.139058	-4.0659	2.005148	1.885838
3.160098	-1.92764	4.117121	1.098495
3.181147	5.291478	3.609524	2.692614
3.202207	7.828664	-0.7265	-1.3062
3.222745	7.771035	1.075174	1.006186
3.243796	3.91333	2.95831	0.268197
3.264557	-2.55535	1.971081	3.195229
3.2856	-7.93358	3.747253	1.704261
3.306656	-4.76551	-0.11323	1.958518
3.327028	-7.90134	3.129618	-0.35788
3.348075	-5.25542	2.713009	1.326539
3.36913	-1.42999	3.086149	1.859397
3.389606	7.256895	2.487351	-0.28386
3.409524	7.774486	0.81942	1.351855
3.430778	7.528105	0.537025	-0.30182
3.451007	3.072304	2.002196	0.835768
3.471089	-1.76349	2.476609	1.245177
3.492143	-7.92614	3.389739	1.816291
3.513186	-5.2654	0.221718	1.759105
3.534251	-7.91925	3.523284	0.397744
3.555296	-4.0734	2.293021	1.057137
3.575741	-0.7818	4.258821	1.633983
3.596784	7.743274	2.206096	1.256672
3.617831	7.797788	0.17802	0.130364
3.638218	7.800735	0.173547	-0.275
3.659273	4.534437	2.847527	0.827482
3.680111	0.195559	2.700897	2.007873
3.701158	-7.94394	4.446228	1.231949
3.721307	-5.82404	0.649831	0.884911
3.743001	-7.45401	3.111862	0.340619
3.764051	-3.56921	2.09717	1.821749
3.785099	0.305977	4.203362	2.236237
3.806151	7.76282	1.231694	1.664667
3.82638	7.819701	-0.59119	-0.47189
3.847435	7.798109	0.449308	-0.80307
3.867479	-0.13746	2.502688	2.162006
3.889546	-7.93205	3.772738	1.40562
3.910591	-5.33997	0.679135	1.669259
3.931176	-7.71068	2.79613	0.402381
3.952229	-5.19709	1.981153	1.329063
3.973284	-1.40484	3.618577	1.426527
3.994325	7.814524	-1.5877	3.533266
4.013653	7.83436	-0.88985	-1.58506

4.035324	5.545693	1.079708	-3.2821
4.056417	-2.89462	2.338195	-1.22648
4.077068	-7.93515	3.015489	4.329017
4.098122	-3.11817	-0.17857	3.504179
4.119163	-6.08849	2.319556	0.485674
4.140212	-3.6291	1.147416	0.509865
4.161294	-1.82382	3.828989	0.206937
4.181513	7.50888	1.089659	1.443298
4.202561	7.834894	-1.34365	-0.17196
4.223606	7.770653	0.834225	-0.19414
4.244662	3.825818	1.54913	0.448255
4.265728	-0.06548	1.182685	2.994067
4.286411	-7.69332	2.899	1.196476
4.307453	-5.7498	1.715297	1.168118
4.327927	-7.58153	3.443875	-0.66948
4.348906	-4.20869	1.638444	0.578394
4.36999	-2.12553	1.2346	1.056043
4.391027	2.049917	2.693701	2.434874
4.411935	7.746771	1.374261	3.485811
4.432338	7.838437	-0.42516	-3.69026
4.453397	3.973479	2.99192	-0.96832
4.474424	-1.7264	2.275402	0.358059
4.495477	-7.94892	3.941248	3.259333
4.516521	-5.81842	1.04164	2.682761
4.536857	-6.40963	2.649287	0.439345
4.557901	-5.10747	2.689623	1.304355
4.578577	-2.3549	3.699735	0.463444
4.599637	6.23611	1.887579	0.617395
4.620676	7.781129	0.418421	1.720454
4.641171	7.770318	1.329558	0.274082
4.661926	3.600295	2.648891	-0.40289
4.68298	0.753357	1.561272	1.82996
4.704039	-3.82558	1.645352	2.080766
4.725076	-6.02745	1.85126	1.380167
4.746076	-7.61856	2.470294	-0.26501
4.767128	-6.24794	3.603225	0.668666
4.788191	-1.02624	2.238885	1.416339
4.809244	4.419836	2.099406	1.715619
4.830038	7.760942	1.191388	2.064725
4.851085	7.80014	0.036229	0.260291
4.871123	3.490046	2.541608	-0.83643
4.89241	-1.99216	1.633408	1.79654
4.912546	-7.37641	1.953964	2.090254
4.933592	-6.63825	2.468879	1.808886
4.954636	-6.59008	2.022128	0.352068
4.975681	-6.08598	2.539189	0.530377
4.996149	-3.54179	2.091479	0.38003
5.016361	1.122677	2.79435	1.34889
5.037394	7.754452	1.360111	2.436471
5.058425	7.796124	0.633261	-1.12294

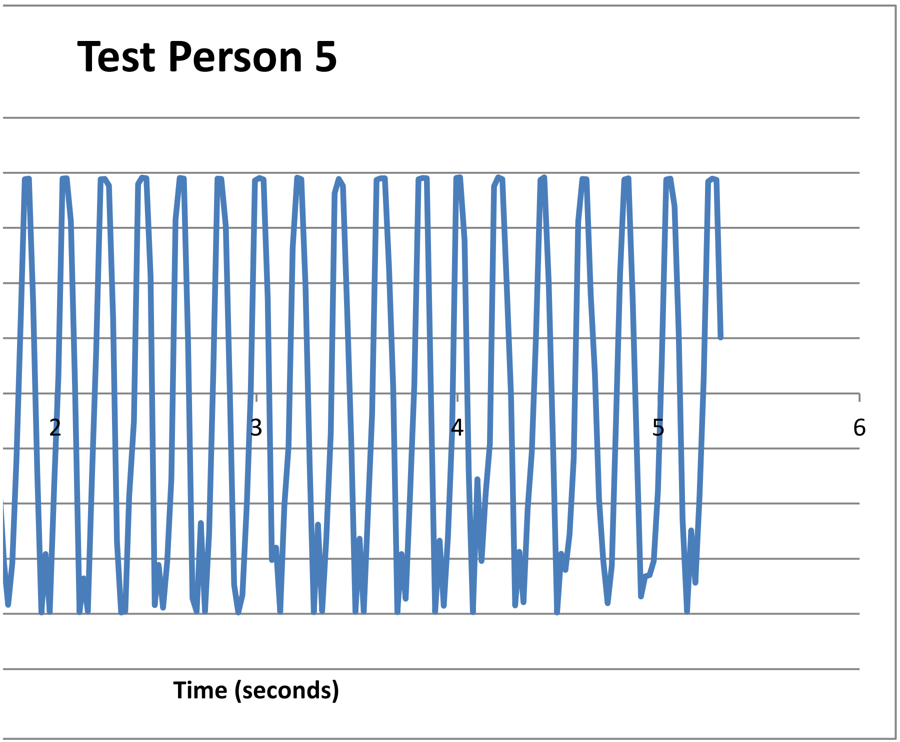
5.078962	6.784548	2.241426	0.759272
5.099669	2.191623	1.654466	0.402199
5.119878	-4.56283	2.519135	2.446613
5.140914	-7.91556	2.982061	1.645007
5.161907	-4.96852	-0.35302	1.775192
5.182941	-6.87498	2.984663	0.658919
5.204064	-3.73833	2.417315	1.199258
5.225103	0.505235	3.602647	0.774082
5.24606	7.684179	2.086047	0.854805
5.267097	7.795757	-0.07939	1.265415
5.28813	7.745794	0.40103	-0.4043
5.309169	2.020217	3.076958	1.226384

Frequency Data

Frequency	X	Y	Z
0	0.286165	2.195724	0.96883
0.187618	0.310083	2.378865	0.975203
0.375235	0.105026	0.182254	0.059652
0.562853	0.155687	0.116662	0.086304
0.750471	0.153319	0.065296	0.049006
0.938088	0.188139	0.069203	0.029829
1.125706	0.209579	0.103165	0.03429
1.313323	0.321798	0.162598	0.039996
1.500941	0.470142	0.16517	0.073805
1.688559	0.284403	0.07535	0.090696
1.876176	0.181817	0.086736	0.076051
2.063794	0.128475	0.058158	0.067244
2.251412	0.09842	0.021255	0.06252
2.439029	0.129901	0.027601	0.070073
2.626647	0.03703	0.083958	0.068623
2.814265	0.057955	0.138868	0.021494
3.001882	0.066443	0.200887	0.059726
3.1895	0.076329	0.218227	0.085373
3.377118	0.153059	0.100539	0.093617
3.564735	0.41839	0.085725	0.101092
3.752353	0.172429	0.136332	0.101256
3.93997	0.569264	0.107302	0.076147
4.127588	0.322864	0.113061	0.081623
4.315206	0.427802	0.053442	0.051949
4.502823	0.524474	0.080126	0.05192
4.690441	1.244013	0.096559	0.113313
4.878059	3.029115	0.387734	0.244533
5.065676	7.546891	0.84465	0.565849
5.253294	5.626768	0.547572	0.430463
5.440912	1.787661	0.165672	0.171623
5.62853	0.691625	0.146999	0.1029
5.816147	0.862493	0.195838	0.161336
6.003765	0.125997	0.042168	0.091747
6.191382	0.527316	0.093042	0.111719

6.379	0.439294	0.087472	0.204961
6.566617	0.095362	0.040879	0.131279
6.754235	0.138093	0.025452	0.052011
6.941853	0.275157	0.055564	0.190803
7.12947	0.309596	0.11301	0.308666
7.317088	0.179265	0.110695	0.156281
7.504706	0.099745	0.13975	0.138151
7.692323	0.161349	0.036168	0.169264
7.879941	0.184383	0.140852	0.224501
8.067558	0.129962	0.078608	0.054658
8.255177	0.108217	0.075887	0.096353
8.442794	0.141345	0.082226	0.10586
8.630412	0.248535	0.251614	0.061932
8.818029	0.398756	0.249686	0.050739
9.005647	0.259783	0.151771	0.05554
9.193265	0.220337	0.157575	0.074558
9.380882	0.309232	0.056151	0.218202
9.5685	0.134696	0.140841	0.092015
9.756118	0.324861	0.304191	0.310927
9.943735	0.420164	0.29158	0.525158
10.13135	0.761438	0.808791	0.560731
10.31897	0.817808	0.865535	0.452598
10.50659	0.477458	0.4437	0.305766
10.69421	0.325816	0.249346	0.256348
10.88182	0.277857	0.235294	0.243662
11.06944	0.138468	0.263716	0.136387
11.25706	0.064371	0.074864	0.043963
11.44468	0.393284	0.202096	0.04477
11.63229	0.41673	0.138237	0.047854
11.81991	0.261537	0.130846	0.037032
12.00753	0.147619	0.240073	0.12525
12.19515	0.237681	0.245308	0.075355
12.38277	0.202548	0.18529	0.158329
12.57038	0.045992	0.08147	0.098244
12.758	0.085541	0.084943	0.065776
12.94562	0.029533	0.040499	0.145835
13.13324	0.082611	0.029203	0.072478
13.32085	0.129751	0.107423	0.128729
13.50847	0.071449	0.060442	0.130889
13.69609	0.274306	0.122999	0.106809
13.88371	0.272153	0.152308	0.087319
14.07132	0.14652	0.225618	0.083592
14.25894	0.059505	0.177556	0.073977
14.44656	0.075209	0.046472	0.123945
14.63418	0.181985	0.063996	0.051864
14.82179	0.241908	0.116785	0.050859
15.00941	0.390138	0.160801	0.032004
15.19703	0.475721	0.189245	0.092357
15.38465	0.538349	0.215758	0.126677
15.57227	0.441115	0.273412	0.054735

15.75988	0.391685	0.24587	0.083863
15.9475	0.313324	0.167038	0.094637
16.13512	0.219837	0.121706	0.100267
16.32274	0.185797	0.049213	0.108866
16.51035	0.243951	0.089246	0.096006
16.69797	0.138016	0.072116	0.107206
16.88559	0.095	0.083132	0.079633
17.07321	0.096184	0.141033	0.097726
17.26082	0.134848	0.078272	0.15575
17.44844	0.225216	0.077037	0.055127
17.63606	0.204205	0.082861	0.031713
17.82368	0.122182	0.081627	0.043381
18.01129	0.117024	0.08218	0.072784
18.19891	0.059883	0.140905	0.073786
18.38653	0.041173	0.15737	0.034799
18.57415	0.034784	0.16257	0.083938
18.76177	0.099567	0.264944	0.06879
18.94938	0.24399	0.341775	0.176466
19.137	0.270557	0.214003	0.099713
19.32462	0.1759	0.110074	0.078243
19.51224	0.078632	0.07161	0.018276
19.69985	0.104871	0.08866	0.029545
19.88747	0.230989	0.240417	0.070408
20.07509	0.21725	0.311211	0.073875
20.26271	0.245609	0.1481	0.091304
20.45032	0.176711	0.156576	0.196936
20.63794	0.330703	0.244671	0.122361
20.82556	0.494479	0.387928	0.088386
21.01318	0.391098	0.319018	0.188304
21.20079	0.18801	0.034821	0.17082
21.38841	0.20319	0.110399	0.048
21.57603	0.253387	0.147013	0.036922
21.76365	0.112996	0.050017	0.151413
21.95127	0.430578	0.314004	0.26552
22.13888	0.472237	0.325567	0.335399
22.3265	0.057102	0.246076	0.335474
22.51412	0.097292	0.308593	0.219625
22.70174	0.166043	0.120434	0.130362
22.88935	0.282722	0.069924	0.140147
23.07697	0.30182	0.168067	0.175613
23.26459	0.089483	0.032208	0.088083
23.45221	0.138252	0.123294	0.13744
23.63982	0.252594	0.189492	0.199312
23.82744	0.472115	0.38845	0.094149



Test Person 5
2
3
4
5
6
Time (seconds)

Vibration iOSApp file: VibrationData 2013-06-29 at 19:54-email.csv

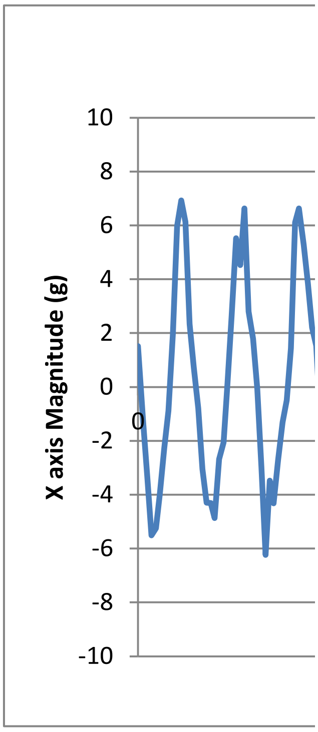
Source Internal Accelerometer

3 Channels

256 Points

50 Sample Rate (Hz)

Time	X	Y	Z
0	1.518368	1.044348	1.067279
0.025065	-1.28224	1.546863	0.911079
0.046096	-3.33146	1.975448	0.991026
0.067126	-5.51554	2.37812	1.057776
0.088161	-5.24908	1.887351	0.985355
0.107011	-3.98782	1.792377	1.113745
0.130234	-2.2577	1.246331	1.112864
0.151272	-0.88899	1.298839	1.093264
0.172311	2.001878	1.122448	1.128099
0.193348	5.974505	0.396861	0.673835
0.213804	6.929185	-0.64901	1.724772
0.234842	6.137039	-0.74196	1.103178
0.255888	2.338199	0.643897	1.193526
0.276924	0.733231	0.924756	1.069286
0.297961	-0.78678	1.615454	1.067309
0.318997	-3.05356	2.176	1.210099
0.340039	-4.29619	2.77317	1.097248
0.361078	-4.30364	1.5325	1.088794
0.379386	-4.86751	2.374271	1.103315
0.402248	-2.67891	0.992722	0.944955
0.423288	-2.05861	1.045109	0.914241
0.443361	0.10623	1.059229	1.272865
0.464393	2.620435	0.593975	1.000955
0.485426	5.527842	0.526222	0.637024
0.506468	4.522511	-0.03741	1.056347
0.527509	6.629481	-1.0176	1.013621
0.548544	2.801155	0.423762	1.042495
0.569587	1.795855	1.018771	1.064116
0.590629	-0.05476	1.713988	1.152746
0.61131	-2.9762	2.762671	1.017559
0.632375	-6.24059	2.870213	0.934008
0.652578	-3.4802	2.13355	0.921494
0.671165	-4.32586	1.484633	1.041978
0.694656	-2.71261	1.070412	1.070472
0.715688	-1.31579	1.152453	0.928017
0.736724	-0.49649	1.202617	1.051694
0.757768	1.438308	0.88019	0.93793
0.778801	6.104636	0.04128	1.015947
0.797746	6.631481	-1.73655	1.281365
0.820864	5.272803	-0.65356	0.948772
0.841985	3.850479	-0.55912	1.049961
0.862567	2.202128	0.36529	1.018897
0.883604	1.535181	0.843932	0.958001
0.904714	-1.54357	1.895461	1.026591



0.925748	-4.08861	2.764452	1.000499
0.946784	-5.75662	2.593858	0.931468
0.967825	-3.76242	2.268646	0.970059
0.988859	-4.55746	2.317898	1.013332
1.009546	-2.33579	1.388822	0.957667
1.029808	-1.18323	1.002765	1.034163
1.050846	2.368739	0.512802	1.081891
1.071882	6.06982	-0.27509	0.88742
1.092918	7.816158	-1.92365	1.064208
1.113685	5.825241	-0.26587	0.950839
1.134718	4.72606	-0.93055	1.061988
1.155856	1.862279	0.359766	1.035516
1.176891	-0.66144	1.36711	1.093675
1.197929	-2.40011	2.031303	0.90822
1.218955	-4.4191	2.675807	0.939421
1.240009	-6.29857	2.784794	0.973312
1.261045	-3.95747	1.746412	1.054142
1.28208	-3.11383	1.692793	1.075368
1.303122	-1.67134	1.052686	1.040412
1.324154	-1.03019	1.002354	1.02732
1.345187	1.021803	0.999539	1.09439
1.365256	4.027275	0.711133	0.914469
1.386294	7.428712	-0.80061	0.897105
1.406806	3.536237	0.487468	1.043331
1.427139	5.75764	-1.28514	1.065257
1.447778	3.440449	-0.18885	0.923775
1.468817	2.143461	0.699098	0.976353
1.489859	-0.23614	1.824451	0.993292
1.510894	-2.58795	2.569072	0.950687
1.531928	-4.49709	2.718851	0.959841
1.552961	-6.01964	2.431039	1.020615
1.574015	-3.93021	1.978262	1.00389
1.595049	-3.80659	1.919638	1.026074
1.61481	-1.88884	0.995431	0.964661
1.637103	-0.90576	1.362211	1.096321
1.657988	1.248303	1.308303	1.06991
1.679023	4.69523	1.061998	0.935984
1.700061	7.387804	0.059325	1.121591
1.721096	5.857277	-0.84661	1.145524
1.741233	4.536346	-0.87943	0.925843
1.763242	2.249282	0.06707	0.9249
1.784279	1.29138	0.631816	1.093721
1.805314	-0.43593	1.276168	1.022379
1.826347	-2.47408	1.941761	1.027184
1.84738	-4.42252	2.580666	1.024051
1.867445	-4.58926	1.96364	1.059205
1.888579	-4.72036	1.968829	0.98055
1.90962	-2.96991	1.469265	1.026454
1.930653	-1.61847	1.106518	1.083746
1.95169	-0.80261	1.432277	1.100578

1.972725	1.233629	1.434879	1.113578
1.993765	6.299542	0.215039	1.037523
2.013531	7.637407	-2.16964	1.151469
2.035727	5.2845	0.154953	0.95274
2.056759	5.031521	-1.20665	0.990007
2.077794	2.251481	0.248877	1.000986
2.098829	1.730484	0.648005	1.118048
2.118912	-0.27789	1.588279	1.050751
2.13995	-3.33722	2.820763	0.914378
2.159426	-5.57314	3.11206	0.94386
2.182018	-4.73059	2.072901	1.045886
2.203052	-4.42946	2.022539	1.052621
2.224087	-3.10421	1.735579	0.990783
2.245123	-1.70104	1.114064	0.923942
2.266157	-0.35094	1.360035	1.018486
2.287189	1.554192	1.531146	1.036231
2.308243	4.633921	0.588361	0.848176
2.329275	6.764956	-0.47817	1.098693
2.35031	5.196651	-0.85196	1.123933
2.370427	5.197964	-1.03695	1.031365
2.391459	3.812044	-0.39102	0.840984
2.412347	2.0676	0.563545	0.973738
2.433475	-0.07739	1.626698	1.058034
2.454595	-2.13733	2.254557	0.824152
2.474727	-4.30106	3.134107	0.780225
2.495775	-6.24974	3.091656	1.034558
2.516834	-3.3532	1.835999	0.97757
2.537962	-4.06454	2.106664	0.984549
2.559008	-1.76228	1.048852	1.018684
2.579935	-1.10122	1.188056	0.880182
2.600979	0.651414	1.043268	1.046874
2.621059	2.877581	0.847614	0.940698
2.64211	5.899086	-0.01896	1.014944
2.663156	6.849934	-1.38167	0.960601
2.684201	4.289506	0.209744	0.902123
2.70476	2.498763	0.037857	1.11297
2.725821	2.433545	0.160157	0.958837
2.746862	0.921846	0.726896	0.995116
2.767917	-0.15845	1.156424	1.055252
2.788868	-1.93651	1.771487	0.894596
2.809913	-3.45011	2.07774	0.999511
2.830967	-5.10224	1.62364	1.026226
2.852026	-4.11909	1.602521	1.087715
2.872114	-4.00861	2.295288	1.000636
2.893156	-2.23843	1.286788	1.020782
2.914199	-1.27158	1.237521	0.950383
2.935265	0.263557	1.463712	0.89335
2.956313	2.690722	1.050388	0.918575
2.976482	6.605125	-0.04558	1.099787
2.997525	5.690361	-1.32498	1.157749

3.018572	4.704759	-0.23928	0.84886
3.039779	4.192588	-0.37242	1.077041
3.060827	2.054437	0.528124	0.990692
3.08187	1.728636	0.621393	1.060893
3.102916	-1.80473	1.970594	0.852798
3.123229	-3.43861	2.339078	1.057153
3.141872	-5.75308	2.855698	0.928731
3.165333	-3.63165	1.690769	0.928473
3.186385	-4.5637	1.931445	1.02361
3.207429	-3.62021	1.999655	0.907292
3.228473	-1.84384	1.214531	1.012526
3.248667	-0.08344	1.687103	1.111495
3.26972	2.441638	1.432596	0.945396
3.290761	5.505075	0.685784	0.772531
3.310992	7.816235	-1.02734	0.939192
3.332038	4.612589	0.771705	1.14785
3.353097	5.467419	-0.95727	1.082119
3.373652	2.752917	0.140149	1.191123
3.394697	1.255022	1.103429	1.021375
3.415738	-0.82043	1.70775	0.936243
3.436783	-3.62064	2.679535	0.986145
3.457076	-5.77031	3.203306	0.953576
3.477302	-4.60114	1.540473	1.044411
3.498368	-4.74906	2.123736	1.061303
3.519423	-3.36537	1.879439	0.903066
3.540464	-1.14535	1.265822	1.065454
3.561521	-0.0006	1.186094	1.147881
3.58257	2.202128	1.063276	0.912888
3.603621	4.982047	0.089132	0.902761
3.624669	7.298872	-1.10883	0.820031
3.645714	4.401787	0.405671	1.26391
3.66677	6.204929	-1.4105	1.001396
3.687831	2.238013	0.760857	1.007326
3.70871	0.675358	1.126297	0.934403
3.729756	-1.77291	1.970959	1.013484
3.750801	-4.15195	2.722883	1.083776
3.771863	-5.91519	3.237708	0.670338
3.792922	-4.36307	1.248142	1.542069
3.813966	-3.85438	1.634108	1.016373
3.835013	-2.42024	1.553999	0.986526
3.856059	-0.82975	1.529564	1.076539
3.876147	1.050587	1.155496	1.381246
3.897196	3.371367	1.48512	0.420931
3.91726	7.155257	0.038146	1.097537
3.93831	6.000601	-1.37065	1.010108
3.959095	5.965511	-1.09439	0.547026
3.979997	2.483906	0.349557	0.985111
3.998019	1.781272	0.610393	1.010397
4.021857	-0.36745	1.435655	1.045855
4.042322	-2.75891	1.980271	0.846199

4.063361	-5.42122	2.485418	0.902199
4.084446	-6.20698	1.800761	1.006733
4.105504	-5.74859	2.430643	1.002795
4.126545	-2.94681	1.500685	0.961422
4.147593	-1.06264	1.65369	1.104759
4.168636	1.560254	1.317067	1.180054
4.189729	4.996843	0.83103	0.853513
4.210038	7.680209	-0.7067	1.453135
4.231086	4.722151	0.474642	0.65714
4.250935	5.188237	-0.71093	1.07739
4.272099	1.798161	0.808389	1.047893
4.293156	0.488865	1.002871	0.942036
4.3137	-2.46044	1.935081	0.977433
4.334748	-4.30352	2.217934	1.001046
4.355796	-6.89207	3.027585	0.944788
4.376839	-4.87825	1.945549	0.940424
4.397901	-3.81427	1.766983	0.989095
4.418952	-1.69955	1.384638	1.049109
4.440003	0.224817	1.673318	1.071065
4.460097	2.961169	1.3272	1.095028
4.48044	5.912417	0.802242	0.607207
4.501506	7.813211	-0.93385	1.370572
4.522558	5.377616	0.432313	1.197403
4.543603	3.194525	-0.02075	1.132341
4.564651	1.990853	0.713948	0.972263
4.585698	0.405262	1.151722	0.938584
4.606762	-1.47591	1.699944	1.03582
4.627809	-3.92543	2.517918	1.104927
4.648849	-6.29343	2.963894	0.911048
4.669895	-4.75516	1.581935	0.984853
4.688663	-4.50671	1.779779	0.988016
4.712001	-1.92743	1.142289	0.948087
4.73305	-0.79869	1.332328	0.935984
4.754093	1.195439	1.304955	0.927561
4.775146	4.184388	0.907045	0.908342
4.795672	7.709283	-0.94332	1.110218
4.817252	5.631709	0.582107	0.925326
4.838312	5.60013	-0.44508	1.068678
4.859355	2.40325	0.817138	1.081769
4.879437	1.460541	1.068434	0.962091
4.900478	-1.54382	1.822762	1.025146
4.921543	-3.73928	2.16611	1.001366
4.941571	-7.71963	3.052112	1.179507
4.963649	-5.31041	1.850606	1.03436
4.984289	-3.90189	1.65973	1.037964
5.005451	-2.16975	1.376924	0.903735
5.026493	-0.57961	1.344713	0.900602
5.047526	1.213091	1.666166	1.073239
5.0685	5.845046	0.993757	0.840695
5.087547	7.811333	-1.01498	1.089235

5.110592	5.527399	0.908871	0.97909
5.130673	6.022315	-0.98409	0.89972
5.151734	2.067065	0.648294	0.97348
5.172759	1.229964	0.902937	0.997929
5.193799	-1.68329	1.669514	0.927789
5.214311	-6.28999	3.364086	1.082165
5.233426	-6.28313	2.524598	0.646147
5.256431	-4.76064	1.62542	1.250833
5.277471	-3.40752	1.606431	0.965375
5.298508	-1.89713	1.500807	0.969085
5.319544	0.566299	1.303769	1.098814
5.340602	4.940909	0.853898	0.89379

Frequency Data

Frequency	X	Y	Z
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0.186513	0.331048	1.038366	0.995584
0.373027	0.038238	0.029875	0.017514
0.55954	0.056791	0.036291	0.020903
0.746054	0.069199	0.043441	0.020712
0.932567	0.020545	0.086979	0.014525
1.11908	0.019855	0.102446	0.021189
1.305594	0.046821	0.054878	0.018408
1.492107	0.06991	0.030565	0.005922
1.67862	0.059626	0.032605	0.007259
1.865134	0.039698	0.05003	0.011048
2.051647	0.041112	0.026746	0.013411
2.238161	0.087461	0.071877	0.014402
2.424674	0.079901	0.091423	0.017433
2.611187	0.330491	0.115571	0.024042
2.797701	1.075333	0.284438	0.026058
2.984214	3.042978	0.828679	0.011196
3.170727	5.096077	1.314434	0.014485
3.357241	2.308852	0.565281	0.010761
3.543754	1.370554	0.31432	0.009989
3.730268	0.67292	0.182309	0.012761
3.916781	0.233029	0.123722	0.016025
4.103294	0.261213	0.127973	0.013822
4.289808	0.144979	0.044239	0.008367
4.476321	0.178701	0.051617	0.010724
4.662835	0.07191	0.071682	0.017129
4.849348	0.118558	0.101675	0.016107
5.035861	0.139511	0.124101	0.009946
5.222374	0.159985	0.110246	0.006879
5.408888	0.195026	0.056328	0.008131
5.595401	0.107294	0.033157	0.013067
5.781915	0.111388	0.046429	0.02318
5.968428	0.17339	0.158567	0.028799
6.154942	0.220088	0.338114	0.026037

6.341455	0.218929	0.417709	0.021593
6.527968	0.154789	0.175602	0.010887
6.714482	0.109043	0.197314	0.012255
6.900995	0.051332	0.145352	0.014912
7.087508	0.114546	0.076717	0.018498
7.274022	0.097732	0.03962	0.01109
7.460535	0.06612	0.033636	0.014295
7.647048	0.175018	0.075526	0.026849
7.833562	0.145214	0.032586	0.022914
8.020075	0.087546	0.017352	0.010868
8.206589	0.063401	0.041007	0.012842
8.393102	0.056545	0.035079	0.014632
8.579616	0.134011	0.058763	0.019391
8.766129	0.104792	0.059057	0.019023
8.952642	0.142598	0.042746	0.015641
9.139155	0.35935	0.085978	0.013156
9.325669	0.537642	0.12461	0.017099
9.512182	0.483046	0.118695	0.024177
9.698696	0.198578	0.072206	0.019684
9.885209	0.260236	0.038909	0.011517
10.07172	0.176241	0.065647	0.010777
10.25824	0.086173	0.028788	0.017061
10.44475	0.140061	0.046987	0.017007
10.63126	0.065696	0.054473	0.013998
10.81778	0.125389	0.133457	0.021308
11.00429	0.084651	0.089994	0.022037
11.1908	0.074009	0.068034	0.013873
11.37732	0.086466	0.04208	0.020152
11.56383	0.077963	0.038097	0.020889
11.75034	0.072486	0.053006	0.009873
11.93686	0.061634	0.063282	0.014415
12.12337	0.084381	0.099519	0.019113
12.30988	0.181751	0.147512	0.031344
12.4964	0.163758	0.139484	0.037393
12.68291	0.048841	0.065995	0.021619
12.86942	0.061473	0.034667	0.021785
13.05594	0.058187	0.04425	0.029314
13.24245	0.027462	0.039289	0.01793
13.42896	0.043488	0.033922	0.026237
13.61548	0.081985	0.02064	0.023138
13.80199	0.110145	0.042227	0.033623
13.9885	0.074958	0.091888	0.030509
14.17502	0.026266	0.04085	0.016899
14.36153	0.071613	0.032235	0.034801
14.54804	0.079552	0.024358	0.038004
14.73456	0.102921	0.054591	0.031779
14.92107	0.136856	0.052642	0.023598
15.10758	0.129385	0.042816	0.016123
15.2941	0.19873	0.139496	0.017058
15.48061	0.26869	0.190827	0.012545

15.66712	0.213164	0.13937	0.019086
15.85364	0.085216	0.051519	0.024008
16.04015	0.136396	0.111594	0.017168
16.22666	0.229021	0.126638	0.026222
16.41318	0.098326	0.042306	0.025649
16.59969	0.143342	0.090699	0.023452
16.7862	0.084307	0.100329	0.026103
16.97272	0.099107	0.111147	0.019154
17.15923	0.07764	0.062532	0.022038
17.34575	0.075289	0.055168	0.021206
17.53226	0.083412	0.055499	0.017128
17.71877	0.09089	0.067661	0.01275
17.90529	0.046955	0.057705	0.022988
18.0918	0.056573	0.052359	0.026816
18.27831	0.03531	0.055182	0.019947
18.46483	0.06133	0.071833	0.011379
18.65134	0.07846	0.082725	0.018035
18.83785	0.033189	0.051758	0.022281
19.02436	0.091538	0.065255	0.019708
19.21088	0.121732	0.070386	0.018446
19.39739	0.093529	0.03057	0.012727
19.5839	0.079183	0.051348	0.014569
19.77042	0.084808	0.084899	0.011591
19.95693	0.140797	0.084575	0.011951
20.14344	0.159668	0.077411	0.013651
20.32996	0.053071	0.059721	0.021352
20.51647	0.069818	0.11087	0.021759
20.70299	0.047382	0.058088	0.0141
20.8895	0.067093	0.032807	0.024544
21.07601	0.090931	0.082172	0.036982
21.26253	0.217534	0.083084	0.039738
21.44904	0.230859	0.086244	0.033439
21.63555	0.144016	0.111929	0.017619
21.82207	0.171861	0.115917	0.022416
22.00858	0.106631	0.058819	0.015019
22.19509	0.16451	0.119765	0.016334
22.38161	0.2225	0.167339	0.026248
22.56812	0.137946	0.085708	0.024991
22.75463	0.041402	0.049147	0.013847
22.94115	0.135592	0.116354	0.011551
23.12766	0.088588	0.086717	0.011077
23.31417	0.144619	0.050016	0.011642
23.50069	0.129584	0.041333	0.01628
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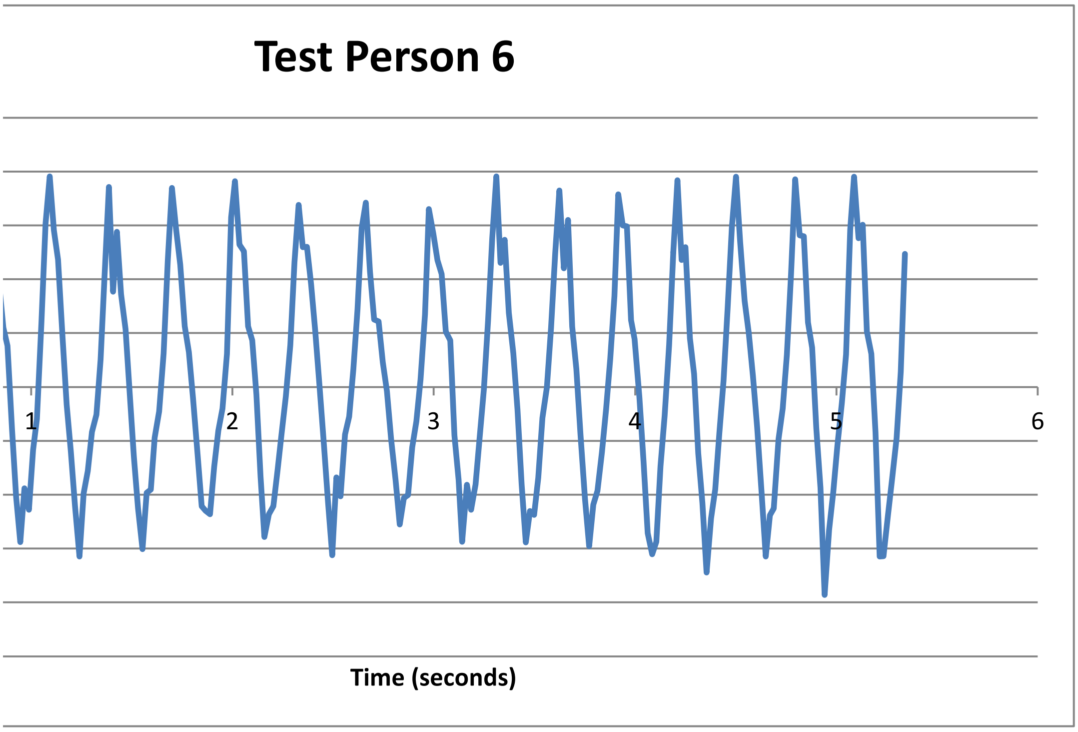
Test Person 6
1
2
3
4
5
6
Time (seconds)

Vibration iOSApp file: VibrationData 2013-06-29 at 20:12-email.csv

Source Internal Accelerometer

3 Channels

256 Points

50 Sample Rate (Hz)

Time	X	Y	Z
0	0.919495	1.083177	1.150405
0.021031	-1.1262	1.481848	1.066717
0.042062	-4.74528	1.158067	1.002035
0.061904	-6.67397	0.939043	1.127415
0.083695	-6.30521	1.136385	0.959157
0.104748	-2.58321	1.52296	0.912827
0.125785	0.458554	1.486793	0.921296
0.14595	3.66643	1.276625	0.960008
0.166982	6.538624	0.996648	0.97018
0.18802	5.317834	0.703815	0.832423
0.207946	5.425304	1.161764	1.027016
0.2301	2.035212	1.108982	1.045369
0.251142	-0.75388	1.469022	1.043711
0.272182	-4.19095	1.679921	1.075581
0.293219	-7.44083	1.136887	0.783646
0.313525	-7.05109	0.875184	0.859792
0.333699	-6.2252	0.818827	0.832545
0.354739	-0.4541	1.364234	0.941975
0.375771	3.288039	1.512857	1.047847
0.396805	6.230094	1.408161	0.972795
0.417844	6.903226	0.934417	1.052956
0.438391	6.484324	0.745291	1.029008
0.458699	4.249285	1.325253	1.005395
0.479737	1.312132	1.209327	0.971366
0.500769	-2.86948	1.226536	0.97681
0.521462	-6.29563	0.800006	0.930115
0.542498	-7.24009	0.602466	1.24054
0.56355	-7.11197	0.585257	1.031943
0.583705	-3.58502	1.004332	1.12375
0.604564	-0.94308	1.270234	1.103406
0.625605	2.506856	1.542557	1.120375
0.646642	6.784807	1.650297	1.196476
0.667675	5.540073	1.170026	1.002932
0.68871	6.157928	1.311954	1.299717
0.709744	3.395723	1.257879	1.061471
0.730783	0.79903	1.217878	1.104394
0.751819	-2.09251	1.299371	1.10219
0.772859	-7.02051	0.744713	0.807746
0.793893	-7.00664	0.510793	0.923653
0.814229	-7.127	0.532186	0.831222
0.834663	-2.93836	1.23002	0.953044
0.855699	1.035898	1.743993	1.103497
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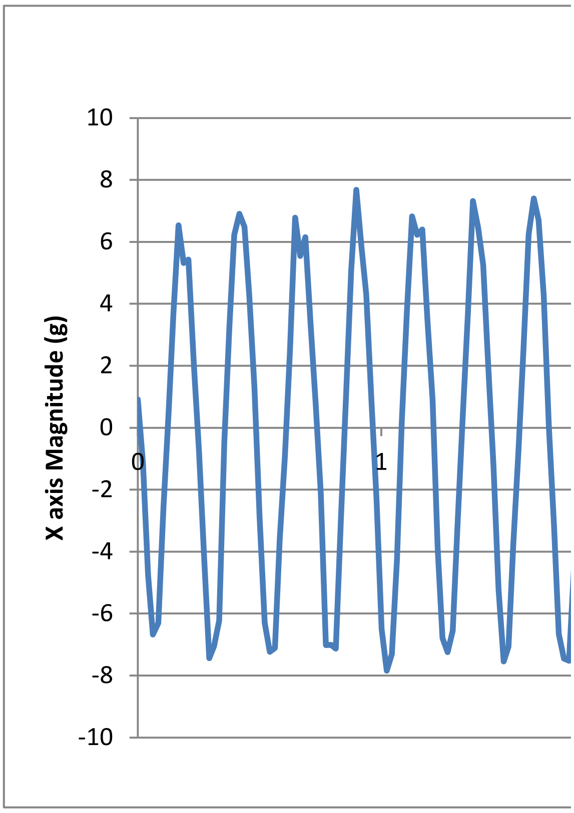

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0.938586	4.305067	1.61766	1.146238
0.960307	0.921159	1.445164	1.154191
0.981354	-2.28319	1.412056	1.173699
1.002395	-6.49913	0.911853	1.062596
1.023445	-7.8491	0.321287	1.059585
1.043861	-7.31016	0.359356	1.003312
1.064907	-4.23856	0.856074	0.833047
1.085297	0.201942	1.548993	0.961772
1.106353	3.775396	1.802678	0.987772
1.127395	6.825914	1.779246	1.208837
1.147791	6.221848	1.278816	1.107998
1.168843	6.400309	1.391317	1.259348
1.189888	3.480975	1.370457	1.027184
1.210933	0.913188	1.234585	1.073467
1.231978	-3.90115	1.148725	0.872504
1.25266	-6.78903	0.721982	0.920551
1.273714	-7.2476	0.424736	1.225456
1.294759	-6.55331	0.507263	0.924489
1.315069	-2.91024	0.991231	0.92265
1.335331	0.320636	1.342552	1.049869
1.356398	3.618054	1.634412	1.001214
1.377109	7.319761	1.585586	1.024416
1.398494	6.472994	1.209997	0.916218
1.419546	5.26529	1.390496	0.868383
1.440191	1.959366	1.222306	1.04099
1.46125	-1.19131	1.265715	1.052287
1.482292	-5.225	1.034945	1.056286
1.503344	-7.5476	0.617011	1.102935
1.523631	-7.06821	0.417706	0.991391
1.542719	-3.76478	0.741701	1.103026
1.564748	-0.77783	1.177177	1.09182
1.584828	2.574502	1.547624	1.089174
1.605877	6.245685	1.804352	1.093416
1.626924	7.40028	1.546224	1.073559
1.647291	6.70099	1.364189	1.04841
1.668342	4.271931	1.562398	1.153096
1.688794	0.052174	1.407811	0.961863
1.709837	-3.13005	1.333986	0.749982
1.730879	-6.65299	0.854963	0.929142
1.751925	-7.44914	0.412518	1.107983
1.772999	-7.52289	0.244876	0.976247
1.794041	-4.39424	0.699935	1.07996
1.814124	-0.94424	1.354588	1.19678
1.835168	5.043997	2.35373	1.051329
1.856223	7.736845	2.456905	1.17972
1.877279	6.340038	2.129	0.935102
1.898323	6.436438	1.921601	0.973191
1.919369	3.142699	1.508825	1.02653
1.939754	-0.06096	1.454446	0.951432

1.960804	-4.42265	1.577872	0.890324
1.981037	-7.85216	0.46005	0.868854
2.002998	-7.85604	0.618472	0.904297
2.024051	-5.58351	1.198129	0.832743
2.045093	-0.94656	2.248532	1.081952
2.066142	4.126056	3.174351	0.913405
2.08633	7.726218	2.892032	1.203364
2.107386	7.621801	2.078729	1.027366
2.127141	6.742158	2.238155	0.89227
2.148936	2.258108	2.061718	1.159087
2.16999	-1.85867	2.187427	1.195533
2.191042	-7.23207	1.719998	0.858211
2.212087	-7.84779	0.248041	0.940926
2.233135	-7.85066	0.401335	0.849666
2.254199	-3.17885	2.314459	0.956116
2.275247	1.906349	3.35835	1.158509
2.296302	7.414022	3.442065	1.171357
2.316541	7.72857	2.900598	1.08031
2.337296	7.746557	2.118456	1.078455
2.358345	6.345947	2.346716	0.944286
2.379393	1.572394	2.411807	1.166689
2.400459	-6.3941	2.638347	1.086818
2.421542	-7.86721	1.04027	1.114947
2.442325	-7.86082	0.825293	0.908342
2.463368	-7.04555	1.60567	0.807822
2.484417	-2.52079	2.395876	1.162721
2.505508	3.142638	3.345447	1.003874
2.526062	7.704153	3.066992	1.017863
2.546292	7.752162	2.432484	-0.7526
2.567332	7.525265	1.928539	0.17198
2.587476	4.533048	2.241548	-0.28957
2.608538	-1.10109	2.785707	0.800204
2.629582	-6.74893	2.745569	0.755334
2.650628	-7.8668	1.10737	0.83551
2.671711	-7.84498	0.195639	1.016358
2.691944	-0.91448	0.97273	1.062824
2.713006	3.399556	1.297911	1.270144
2.734063	5.355337	1.167927	1.282931
2.755138	5.598894	1.040179	0.835267
2.776177	4.702071	0.902389	0.85923
2.797219	3.540147	0.558509	0.966242
2.817451	2.399417	0.481093	0.997215
2.838539	-3.67526	1.137009	1.234792
2.85958	-7.85171	0.418056	0.942081
2.880641	-7.84747	0.276645	0.803777
2.901686	-5.0575	1.356064	1.069377
2.922779	1.410349	2.344068	1.151119
2.943581	6.765613	2.498397	1.051147
2.964627	5.790639	1.358711	0.969861
2.98567	7.601279	1.717548	1.049459

3.005778	2.999772	2.212943	1.13003
3.026832	-2.42459	2.642699	1.034102
3.047874	-7.73313	1.78127	0.394019
3.068918	-7.84064	0.465376	-0.79086
3.089864	-7.81357	0.568855	0.41938
3.110909	-0.49761	2.208089	0.874359
3.131967	3.84886	2.571172	1.233637
3.153001	7.747565	2.040539	1.189132
3.174049	5.717068	1.192301	0.979197
3.194895	7.459726	1.855384	1.077497
3.215944	3.206177	2.062205	1.052789
3.237006	-0.92766	2.711502	0.954747
3.258063	-7.85782	1.001578	-0.09583
3.279107	-7.80665	0.456992	2.116954
3.300154	-5.79503	1.358681	0.857405
3.320599	-2.0258	1.886606	0.828835
3.340939	2.102125	2.247984	1.180419
3.361986	7.134735	2.094051	1.133801
3.383031	7.65987	1.374155	1.070594
3.404078	6.530913	1.451737	1.261583
3.425129	2.568944	1.565563	1.074547
3.446191	-0.45149	1.948258	1.00506
3.467243	-4.72613	1.738971	0.719876
3.48829	-7.85886	0.703039	1.028537
3.509344	-7.60147	0.589669	0.908311
3.530384	-3.80281	1.64307	0.987483
3.549159	0.141488	2.184171	0.929841
3.57185	5.297723	2.12509	1.122017
3.59212	7.75178	1.868636	1.149568
3.61317	5.109796	1.432901	0.982207
3.634219	6.784441	1.607146	1.08291
3.655318	2.76695	1.513664	0.986784
3.676358	-1.26164	1.833185	1.188371
3.697408	-5.87365	1.426769	1.192994
3.718449	-7.85767	0.66287	0.99133
3.738721	-7.85828	0.717432	0.898899
3.759803	-5.56344	1.327474	0.847643
3.780847	-1.43493	1.751524	1.118261
3.801889	3.023517	2.120221	1.038998
3.821894	7.745091	1.86786	1.119128
3.843387	5.732475	1.504397	1.026621
3.864441	6.679017	1.512385	1.211665
3.885495	3.023792	1.401801	1.144992
3.906543	0.287851	1.777131	0.895372
3.926632	-4.67684	1.941852	0.786033
3.947751	-7.86349	0.937491	0.91973
3.96881	-7.85164	0.39362	1.011887
3.989871	-3.93243	1.42365	1.057533
4.010464	-0.31765	2.059253	0.955036
4.031624	4.160032	2.304174	0.996074

4.052669	7.64011	2.253537	0.938402
4.073721	6.718368	1.743156	0.939466
4.094626	5.703524	1.893681	1.16009
4.115678	1.8626	2.123934	1.131094
4.136724	-1.9968	2.352011	1.024903
4.157815	-7.11469	1.539104	0.946521
4.178869	-7.84438	0.102628	0.932244
4.199429	-7.84791	0.243187	0.975958
4.220473	-4.68127	1.400355	1.084324
4.241518	1.366921	2.344951	1.246181
4.262568	6.207739	2.581746	1.12968
4.283622	7.741259	2.307308	1.212867
4.304679	6.65973	1.859796	1.226764
4.325418	6.255656	1.924035	0.945579
4.345873	2.280723	1.736522	1.044274
4.366916	-1.06742	2.08515	1.085875
4.388131	-7.73186	0.755197	0.646999
4.409176	-7.22781	0.250292	1.119098
4.430228	-7.72499	0.229737	0.8826
4.451281	-3.35023	1.255886	0.957074
4.472329	-0.18172	1.853041	1.002126
4.493389	4.357656	2.272161	0.964235
4.513548	7.748161	2.051296	1.067796
4.535483	6.739409	1.33423	0.979851
4.556534	4.755715	1.636055	1.150192
4.577574	1.938507	1.782883	0.987195
4.597695	-1.25225	1.863463	1.110583
4.618546	-5.43611	1.520754	1.183506
4.639587	-7.85229	0.415987	1.032308
4.660636	-7.77636	0.450039	0.98169
4.679173	-3.88153	1.605686	1.03468
4.702751	-0.34752	2.301709	0.949669
4.723803	4.597472	2.594512	1.03807
4.744846	7.647211	2.365613	1.055632
4.765891	6.493165	1.662728	0.844481
4.786255	5.464273	1.821667	0.927606
4.807122	1.896499	1.724015	1.112195
4.827993	-0.75862	1.982188	0.953561
4.84831	-4.84818	1.731075	0.894961
4.869372	-7.85778	0.789781	0.965512
4.890417	-6.6254	0.763322	0.869508
4.911479	-5.78436	0.826876	0.94275
4.932498	-1.39941	1.401359	0.978497
4.953428	1.227154	1.677426	1.242121
4.973474	4.726045	1.939981	0.94979
4.994378	7.541374	1.748542	1.016266
5.015368	5.421838	1.500274	1.160425
5.03632	5.464945	1.311726	1.00947
5.057353	2.619671	1.380651	1.118672
5.078384	-1.09028	1.837247	1.043027

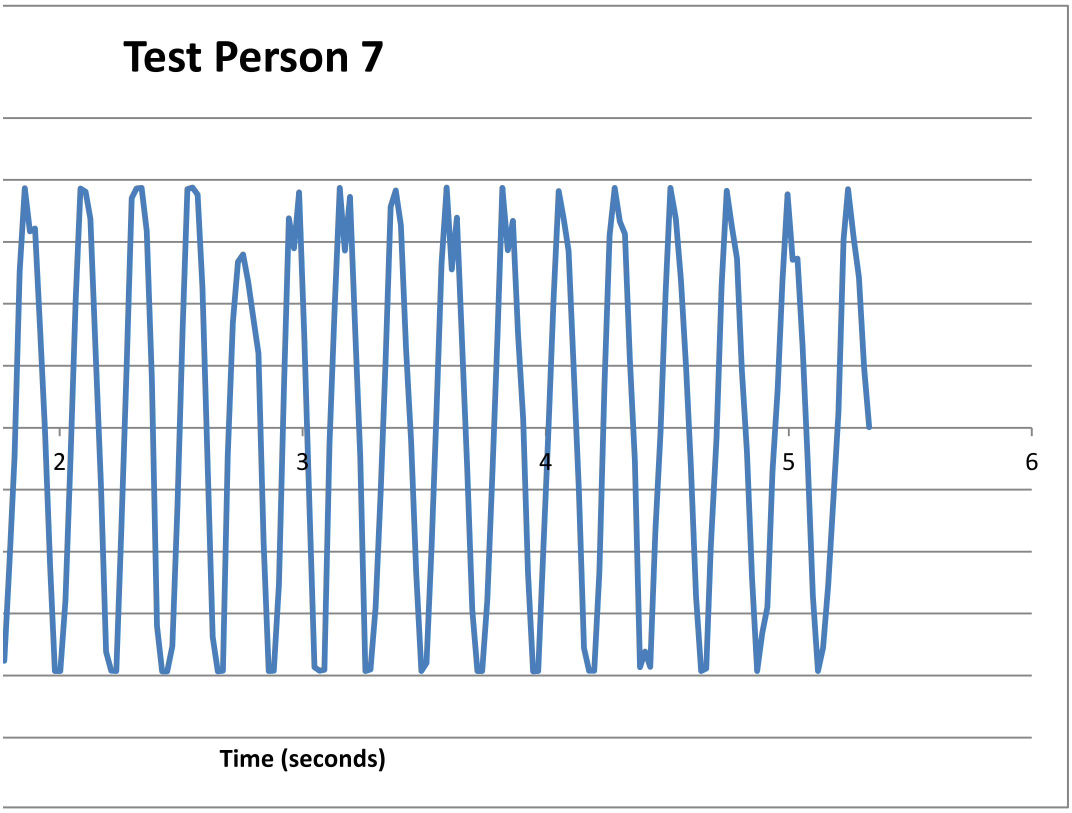
5.099422	-5.42027	1.371948	1.185346
5.120286	-7.85807	0.653604	1.079367
5.141321	-7.10038	0.674479	0.958776
5.162354	-5.07473	1.133494	0.919517
5.183391	-2.34227	1.496288	0.812657
5.204425	0.495126	1.79755	1.084598
5.225461	6.079638	1.90707	1.084567
5.244176	7.698747	1.627946	1.026013
5.267533	6.092435	1.039327	0.947008
5.288567	4.856115	1.318984	0.941762
5.309602	1.955778	1.380849	1.134318
5.330637	0.01545	1.659183	0.882052

Frequency Data

Frequency	X	Y	Z
0	0.064269	1.582673	0.969613
0.186862	0.149375	1.732488	0.914803
0.373724	0.103715	0.256087	0.098382
0.560586	0.028962	0.267372	0.069947
0.747448	0.048848	0.252201	0.047479
0.93431	0.095394	0.251601	0.02663
1.121172	0.097564	0.230266	0.028132
1.308034	0.090732	0.199431	0.057608
1.494896	0.119888	0.149254	0.088244
1.681758	0.127932	0.164087	0.10932
1.868621	0.104486	0.184838	0.11642
2.055483	0.073564	0.153743	0.119181
2.242345	0.09035	0.132092	0.113959
2.429207	0.275775	0.110703	0.076329
2.616069	0.20999	0.105077	0.052139
2.802931	0.195831	0.131622	0.034211
2.989793	0.327527	0.132966	0.028532
3.176655	0.270698	0.105662	0.058141
3.363517	0.173455	0.102977	0.085093
3.550379	0.374436	0.091165	0.091749
3.737241	0.298629	0.081698	0.090182
3.924103	1.609664	0.164476	0.090146
4.110965	3.349059	0.330157	0.087272
4.297827	2.343657	0.22225	0.102521
4.484689	6.105749	0.458353	0.115069
4.671551	5.046807	0.361174	0.073687
4.858413	3.015058	0.186945	0.033322
5.045275	1.632946	0.105098	0.017433
5.232138	0.818397	0.046492	0.02763
5.419	0.46191	0.102652	0.05596
5.605862	0.500398	0.067513	0.0765
5.792724	0.426086	0.03486	0.096945
5.979586	0.148332	0.037451	0.104179
6.166448	0.141097	0.040146	0.083686

6.35331	0.159304	0.037938	0.054652
6.540172	0.192417	0.063214	0.052736
6.727034	0.283438	0.068966	0.045355
6.913896	0.319137	0.037704	0.036529
7.100758	0.316596	0.027252	0.046534
7.28762	0.27956	0.035265	0.063003
7.474482	0.237197	0.05989	0.067523
7.661344	0.246195	0.092422	0.055571
7.848206	0.276686	0.079377	0.056831
8.035069	0.319344	0.043735	0.062478
8.221931	0.281631	0.094881	0.052785
8.408792	0.197381	0.180817	0.033897
8.595654	0.198956	0.330464	0.031618
8.782516	0.051706	0.177715	0.037401
8.969378	0.229245	0.132399	0.043459
9.15624	0.417484	0.324088	0.057114
9.343102	0.44295	0.327411	0.070494
9.529964	0.317962	0.282611	0.073278
9.716826	0.213255	0.22737	0.068186
9.903688	0.177921	0.140975	0.067316
10.09055	0.205528	0.131024	0.072303
10.27741	0.229551	0.133574	0.079327
10.46428	0.210763	0.105004	0.066537
10.65114	0.130533	0.092576	0.041294
10.838	0.140316	0.072161	0.040199
11.02486	0.187425	0.050944	0.03614
11.21172	0.085315	0.045842	0.035592
11.39859	0.13818	0.050387	0.049025
11.58545	0.233764	0.059245	0.060452
11.77231	0.18775	0.064792	0.063664
11.95917	0.097182	0.061641	0.051102
12.14603	0.063736	0.049365	0.023343
12.3329	0.115494	0.032443	0.03042
12.51976	0.131549	0.017877	0.034638
12.70662	0.09646	0.02353	0.027642
12.89348	0.169442	0.054421	0.035614
13.08034	0.270609	0.088462	0.041966
13.26721	0.214901	0.085878	0.033145
13.45407	0.054218	0.055455	0.026688
13.64093	0.181218	0.052046	0.017904
13.82779	0.220515	0.062709	0.021647
14.01465	0.21307	0.047256	0.030223
14.20152	0.208936	0.039819	0.039398
14.38838	0.148116	0.038096	0.035202
14.57524	0.059094	0.031609	0.018145
14.7621	0.081506	0.033862	0.024229
14.94896	0.082455	0.034147	0.038825
15.13583	0.027684	0.03817	0.039953
15.32269	0.101368	0.047617	0.042832
15.50955	0.139531	0.056246	0.044324

15.69641	0.127066	0.044673	0.049088
15.88327	0.11071	0.017642	0.055784
16.07014	0.126282	0.035541	0.055545
16.257	0.110228	0.045203	0.047436
16.44386	0.082618	0.050097	0.041183
16.63072	0.114576	0.044541	0.046416
16.81759	0.119058	0.01815	0.073846
17.00445	0.169328	0.037387	0.067366
17.19131	0.262126	0.062225	0.032214
17.37817	0.212137	0.047301	0.015277
17.56503	0.073321	0.026398	0.018939
17.75189	0.052437	0.058769	0.032001
17.93876	0.099981	0.056739	0.036152
18.12562	0.131102	0.038744	0.032489
18.31248	0.131828	0.025906	0.037912
18.49934	0.070436	0.026004	0.0472
18.68621	0.078023	0.030044	0.026997
18.87307	0.07192	0.034374	0.013639
19.05993	0.101598	0.033904	0.023302
19.24679	0.075803	0.018927	0.035768
19.43365	0.041784	0.018051	0.052094
19.62052	0.043774	0.024849	0.066147
19.80738	0.022492	0.032556	0.058254
19.99424	0.046299	0.045031	0.042831
20.1811	0.070075	0.051429	0.028
20.36796	0.100632	0.056688	0.02741
20.55483	0.036266	0.033615	0.037825
20.74169	0.148268	0.011678	0.064421
20.92855	0.051037	0.018824	0.073541
21.11541	0.091683	0.021028	0.07211
21.30228	0.120064	0.027281	0.067226
21.48914	0.136044	0.022493	0.044751
21.676	0.106825	0.013566	0.023036
21.86286	0.127553	0.020005	0.018906
22.04972	0.070798	0.014711	0.028189
22.23658	0.232658	0.018397	0.058293
22.42345	0.229949	0.035175	0.072689
22.61031	0.119838	0.042018	0.077649
22.79717	0.037408	0.042353	0.071501
22.98403	0.147677	0.037075	0.044991
23.1709	0.22512	0.024414	0.019289
23.35776	0.24322	0.032662	0.020037
23.54462	0.281742	0.036254	0.039455
23.73148	0.264176	0.033595	0.05383


Test Person 7
2
3
4
5
6
Time (seconds)

Vibration iOSApp file: VibrationData 2013-06-30 at 21:26-email.csv

Source Internal Accelerometer

3 Channels

256 Points

50 Sample Rate (Hz)

Time	X	Y	Z
0	4.442802	0.815236	0.710525
0.018094	2.427926	1.405392	0.810832
0.038409	-1.68375	2.311264	1.06769
0.058739	-7.4092	2.062646	1.032338
0.07906	-7.88407	1.922803	0.625788
0.099691	-7.48152	2.376325	0.175067
0.120715	-4.48268	3.080671	0.000894
0.141288	0.848978	3.20113	0.586605
0.161772	7.35589	2.619252	1.298911
0.182808	7.813119	-0.89308	1.454732
0.20311	7.802827	-0.22281	0.725365
0.223726	2.670917	2.927362	0.855428
0.24465	-2.33111	2.940492	0.987879
0.265689	-7.86747	3.573844	1.150739
0.2868	-4.46173	1.308455	1.69903
0.306899	-7.89241	2.227641	0.814846
0.3272	-4.4644	3.466485	1.029145
0.347719	0.714312	2.425866	0.921357
0.368656	4.427135	3.01593	1.521588
0.389074	7.78997	0.311625	0.807594
0.410111	7.797987	0.024635	0.606599
0.430744	3.943122	1.973728	1.221001
0.450957	-2.17112	2.770416	1.330614
0.471486	-7.56406	3.061287	1.327345
0.491608	-7.90139	2.542232	1.065439
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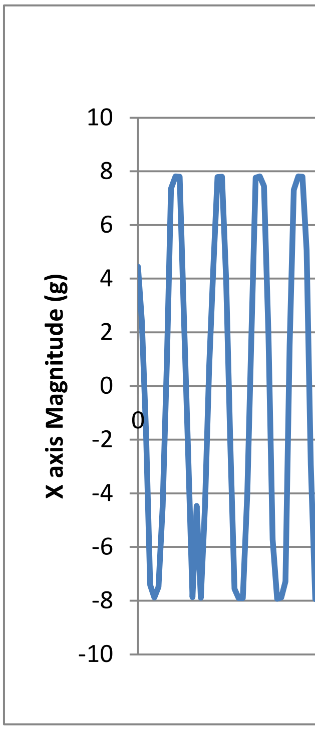

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Frequency Data

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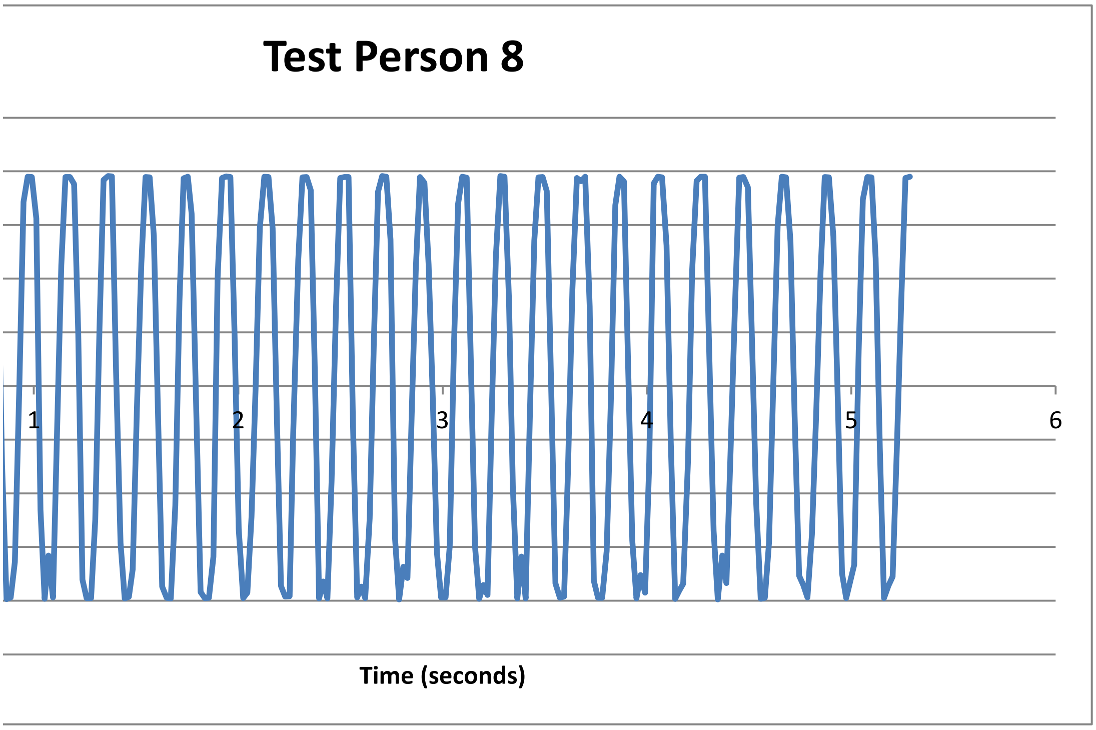
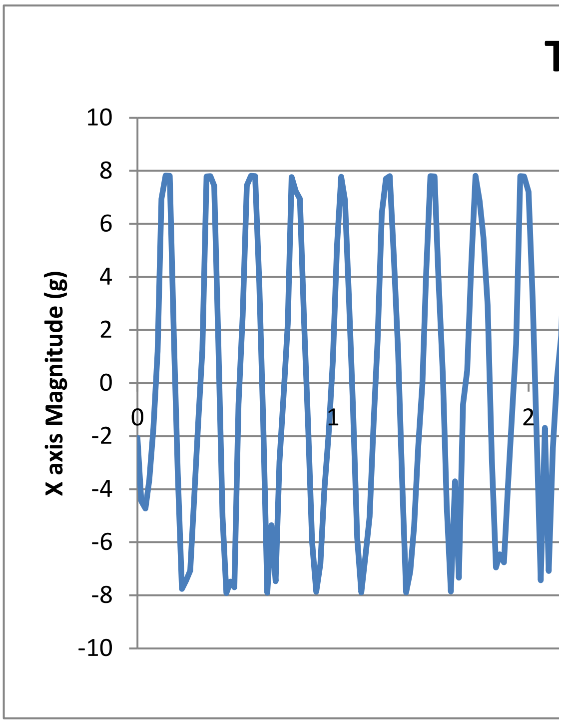
20.72853	0.148551	0.39338	0.108295
20.91697	0.066809	0.173456	0.055937
21.10542	0.031209	0.056953	0.025374
21.29386	0.10241	0.050356	0.021601
21.4823	0.224399	0.112366	0.017719
21.67074	0.180646	0.097314	0.029834
21.85918	0.102913	0.024068	0.028659
22.04762	0.054445	0.063946	0.058231
22.23606	0.15247	0.239433	0.131971
22.4245	0.133217	0.31374	0.133251
22.61294	0.054365	0.192135	0.036353
22.80139	0.04916	0.139762	0.020064
22.98983	0.107645	0.173645	0.038963
23.17827	0.081005	0.124918	0.046506
23.36671	0.146166	0.112886	0.036204
23.55515	0.162936	0.135453	0.029774
23.74359	0.049631	0.18385	0.032121
23.93203	0.011724	0.111155	0.073312



Test Person 8
1
2
3
4
5
6
Time (seconds)

Vibration iOSApp file: VibrationData 2013-06-30 at 21:27-email.csv

Source	Internal Accelerometer		
3	Channels		
256	Points		
50	Sample Rate (Hz)		
Time	X	Y	Z
0	-2.05739	0.384948	0.998325
0.020148	-4.4519	1.150642	0.913131
0.040233	-4.72523	1.30844	0.507706
0.060301	-3.65363	1.391272	0.926952
0.081025	-1.68067	1.346447	0.931803
0.102091	1.184826	1.890972	0.791628
0.12314	6.939889	1.28122	1.870451
0.14403	7.818693	-1.2701	1.898215
0.165075	7.81544	-0.32859	-0.7259
0.186125	1.683361	2.228797	0.546296
0.206385	-3.37759	2.452614	1.31068
0.227437	-7.76156	3.136389	1.198665
0.248481	-7.44579	2.588897	1.087927
0.269015	-7.0774	2.463615	0.836088
0.289123	-4.41506	2.381924	0.883573
0.310179	-1.48768	1.691409	0.940166
0.331237	1.261313	2.216808	1.613517
0.352286	7.790077	0.04163	1.678549
0.372331	7.796109	0.16775	0.404936
0.392636	7.442318	1.197505	0.848723
0.413725	1.48114	2.549186	1.510686
0.434779	-5.03492	3.059491	1.117182
0.4551	-7.91678	3.289835	0.81027
0.47542	-7.48446	1.240108	0.880623
0.496051	-7.69801	2.879936	0.667267
0.517105	-0.79563	1.368768	0.995573
0.538154	2.531441	2.062814	1.080249
0.559231	7.448533	0.465345	1.648595
0.580314	7.805683	-0.38507	0.851171
0.601356	7.80185	0.067085	-0.08673
0.622411	3.750308	2.053974	0.814147
0.642468	-1.37954	2.298955	1.496348
0.663514	-7.90869	2.841958	1.124404
0.684564	-5.35912	1.535345	1.12001
0.705609	-7.46828	2.784307	0.623963
0.726759	-2.96661	1.580885	0.868611
0.747099	-0.44532	1.531374	1.082089
0.768143	2.217979	1.34348	1.304705
0.788948	7.768668	1.185059	0.504422
0.809862	7.234722	1.602003	1.523656
0.830918	6.946303	0.265812	1.422558
0.85155	2.321097	1.661419	0.738365
0.872603	-1.73118	1.83959	0.798319
0.893647	-5.97381	1.462418	0.963536



0.914693	-7.86553	0.991749	1.03547
0.935746	-6.82262	1.182168	0.869873
0.954691	-4.10082	1.023229	1.131748
0.97785	-1.88591	1.289253	0.981614
0.998796	0.864553	1.638246	0.867805
1.019843	5.195231	1.442578	0.716181
1.040915	7.777892	0.252088	0.718021
1.061552	6.878458	0.318548	0.680389
1.081228	3.293322	1.375646	0.845834
1.102876	-0.93531	1.726251	0.920217
1.123931	-5.82696	1.895765	1.029723
1.144969	-7.89163	2.162961	0.916279
1.166021	-6.50365	1.034123	0.965756
1.187067	-5.02986	1.648395	0.971457
1.207822	-1.35119	1.312533	1.029388
1.228863	1.633779	1.555475	1.007995
1.249914	6.394781	0.325015	1.017392
1.27063	7.701159	-0.80471	1.065394
1.290764	7.80159	-0.20227	0.835038
1.311811	4.68897	1.261424	0.767604
1.332855	1.183009	1.384045	0.979029
1.353228	-3.44382	1.690709	1.068982
1.374277	-7.88963	2.044099	1.019931
1.394357	-7.11214	1.296678	0.799003
1.4154	-5.41943	1.941837	0.932244
1.436449	-2.37299	1.43176	0.876685
1.456749	-0.02292	1.750566	1.085799
1.477413	4.234046	1.547381	1.360552
1.498458	7.80185	-0.44757	1.602403
1.519504	7.787771	-0.1254	0.646938
1.538761	4.004034	1.484952	0.909984
1.561137	0.288844	1.605047	1.182852
1.582189	-4.63381	2.251666	1.020417
1.603238	-7.85865	2.609727	0.977889
1.624282	-3.70115	-1.29097	0.8051
1.644415	-7.33244	3.625515	0.894505
1.665364	-0.80577	0.953148	0.910273
1.686409	0.474328	1.81345	1.040457
1.707456	4.524405	0.887843	1.190835
1.728499	7.805851	-0.53832	0.95312
1.749549	6.855141	0.744059	0.976566
1.770356	5.472382	0.068302	0.891434
1.791411	2.929057	0.816423	1.020782
1.812458	-2.83031	1.637638	0.988837
1.832988	-6.94817	1.689126	0.944347
1.853813	-6.45399	0.823833	0.93717
1.874871	-6.76327	1.661663	0.637115
1.895284	-3.77785	1.36991	1.114186
1.916334	-1.03201	0.894584	1.164986
1.936565	1.467672	1.594122	1.186699

1.957611	7.795467	-0.06323	1.254239
1.976723	7.792673	0.101685	1.111161
1.99973	7.206809	1.03639	0.619691
2.020782	3.090277	2.273089	0.7198
2.04135	-1.89362	2.103515	1.078622
2.061996	-7.4384	2.242354	0.964752
2.083056	-1.68687	-1.19934	2.159163
2.10411	-7.0784	3.26826	1.164667
2.125152	-2.43219	1.072146	0.969329
2.146078	0.193223	0.780393	1.082058
2.167125	1.785105	1.659426	0.937155
2.188182	6.434422	0.818249	0.688706
2.209234	7.033662	-0.1174	0.875286
2.230282	6.644247	-0.41128	1.00576
2.249399	2.586719	1.40317	0.809616
2.272085	-1.81092	1.421291	0.780681
2.292411	-6.23329	1.337486	1.104714
2.313413	-7.85784	0.64977	1.057244
2.334554	-7.21688	0.927479	0.91567
2.355609	-4.49422	1.503028	1.097841
2.376659	-0.61418	1.969392	1.127126
2.396799	3.514508	2.130157	1.208837
2.417846	7.778914	0.735888	0.994675
2.438422	7.759232	1.633803	0.856888
2.459483	7.309912	0.859452	0.78991
2.479666	2.55259	1.863143	1.068769
2.500544	-3.42404	2.125927	0.970971
2.521591	-7.87848	1.587412	0.928929
2.542634	-7.04528	0.993301	0.836696
2.56368	-5.13851	1.716149	1.093812
2.584723	-2.71394	1.269626	0.980915
2.605789	-1.34702	1.750839	1.142863
2.62684	3.312456	1.766374	1.330279
2.647075	7.768287	0.458483	1.205021
2.668018	7.785236	0.669961	0.308187
2.689174	5.412035	1.489152	0.991346
2.710329	0.250409	1.65509	1.498279
2.731384	-4.67523	1.952579	1.13526
2.752046	-7.88732	1.936649	1.045019
2.772994	-5.7462	0.678222	0.889016
2.794039	-6.47948	2.177796	0.918635
2.8151	-1.55559	0.867394	1.03509
2.836148	0.312176	1.657159	1.292434
2.857203	4.458606	1.155876	1.56027
2.878247	7.791054	0.226207	0.934068
2.898324	7.782778	0.819451	0.17046
2.919379	5.506663	1.425202	0.915579
2.940438	-1.25228	1.578405	1.165382
2.961486	-5.69316	1.618786	1.099438
2.982528	-7.87593	1.440585	1.04549

3.002877	-7.07423	0.92331	0.836285
3.022948	-5.02938	1.71872	0.941777
3.044002	-1.61354	0.802121	0.972005
3.065056	-0.15147	1.642887	1.256991
3.086104	3.655924	1.356687	1.446552
3.106673	7.785389	0.633687	0.406198
3.127736	7.782625	0.665061	0.697768
3.14879	3.771701	2.149419	0.786276
3.169836	-0.58909	1.861911	1.204641
3.190887	-5.32322	1.739032	1.116999
3.211863	-7.88187	1.730177	0.944925
3.232924	-6.77222	1.321418	0.814208
3.252081	-3.63996	1.123802	1.112681
3.275027	-0.77288	1.06959	1.178929
3.295706	1.739142	1.3721	1.288633
3.315876	5.865324	0.871015	1.345956
3.336938	7.789145	0.442842	0.496013
3.357092	7.784992	0.66602	0.355368
3.378138	4.010982	2.205351	1.302105
3.399186	-1.89713	2.013988	1.124571
3.420232	-6.74662	2.135573	1.066321
3.441282	-7.87744	1.544322	0.920688
3.461735	-6.94993	1.183903	0.807077
3.482078	-4.12034	1.350753	1.105778
3.503117	-1.62736	1.093159	1.103877
3.523929	0.516794	1.389796	1.309084
3.545003	7.002389	0.356815	1.225654
3.563472	7.413671	0.134306	0.590816
3.58675	7.735212	-0.27412	0.62889
3.607801	3.978594	1.497581	0.988609
3.628843	0.253875	1.915956	1.030818
3.649862	-5.44002	2.135893	0.985568
3.670564	-6.96248	1.032526	1.086711
3.691957	-6.40853	1.421641	0.935574
3.712073	-3.29745	0.860806	1.157186
3.733121	-1.37649	0.754664	1.11963
3.754179	0.485216	1.768094	0.960525
3.774547	5.326706	1.519156	0.979136
3.795589	7.787023	0.33667	1.146588
3.815982	7.786229	0.583294	0.449501
3.836048	1.954816	2.374347	1.079063
3.85809	-1.38296	1.516281	1.181149
3.879148	-6.05463	1.780707	1.096701
3.900191	-7.87193	1.263357	1.055282
3.921002	-6.97679	0.629336	0.805358
3.941921	-4.4898	1.454126	0.931544
3.963024	-0.06933	1.66323	1.151469
3.984064	3.138271	1.627885	1.131034
4.005108	7.524806	0.38545	0.903218
4.025187	7.245152	0.351565	0.798151

4.046235	6.552444	0.343851	0.663526
4.066346	2.457977	1.442791	1.167525
4.087399	-0.87676	1.163362	1.08294
4.108449	-7.62008	1.602993	0.991543
4.128065	-5.87452	0.658367	0.942477
4.150535	-5.861	1.713364	0.796327
4.170878	-2.48686	1.233854	1.018304
4.191935	-0.30224	1.302977	1.068419
4.212977	2.24945	1.483279	1.126366
4.234022	6.931796	0.341965	0.926572
4.255065	7.7552	0.434839	0.629543
4.27582	3.92153	1.174226	1.100471
4.296629	1.145521	1.012974	1.208214
4.316918	-2.78769	1.741284	1.00465
4.337965	-6.68353	1.970244	0.91526
4.359012	-5.76519	0.550353	0.853421
4.380077	-6.6561	1.909124	0.744462
4.401119	-2.0116	0.803627	1.161687
4.422006	-0.04589	0.982574	0.994706
4.44309	2.713307	1.113364	1.16821
4.464109	7.07454	-0.11675	1.206283
4.484646	6.89127	-0.04081	0.676922
4.505693	7.517981	-0.11755	0.496941
4.525892	3.006949	1.835467	0.936836
4.546935	-1.86891	2.137049	1.0525
4.567976	-5.94697	2.38095	1.09962
4.589033	-4.23772	2.717528	1.213125
4.610164	-7.01455	0.399265	0.612103
4.630737	-3.61573	1.830385	1.196765
4.651782	-1.0759	0.905737	1.022212
4.672823	0.902865	0.965852	1.112651
4.693984	5.70557	-0.31488	0.920201
4.712109	6.984569	-0.37026	0.776575
4.73576	7.275951	-0.48525	0.987772
4.756804	3.650045	0.654319	0.911459
4.777854	1.4475	1.056855	0.989019
4.798913	-1.777	1.673683	0.90191
4.819942	-6.7272	1.697829	1.090634
4.838657	-4.85486	1.128656	1.097917
4.86204	-5.89444	1.70568	0.859853
4.882341	-2.91349	1.369316	0.999845
4.903402	-0.36135	1.149972	0.945548
4.92352	2.153387	1.515718	1.070791
4.944595	6.21406	0.169332	1.259029
4.965636	7.33836	0.174292	0.681058
4.986225	4.458011	0.489568	0.834248
5.007288	1.604308	1.031811	1.139305
5.027464	-2.26616	1.53813	1.021527
5.048502	-5.82758	1.537552	1.067264
5.068782	-7.07333	1.056201	0.954215

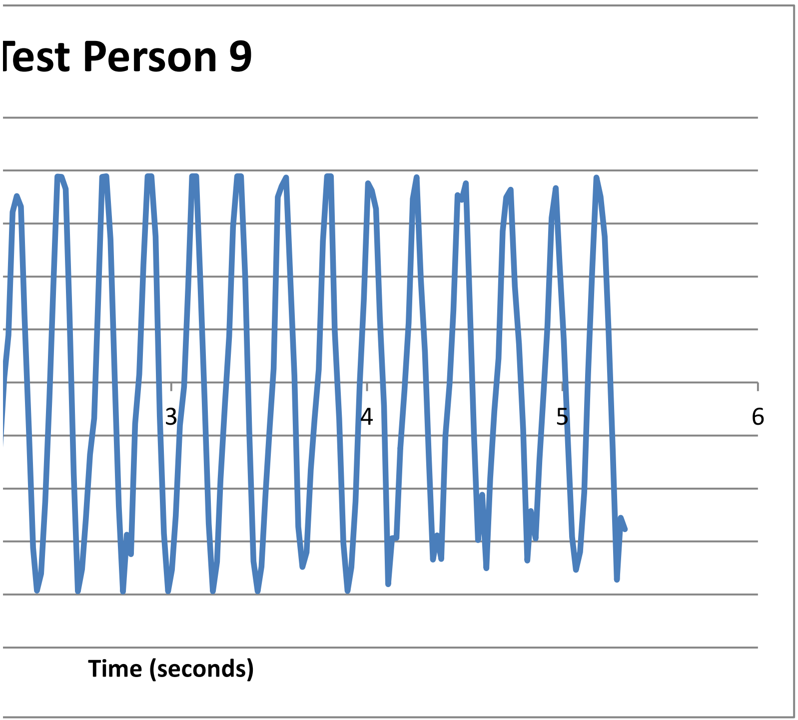
5.089554	-6.39062	1.441041	0.769095
5.110689	-4.14636	1.437511	1.024842
5.131725	0.323766	1.223249	0.960905
5.152757	4.273	0.818462	0.953409
5.173757	7.74161	-0.50869	1.541948
5.194492	7.016575	0.226998	1.095408
5.215529	5.511274	0.627571	0.522835
5.235611	1.959656	1.266537	0.922543
5.256643	-2.51916	1.806816	1.02355
5.277676	-7.44097	1.218502	0.943404
5.298708	-5.09911	0.862525	0.997519
5.319256	-5.53414	1.568043	0.886659

Frequency Data

Frequency	X	Y	Z
0	0.022505	1.237135	0.996745
0.187262	0.097009	1.273237	1.01097
0.374524	0.181049	0.138505	0.022405
0.561786	0.159181	0.084578	0.012246
0.749047	0.115096	0.053325	0.010695
0.936309	0.053336	0.060489	0.015416
1.123571	0.025498	0.071626	0.015928
1.310833	0.073258	0.064022	0.027045
1.498095	0.118873	0.082671	0.038659
1.685357	0.031137	0.105858	0.036579
1.872619	0.060277	0.068739	0.016226
2.05988	0.151124	0.095027	0.011812
2.247142	0.068446	0.127189	0.020914
2.434404	0.359719	0.062837	0.025684
2.621666	0.383147	0.075715	0.025789
2.808928	0.141485	0.118138	0.019086
2.99619	0.083389	0.117432	0.026292
3.183452	0.124044	0.084317	0.039175
3.370713	0.128004	0.051816	0.044965
3.557976	0.122086	0.033324	0.037711
3.745237	0.279029	0.108987	0.014679
3.932499	0.727868	0.174572	0.016614
4.119761	1.678017	0.101466	0.035822
4.307023	6.784338	0.357971	0.075229
4.494285	5.715158	0.336264	0.085324
4.681547	1.517684	0.053053	0.04495
4.868808	0.425997	0.055302	0.017731
5.05607	0.382348	0.10441	0.042161
5.243332	0.263427	0.030507	0.039447
5.430594	0.107055	0.040138	0.035646
5.617856	0.127976	0.078087	0.034542
5.805118	0.145664	0.054683	0.019587
5.99238	0.100104	0.04261	0.029019
6.179642	0.051023	0.041816	0.041148

6.366903	0.18534	0.022139	0.051207
6.554165	0.217593	0.065725	0.035582
6.741427	0.172447	0.082193	0.045189
6.928689	0.137916	0.032542	0.052029
7.115951	0.060936	0.054401	0.024131
7.303213	0.029291	0.060472	0.030283
7.490475	0.1031	0.046958	0.03836
7.677736	0.123929	0.018922	0.054389
7.864998	0.070149	0.047189	0.051998
8.05226	0.110435	0.081667	0.065175
8.239522	0.088395	0.12045	0.061705
8.426784	0.193297	0.109495	0.055979
8.614046	0.76014	0.360979	0.097169
8.801308	0.925521	0.450218	0.165985
8.988569	0.479201	0.135446	0.131121
9.175832	0.212426	0.038074	0.085782
9.363093	0.072998	0.037614	0.060936
9.550355	0.051914	0.082574	0.055246
9.737617	0.061087	0.04424	0.017192
9.924879	0.084052	0.019974	0.028729
10.11214	0.117051	0.028147	0.01963
10.2994	0.154547	0.038472	0.017076
10.48667	0.202094	0.051575	0.029992
10.67393	0.191867	0.051842	0.007004
10.86119	0.106017	0.082704	0.010387
11.04845	0.102772	0.087535	0.014144
11.23571	0.168665	0.10665	0.014577
11.42297	0.230574	0.121996	0.008393
11.61024	0.103979	0.085481	0.014723
11.7975	0.044585	0.057752	0.023427
11.98476	0.087614	0.043059	0.03038
12.17202	0.099899	0.050064	0.048805
12.35928	0.112988	0.070111	0.026077
12.54655	0.05804	0.107493	0.034058
12.73381	0.050144	0.11066	0.056526
12.92107	0.18827	0.03435	0.066759
13.10833	0.213579	0.089908	0.089367
13.29559	0.039421	0.14846	0.074254
13.48285	0.148195	0.161164	0.033262
13.67012	0.092779	0.095291	0.043762
13.85738	0.043986	0.083689	0.056793
14.04464	0.054957	0.045883	0.037701
14.2319	0.119344	0.046348	0.028648
14.41916	0.181056	0.07822	0.035984
14.60643	0.152209	0.07378	0.047808
14.79369	0.151552	0.029795	0.062566
14.98095	0.090717	0.053247	0.036484
15.16821	0.08351	0.104616	0.03408
15.35547	0.082783	0.104933	0.031571
15.54274	0.173825	0.077168	0.028034

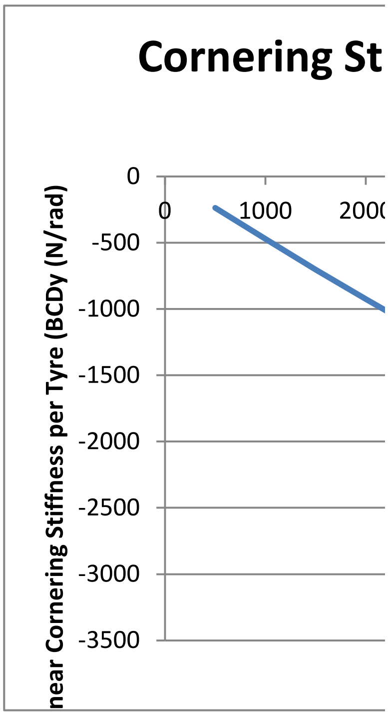
15.73	0.125704	0.108388	0.017017
15.91726	0.04745	0.074525	0.018258
16.10452	0.068983	0.035262	0.017972
16.29178	0.161674	0.096348	0.035586
16.47904	0.188037	0.115691	0.065092
16.66631	0.158357	0.114597	0.032129
16.85357	0.129594	0.091738	0.02295
17.04083	0.203224	0.070614	0.039586
17.22809	0.240017	0.175523	0.040242
17.41535	0.282267	0.281534	0.036604
17.60262	0.382657	0.252398	0.05679
17.78988	0.263047	0.112462	0.04545
17.97714	0.195506	0.077836	0.044419
18.1644	0.036095	0.030709	0.049529
18.35166	0.117899	0.066137	0.029357
18.53893	0.102116	0.034442	0.011584
18.72619	0.029841	0.044115	0.01759
18.91345	0.102405	0.089161	0.02397
19.10071	0.210243	0.152284	0.04132
19.28797	0.198893	0.112329	0.037226
19.47523	0.128763	0.099279	0.028529
19.6625	0.06529	0.096622	0.020092
19.84976	0.111546	0.111245	0.015499
20.03702	0.121695	0.118993	0.029273
20.22428	0.148116	0.122455	0.03609
20.41154	0.097394	0.059745	0.032538
20.5988	0.11743	0.055244	0.019126
20.78607	0.190517	0.060535	0.02699
20.97333	0.13006	0.066847	0.039152
21.16059	0.117693	0.098863	0.040635
21.34785	0.232603	0.143365	0.016244
21.53511	0.346926	0.188952	0.01739
21.72238	0.24415	0.165877	0.012934
21.90964	0.412367	0.25574	0.01665
22.0969	0.314946	0.185934	0.031473
22.28416	0.082689	0.04626	0.024766
22.47142	0.054727	0.060803	0.020966
22.65869	0.033636	0.045003	0.037199
22.84595	0.038563	0.034765	0.041583
23.03321	0.106022	0.052967	0.027042
23.22047	0.118203	0.046445	0.025749
23.40773	0.178743	0.099665	0.031711
23.595	0.19849	0.097829	0.01749
23.78226	0.141984	0.122995	0.021844

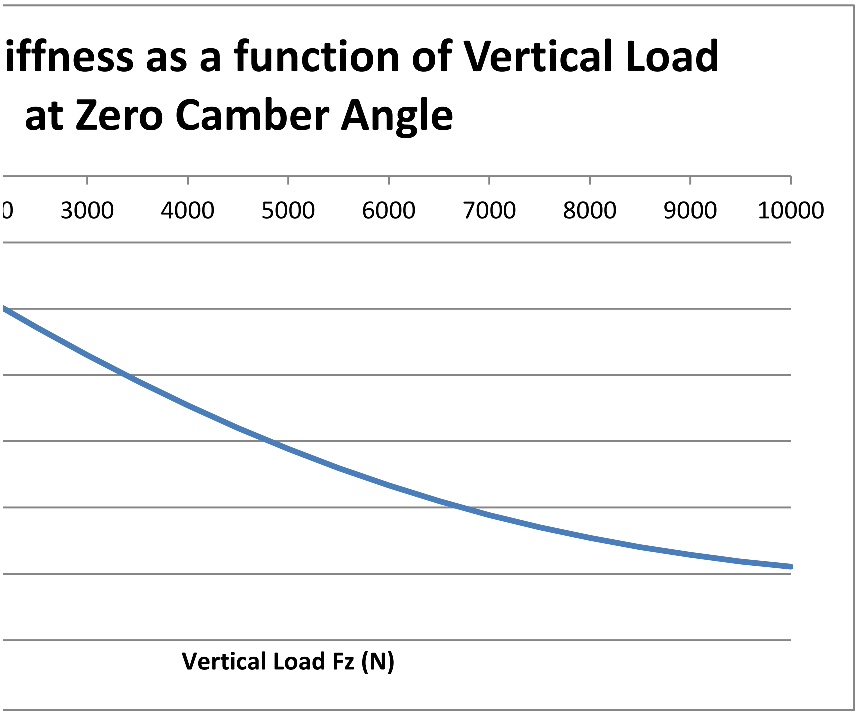

Test Person 9
3
4
5
6
Time (seconds)

a3		3036	N/deg		
a4		12.8	1/kN		

Fz (N)		Fz/a4	atan(Fz/a4)	2*atan(Fz/a4)	sin
500	0.5	0.0390625	0.03904265	0.0780853	0.078006
1000	1	0.078125	0.077966634	0.155933268	0.155302
1500	1.5	0.1171875	0.116655435	0.233310871	0.2312
2000	2	0.15625	0.154996742	0.309993484	0.305052
2500	2.5	0.1953125	0.192884312	0.385768625	0.376271
3000	3	0.234375	0.230219587	0.460439175	0.444342
3500	3.5	0.2734375	0.266912988	0.533825975	0.508831
4000	4	0.3125	0.302884868	0.605769737	0.569395
4500	4.5	0.3515625	0.338066123	0.676132246	0.625781
5000	5	0.390625	0.372398447	0.744796893	0.677822
5500	5.5	0.4296875	0.405834293	0.811668586	0.725437
6000	6	0.46875	0.43833656	0.87667312	0.768615
6500	6.5	0.5078125	0.469878058	0.939756116	0.807414
7000	7	0.546875	0.500440813	1.000881626	0.841947
7500	7.5	0.5859375	0.530015251	1.060030503	0.87237
8000	8	0.625	0.558599315	1.117198631	0.898876
8500	8.5	0.6640625	0.586197551	1.172395103	0.921682
9000	9	0.703125	0.612820202	1.225640404	0.941023
9500	9.5	0.7421875	0.63848233	1.276964661	0.957141
10000	10	0.78125	0.663202993	1.326405985	0.970285

a3	
-236.826	-236.826
-471.497	-471.497
-701.923	-701.923
-926.139	-926.139
-1142.36	-1142.36
-1349.02	-1349.02
-1544.81	-1544.81
-1728.68	-1728.68
-1899.87	-1899.87
-2057.87	-2057.87
-2202.43	-2202.43
-2333.51	-2333.51
-2451.31	-2451.31
-2556.15	-2556.15
-2648.52	-2648.52
-2728.99	-2728.99
-2798.23	-2798.23
-2856.94	-2856.94
-2905.88	-2905.88
-2945.79	-2945.79





iffness as a function of Vertical Load
at Zero Camber Angle
0
3000
4000
5000
6000
7000
8000
9000
10000
Vertical Load Fz (N)

30 psi	2.068 bars	
Extension (mm)	Compressive Load (N)	Equivalent Stiffness (N/m)
-1.701	93.4	-54908.87713
-3.229	190.7	-59058.53205
-4.656	294	-63144.3299
-5.991	391.7	-65381.40544
-7.246	490.1	-67637.31714
-8.587	591.9	-68929.77757
-9.878	696.6	-70520.34825
-11.16	791	-70878.1362
-12.38	891	-71970.92084
-13.57	990	-72955.0479

25 psi	1.724 bars	
Extension (mm)	Compressive Load (N)	Equivalent Stiffness (N/m)
-1.986	92	-46324.26989
-3.826	195.3	-51045.47831
-5.369	296	-55131.30937
-6.796	395.4	-58181.28311
-8.205	493.4	-60134.06459
-9.502	594.2	-62534.20333
-10.75	688.5	-64046.51163
-12.07	796.2	-65965.20298
-13.31	894.2	-67182.5695
-14.56	993	-68200.54945

20 psi	1.379 bars	
Extension (mm)	Compressive Load (N)	Equivalent Stiffness (N/m)
-2.173	95.21	-43815.0023
-3.971	198.6	-50012.59129
-5.644	296	-52445.07442
-7.395	396.2	-53576.74104
-9.059	498.1	-54983.99382
-10.61	594.6	-56041.47031
-12.02	693.5	-57695.50749
-13.36	793.8	-59416.16766
-15.15	899.6	-59379.53795
-15.96	994.7	-62324.5614

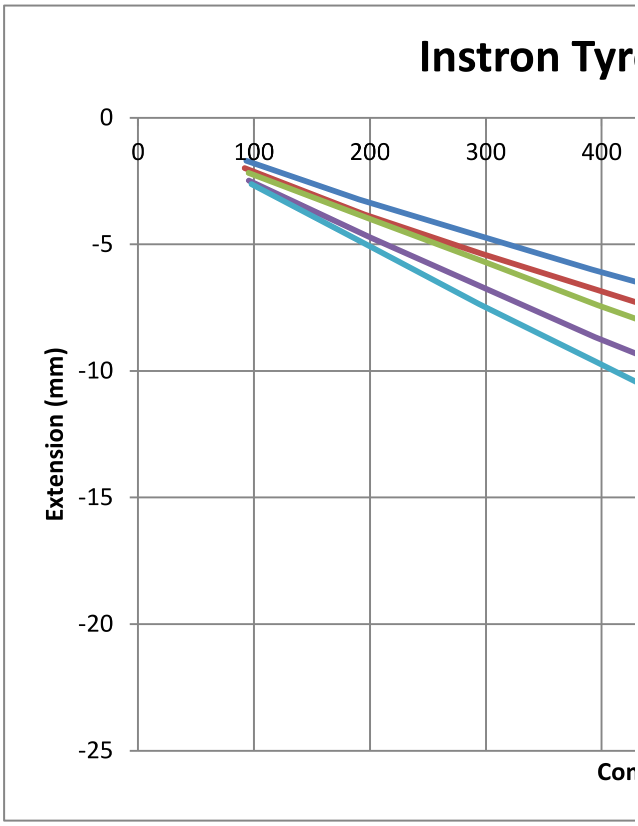
15 psi	1.034 bars

Extension (mm)	Compressive Load (N)	Equivalent Stiffness (N/m)
-2.478	95.55	-38559.32203
-4.741	201.2	-42438.30416
-6.691	297	-44387.98386
-8.666	394.1	-45476.57512
-10.55	496.6	-47071.09005
-12.22	590.8	-48346.97218
-13.85	690.8	-49877.25632
-15.5	796.1	-51361.29032
-16.97	890.2	-52457.27755
-18.5	993	-53675.67568

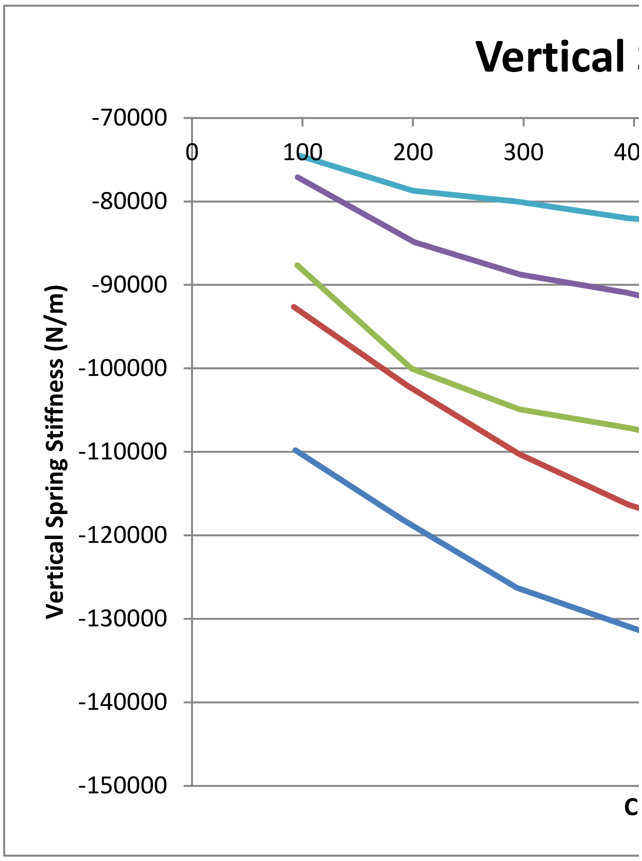
10 psi 0.689 bars

Extension (mm)	Compressive Load (N)	Equivalent Stiffness (N/m)
-2.623	97.73	-37258.8639
-5.077	199.8	-39353.94918
-7.36	294.4	-40000
-9.62	394.5	-41008.31601
-11.92	495.1	-41535.2349
-13.89	589.3	-42426.2059
-15.86	698.1	-44016.39344
-17.56	790.1	-44994.30524
-19.41	893.6	-46038.12468
-21.18	995.7	-47011.33144

Vertical Spring Stiffness (N/m)
-109817.7543
-118117.0641
-126288.6598
-130762.8109
-135274.6343
-137859.5551
-141040.6965
-141756.2724
-143941.8417
-145910.0958



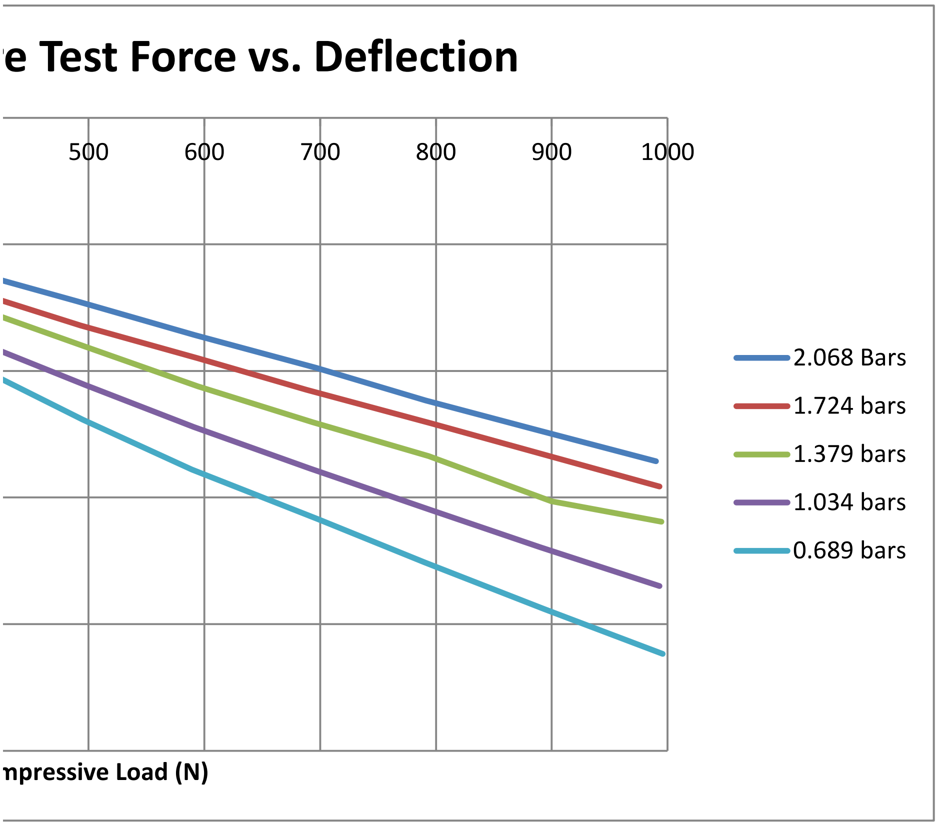
Vertical Spring Stiffness (N/m)
-92648.53978
-102090.9566
-110262.6187
-116362.5662
-120268.1292
-125068.4067
-128093.0233
-131930.406
-134365.139
-136401.0989



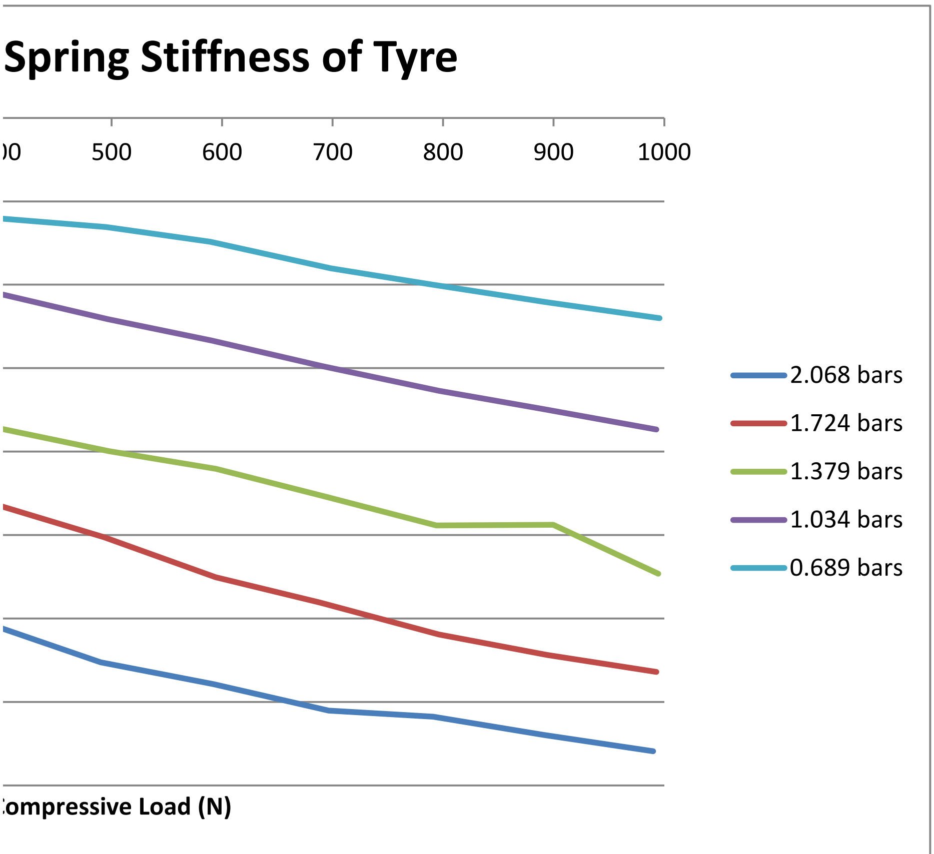
Vertical Spring Stiffness (N/m)
-87630.0046
-100025.1826
-104890.1488
-107153.4821
-109967.9876
-112082.9406
-115391.015
-118832.3353
-118759.0759
-124649.1228

Vertical Spring Stiffness (N/m)
-77118.64407
-84876.60831
-88775.96772
-90953.15024
-94142.18009
-96693.94435
-99754.51264
-102722.5806
-104914.5551
-107351.3514

Vertical Spring Stiffness (N/m)
-74517.72779
-78707.89837
-80000
-82016.63202
-83070.4698
-84852.41181
-88032.78689
-89988.61048
-92076.24936
-94022.66289



e Test Force vs. Deflection
500
600
700
800
900
1000
2.068 Bars
1.724 bars
1.379 bars
1.034 bars
0.689 bars
npressive Load (N)



Spring Stiffness of Tyre
)0
500
600
700
800
900
1000
2.068 bars
1.724 bars
1.379 bars
1.034 bars
0.689 bars
ompressive Load (N)