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Evaluating a set of stall recovery actions for single engine light aeroplanes

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ABSTRACT

This paper considers four alternative sets of actions that a pilot may use to recover an aeroplane from the stall. These actions: those published by the UK CAA and the US FAA, as well as a power delayed sequence and a pitch delayed sequence, were evaluated on 14 single engine piston aeroplane types. In a limited number of types (5 in cruise configuration, 2 in landing configuration) the pitch delayed recovery gave a safe response and least height loss, but in a greater number of types (6 and 8 in cruise and landing configurations respectively) it resulted in further post-stall uncommanded motion. The other sets of actions all gave a consistent recovery from the stall, but the least height loss in recovery was also consistently the CAA sequence of simultaneous full power and nose-down pitching input, which normally resulted in approximately two thirds the height loss of the FAA's pitch first then power method, which in turn resulted in about 90% of the height loss of the trialled power delayed recovery. Additionally the CAA recovery gave the least variation in height loss during stall recovery. It was also found that all of the aeroplane types evaluated except for one microlight aeroplane of unusual design, displayed a pitch-up with increased power in the normal (pre-stall) flight regime. Reducing this to separate components it was therefore shown that pitch control is of primary importance and should be used to provide immediate stall recovery. The thrust control can additionally be used as early as possible to minimise height loss, but if the thrust control is used before the pitch control in the stall or post-stall flight regime, there is some risk of subsequent loss of control. Finally, from the discussion on stall recovery methods, questions for Regulatory Authorities are put forward that should address the current practices.

NOMENCLATURE

Quantity	**Definition**	**Units**
aLSS	Apparent Longitudinal Static Stability	N / kn
AR	Wing Aspect Ratio (span²/area)	-
CAS	Calibrated Airspeed	kn (knots)
CG	Centre of Gravity	*Described as fwd/mid/aft within certified range*

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Quantity	Definition	Units
F_S	Control force	daN (decaNewtons)
IAS	Indicated Airspeed	kn
IFR	Instrument Flight Rules	-
M_T	Pitching moment due to thrust application	Nm/N
MTOW	Maximum Take-Off Weight	kg.f
S	Wing Area	m²
T	Thrust	N
U_T	Airspeed change due to thrust	kn/N
V_S	Stalling speed	kn
V_{S0}	Stalling speed in the landing configuration	kn
V_{S1}	Stalling speed in the cruise configuration	kn
W	Weight	kg.f (kg)
W/S	Wing Loading	kg/m²
α (alpha)	Angle of Attack	° (degrees)
α_{CRIT}	Critical (stalling) angle of attack	° (degrees)
δh_{max}	Maximum height loss during stall recovery	ft

Acronyms

BCAR	British Civil Airworthiness Requirements
BMAA	British Microlight Aircraft Association
CS	Certification Specification
FAA	(US) Federal Aviation Administration
FAR	(US) Federal Aviation Requirements
FC	Fully Controllable
FI	Flight Instructor
LSS	Longitudinal Static Stability
MEP	Multi Engine Piston (aeroplane class)
NTPS	National Test Pilots' School (based Mojave, CA, USA)
SEP	Single Engine Piston (aeroplane class)
TRI	Type Rating Instructor
VFR	Visual Flight Rules
VLA	Very Light Aeroplanes (normally defined as non-aerobatic with MTOW<750kg)

INTRODUCTION

It is well established that stall-related loss of control is a contributing factor for somewhere between a quarter and a third of all light aeroplane fatal accidents[1]. Given this, it is unsurprising that training for low speed flight, stall avoidance, and stall recovery, are regarded as essential parts of flying training[2,3] and have been for many years.

However, if stall avoidance has been unsuccessful, there is not a universal consensus on how an aeroplane should best be recovered from the stall. It is accepted that treatment of large aeroplanes is not necessarily identical to smaller aeroplanes, and that single and multi-engined aeroplanes have differences between them. In the arena of single engine piston (SEP) aeroplanes various environments have developed subtly different interpretations of a "universal" set of stall recovery actions that are taught as being applicable to all such aeroplanes; it is not in that environment normally considered that recovery actions should vary between types.

It seems unlikely that, however subtle the variations between them, each set of taught recovery actions is equally correct. Also, given that there are significant handling and performance differences within that fleet, it seems at-least possible that there are differences in optimal stall recovery actions between aeroplane types.

This research project, therefore, set out to evaluate a series of alternate stall recovery actions, on a variety of SEP category aeroplanes. The objectives were to establish whether there was a single best universal set of recovery actions from the perspective of controllability and height loss, or whether the optimal recovery depends upon the aeroplane's design and handling characteristics.

EXISTING STALL RECOVERY ACTION SETS

It is well established that in order to recover an aeroplane from the stall, the primary action is to reduce the angle of attack, and where power is available, height loss during the stall recovery may be reduced by increasing power, and thus thrust. The precise interpretation of this however does vary.

At present the FAA (US Federal Aviation Administration), which is the world's largest aviation safety regulator, recommend the following standard stall recovery actions[4]:

- Immediately lower the nose to reduce α
- Next, smoothly increase power to maximum allowable "to increase airspeed and minimise loss of altitude"
- Adjustment of power and normal use of the controls to return to straight and level flight.

The FAA document also notes the risk of secondary stall or spin "caused by attempting to hasten the completion of a stall recovery before the aircraft has regained sufficient flying speed".

In the United Kingdom, the CAA (Civil Aviation Authority) advice differs slightly[5] and is as follows:

- Move the control column forwards to reduce α / until stall warning cues have ceased.
- Simultaneously, apply full power, keeping the aeroplane in balance.
- Retract gear and flaps

This coincides with the instructions within current and known previous UK military training manuals for aircraft including the Chipmunk[6,7,8], Bulldog and Firefly[9], and appears to match the teaching in most other European countries.

A point of view expressed in recent years however, in particular from Séan Roberts, previously at the US based National Test Pilots School (NTPS) has been that there should be a significant delay between the nose-down pitching motion, and an increase in power, so as to minimise the risk of an unwanted post-stall gyration[10]. This has been expressed as a recommendation that airspeed should be allowed to increase to at-least 1.2Vs before increasing power. A further dichotomy was identified during preparation for this study which is that normal practice in aircraft certification is primarily to test aircraft by stalling at 1kn/s deceleration[11], usually in descending flight – whilst the most common practice in flying instruction and examining is to close the throttle and decelerate at a greater rate to the stall, whilst maintaining level flight[12,13].

A further issue raised since about 2009 has been the use of power alone to initially recover an aeroplane from the stall, a practice considered unacceptable by the UK CAA who in the reference[14] stated:

> *"CAA Training Inspectors have raised concerns that some instructors (both SFIs and TRIs) have been teaching inappropriate stall recovery techniques. It would appear that these instructors have been encouraging their trainees to maintain altitude during recovery from an approach to a stall. The technique being taught is to apply maximum power and allow the aircraft to accelerate out of this high alpha stall-warning regime. There is no mention of any requirement to reduce angle of attack – indeed one trainee was briefed that he may need to increase back pressure in order to maintain altitude."*

This document goes on to state that reduction in α is paramount in stall recoveries and that power alone should not be used – but do not reference any research in support of that statement. Similar advice has also recently been published by the US FAA[15].

CERTIFICATION AND TRAINING PRACTICES

It is known that stall characteristics can be a function of deceleration rate prior to the stall[16]. Airworthiness standards only poorly address this: CS.VLA[17], CS.23[18] and FAR-23[19] paragraphs 201 and 203 allow for 1 kn/s with the wings level and an accelerated stall with 30° of bank at 3-5 kn/s. BCAR Section S[20] does not formally require assessment at more than 1kn/s deceleration, although BMAA does normally require tests at up to 5kn/s[21]. Nonetheless, it has been demonstrated[16] that following an engine failure greater deceleration rates will probably be experienced, and this is reflected in common flight instructional practice which will normally require student pilots to perform a stall by minimising height loss following throttle closure. This is mandated by UK standards documents[12,13], although equivalent US documents[22,23] require the stall from a descent, which would allow for a lower rate of deceleration. These disparities – both between certification standards and operational practices, and between national operational practice is interesting and may have safety relevance, in particular in the UK where the greatest disparity exists between certification requirements and operational standards.

Most stalls are flown in the flying training environment, and clearly this is where most pilots will get their practices and habits from. The two most typical scenarios flown during either private or commercial flying training are a wings level, idle power stall in cruise configuration typically at some deceleration rate between 1kn/s and that achieved by closing the throttle and minimising height loss during deceleration to the stall, and a landing configuration, approach power, stall either with the wings level or with up to 30º of bank simulating a stall from a finals turn. Considerable attention will normally be given to stall avoidance and recovery from the signs of impending stall, as well as to the full stall and stall recovery.

TRIAL SETS OF STALL RECOVERY ACTIONS

It was decided to evaluate four different stall recoveries for this research project, these were:

- The “FAA recovery”, defined as [i] pitch nose-down to unstall the wing, followed by [ii] over a period of 2 seconds increase power to full throttle.
- The “CAA recovery”, defined as a pitch nose-down to unstall the wing and commenced at the same moment, an increase of power over to full throttle in 2 seconds.
- The “power delayed” recovery defined here as [i] pitch nose-down to unstall the wing, [ii] 2 second pause, followed by [iii] over a period of 2 seconds increase power to full throttle. Note that although Roberts[10], upon whose work this method is based, has advocated that power should be increased at 1.2Vs, it was considered that with the pilot being expected to maintain their attention outside of the cockpit, plus typical airspeed indicator (ASI) non-linearities below 1.3Vs plus the risk of instrument lag, there was no reliable measure to determine the 1.2Vs point. Therefore, a 2 second time delay was used in lieu of a reliable measure of airspeed increasing through 1.2Vs.
- The “pitch delayed” recovery, defined here as [i] increase power to full throttle over 2 seconds, [ii] 2 second pause, [iii] pitch nose-down to approximately the level flight attitude.

SIGNIFICANCE AND MEASUREMENT OF PITCH CHANGE WITH POWER

In most aeroplanes the powerplant thrustline will not go right through the vertical centre of gravity, and in most piston engine aeroplanes there will be some propeller wash effect over the mainplane and/or tailplane, as well as propeller torque effects due to airflow at the propeller disc. So, there will almost certainly be a net pitching moment due to changes in power, and which is a function of configuration (including gear and flap settings). This can be hard to predict given the confidentiality of detailed design information, but is relatively straightforward to measure – classically either by determining the changed trim speed condition with changes in power, or by determining the pitch control forces required to maintain a constant airspeed as power is changed.

This has significance to the stall recovery, since if power (and thus thrust) is increased as part of the stall recovery, a net nose-down pitching moment will assist the recovery from the stall, but may potentially increase height loss during recovery. Conversely, a net nose-up pitching moment might be expected to counter the stall recovery, at-the least requiring greater pitch control input to ensure effective stall recovery, but may potentially decrease height loss during that recovery. We cannot of-course be absolutely certain that pitching moment effects with power in the pre-stall flight regime will be identical to those during the stall or immediately post-stall; however it is a reasonable assumption that will be made. It appears most likely that apart from this, the effect of power on height loss will be a function of pitch attitude. Whether the change in thrust leads to any (exacerbation of) departure from controlled flight is less clear.

An extreme example of power effects on stall recovery is the Goldwing (Figure 1) a late 1970s era American designed single seat canard configuration microlight aeroplane, which has a very high thrustline, although negligible wash effects over the mainplane and canard. This aeroplane if stalled will not recover without the use of power – the elevator alone not having sufficient pitching authority to effect a stall recovery, requiring the additional and large nose-down pitching moment created by the large offset between the high thrustline and low vertical centre of gravity.

Figure 1, Goldwing single seat microlight aeroplane

STABILITY MODIFICATION AND UNCOMMANDED MOTION

The stall is typically defined as follows[17,18,19]:

> *(1) An uncontrollable downward pitching motion of the aeroplane; or*
>
> *(2) A downward pitching motion of the aeroplane which results from the activation of a device (e.g. stick pusher); or*
>
> *(3) The control reaching the stop.*

So there is always a degree of uncommanded motion and/or loss of full authority control when the stall occurs, and this can be attributed to modified stability characteristics[24]. Formal evaluation of these is problematic as the stall is a transient manoeuvre and maintaining post-stall conditions can be hazardous. However, formal evaluation of the approach to the stall is important and can offer valuable safety lessons[25,26], including typically that power tends to reduce longitudinal static stability (LSS) in a tractor-prop aeroplane, and that low apparent longitudinal static stability (aLSS) can increase workload and the potential risk of an inadvertent stall[27]. In some cases neutral or negative aLSS may occur, as evidenced by an uncommanded post-stall pitch-up. Where the aeroplane does remain controllable immediately post-stall in all axes except for the ability to pitch further nose-up, then it can be referred to by the shorthand “Fully Controllable” (FC), although the inability to pitch up makes this technically an incorrect description.

Post stall, there are two priorities for the aircraft pilot – restoration of full 6 axis control over the aeroplane, and minimisation of height loss. A successful stall recovery then is achieved with a timely recovery to a pre-stall condition, without levels of height loss or uncommanded motion that endanger the aircraft. Delayed response by the pilot, or incorrect control inputs can prevent such as recovery, but are not necessarily unlikely.

TESTING METHODOLOGY AND COMPLETION

A series of SEP and microlight class aeroplanes were subjected to a three part flight tests, normally all flown during a single sortie using effectively a single weight and balance condition. The parts were:

(1) A basic stalling characteristics assessment in each of the landing and cruise configuration, decelerating at idle power and 1kn/s (so accepting any height loss) to confirm the normal certification requirements of a maximum of 20º wing drop and no tendency to spin.
(2) Determination from a representative level-flight trimmed condition of the aeroplane’s longitudinal trim change with power as evidenced both by the hands-off trim speed at a range of power settings from flight idle (throttle closed) to full throttle, and the control inceptor (stick) force required to maintain the aeroplane at a constant airspeed.
(3) Determination of stall recovery characteristics and height loss for all of the conditions shown below, using a nominal deceleration rate of 1kn/s.

All testing was conducted by a test pilot, the use of an observer varying. All testing was conducted clear of cloud, with sight of the surface, at a height judged sufficient for safe stall and in extremis inadvertent spin recovery. In each case, stall and spin recoveries were pre-briefed.

Table 1, Test and configuration target grid

Recovery Method	Configurations	
FAA	Landing configuration (gear fixed or down, flaps for landing), nominal approach speed (typically ~1.3V_{S0}), nominal approach power, 30º bank. (In a few cases, this was replaced by idle / wings level, or both options flown – this to some extent was a function of ongoing development of the research task)	Cruise configuration (gear fixed or up, flaps up, airbrakes in), nominal cruise speed (~2.0V_{S1}), idle power
CAA		
Power delayed		
Pitch delayed		

Some other tests were flown on some sorties, and in a few cases operational difficulties prevented all test points being completed, but these were the core objective of the research.

The primary data source was handheld instrumentation and manually recorded flight test notes.
Table 2 summarises what results were obtained.

Table 2, Test completion grid for stall recovery tests (for aeroplane characteristics see Appendix A, pitch change with power tests were completed for every type except the C182P)

Aircraft type	Cruise configuration / idle /wings level, all test points completed	Landing configuration / 30º bank / approach power, all test points completed	Landing configuration / wings level / idle power, all test points completed	Other relevant tests carried out
1. Auster J5L Aiglet	X	X	X	
2. Cessna C152	X	X	X	
3. Cessna C172P	X	X	X	
4. Cessna C182P	X	X	X	
5. Easy Raider J2.2(2)	X		X	
6. Flightdesign CTSW	X		X	
7. Grumman AA5a Cheetah	X	X		
8. Piper PA28-161 Warrior II	X	X	X	
9. Piper PA38-112 Tomahawk	X	X		

Aircraft type	Cruise configuration / idle /wings level, all test points completed	Landing configuration / 30° bank / approach power, all test points completed	Landing configuration / wings level / idle power, all test points completed	Other relevant tests carried out
10. Reims-Cessna FR172J Reims Rocket	X	X	X	
11. Saab Safir	X	X	X	
12. Slingsby T67M200 Firefly	X	X	X	
13. Thruster TST	X	X		- Cruise config tests repeated at 2kn/s and 5kn/s deceleration. - Landing config tests repeated at 2kn/s and 5kn/s deceleration – Cruise config tests at 1kn/s, 2kn/s and 5kn/s were also investigated in a climbing turn at full throttle
14. Vans RV8	X	X		

RESULTS FOR STALL RECOVERIES

Results for the four sets of stall recovery actions are shown in Table 3 for the cruise configuration wings-level idle case,

Table 4 for the landing configuration wings-level idle case, and Table 5 for the landing configuration, 30º bank, approach power case. In all cases the recoveries were flown as described above; it should be recognised that the target here was very much for consistency of technique, and that with aggressive handling supplemented by detailed knowledge of any type: height loss and controllability can almost certainly be improved in every case.

Please note that there is apparently some inconsistency of wording in the tables below. This is deliberate because where there is any complexity to the results, the authors have tried to use the wording from the Test Pilots' post flight report.

Table 3, Recovery characteristics in Cruise Configuration, wings level, idle

	Recovery Method			
Aircraft type	**Height loss and controllability in recovery using CAA method**	**Height loss and controllability in recovery using FAA method**	**Height loss and controllability in recovery using Power Delayed Method**	**Height loss and controllability in recovery using Pitch Delayed Method**
Auster J5L Aiglet	175ft FC	150ft FC	175ft FC	100ft FC, considerably less nose-down rotation than other techniques
Cessna C152	60ft FC	120ft FC	140ft FC	Slight pitch-up, moderate pilot compensation required to keep aircraft in balance, no tendency to a secondary loss of control.
Cessna C172P	40ft FC	70ft FC	110ft FC	Gentle pitch up followed by a roll off to the left – uncomfortable but not a full secondary loss of control
Cessna C182P	125ft FC	175ft FC	250ft FC	Pitch up with application of power and a slight left wing drop. No tendency towards a secondary loss of control
Easy Raider J2.2(2)	80ft FC	130ft FC	100ft FC	20ft FC
Flightdesign CTSW	0ft FC	20ft FC	80ft FC	0ft FC
Grumman AA5a Cheetah	120ft FC. Slight left wing drop.	230ft FC. Slight left wing drop.	240ft FC. Slight left wing drop.	110ft Controllable from resultant spiral dive. .Slight left wing drop.
Piper PA28-161 Warrior II	90ft FC	120ft FC	160ft FC	30ft Full controllable
Piper PA38-112 Tomahawk	180ft FC	250ft FC	190ft FC	Severe right wing drop which may have been an incipient spin but recovered from this immediately the stick was moved forward
Reims-Cessna FR172J	160ft FC	180ft FC	200ft FC	10ft 10-15° nose up, slight left wingdrop. No tendency for secondary stall.
Saab Safir	140ft FC	200ft FC	240ft FC	Pitch-up, right wing-drop, buffeting and nose seemed to stay high. Recovery immediate

	Recovery Method			
Aircraft type	**Height loss and controllability in recovery using CAA method**	**Height loss and controllability in recovery using FAA method**	**Height loss and controllability in recovery using Power Delayed Method**	**Height loss and controllability in recovery using Pitch Delayed Method**
				when stick was moved forward (pitch down).
Slingsby T67200 Firefly	100ft FC	150ft FC	200ft FC	Pitch up and left wing drop, did not recover from stalled condition until stick moved forward
Thruster TST	100ft FC	200ft FC	200ft FC	200ft FC
Vans RV8	100ft FC	150ft FC	200ft FC	0ft, initial pitch up but FC

Table 4, Recovery characteristics in Landing Configuration, Wings Level, flight idle power, where tested

Aircraft type	Height loss and controllability in recovery using CAA method	Height loss and controllability in recovery using FAA method	Height loss and controllability in recovery using Power Delayed Method	Height loss and controllability in recovery using Pitch Delayed Method
Auster J5L Aiglet	125ft FC Caution required to avoid flap overspeed on recovery.	150ft FC Caution required to avoid flap overspeed on recovery.	150ft FC	150ft, aircraft showed strong inclination to try and enter a spin, requiring pitch input at about 1 second
Cessna C152	100ft FC	130ft FC	140ft FC	60ft, slight pitch up, no further tendency to loss of control within 2 seconds.
Cessna C172P	80ft FC	110ft FC	130ft FC	Pitch up and roll off to the left
Cessna C182P	125ft FC	150ft FC	175ft FC	Pitched 5-10° nose-up with application of power, then 10-20° right wing drop. Immediate recovery when stick moved forwards.
Easy Raider J2.2(2)	80ft FC	60ft FC	80ft FC	This test could not be performed because with application of power, the aeroplane entered an uncontrollable pitch-up immediately requiring either 2+daN push force or reduction of throttle setting.
Flightdesign CTSW	40ft FC	10ft FC	50ft FC	0ft Uncomfortable and rapid, but just acceptable pitch up, immediately recovered once the pitch control was introduced.
Grumman AA5a Cheetah	80ft FC	250ft FC	230ft FC	130ft FC, but in investigation would re-enter powered stall if stick held back for 2 secs.
Piper PA28-161 Warrior II	60ft FC	90ft FC	140ft FC	40ft FC
Reims-Cessna FR172J	120ft FC	140ft FC	240ft FC	80ft FC
Saab Safir	160ft FC	280ft FC	240ft FC	Pitch-up initially and then an oscillation in pitch with nose staying high. Buffeting. Recovery immediate when stick was moved forward.
Slingsby T67M200 Firefly	90ft FC	100ft FC	200ft FC	Pitch up and left wing drop, but did not recover from stalled condition until stick moved forward after about 2 seconds.

Table 5, Recovery characteristics in Landing Configuration, 30° left bank, power for approach, where tested

Aircraft type	Height loss and controllability in recovery using CAA method	Height loss and controllability in recovery using FAA method	Height loss and controllability in recovery using Power Delayed Method	Height loss and controllability in recovery using Pitch Delayed Method
Auster J5L Aiglet	150ft FC	100ft FC	100ft Rolled to wings level at stall in about ½ sec. Satisfactory.	150ft Aircraft recovered immediately into level flight attitude. Repeated to right, with identical results.
Cessna 182P	150ft	190ft	Data missed	Aircraft climbed in stall, no apparent stall recovery until back pressure relaxed.
Cessna C152	100ft FC	130ft FC	140ft FC	100ft, slight pitch up, no further tendency to loss of control within 2 seconds.
Cessna C172P	100ft FC	60ft FC	200ft FC	Aircraft tightened in the turn with no other response – no height loss.
Grumman AA5a Cheetah	200ft FC	210ft FC	290ft FC	210ft Rolled wings level then controllable.
Piper PA28-161 Warrior II	40ft FC	40ft FC	120ft FC	Controllable with zero height loss
Piper PA38-112 Tomahawk	90ft FC	200ft. Rolled to 45º left at the point of stall, but then once stick had been moved forwards control immediately returned and wings could be rolled wings level	240ft FC	With the increase in power, the aeroplane dropped the left wing about 90° – this was recovered from immediately to avoid further loss of control.
Reims-Cessna FR172J	100ft FC	120ft FC	220ft FC	60ft FC
Saab Safir	190ft, 20° right wing drop then immediate stall recovery	270ft, 30° right wing drop, then immediate stall recovery	300ft, 30° right wing drop, then immediate stall recovery	Pitch up initially then pitch oscillation with nose staying high. Recovery immediate when stick moved forwards.
Vans RV8	120ft FC	150ft FC	200ft FC	0ft, powered out of stall whilst maintaining 30° bank angle.

ANALYSIS OF THE EFFECTIVENESS OF STALL RECOVERY TECHNIQUES

The first and most obvious observation from these results is that the pitch delayed recovery is potentially hazardous: causing or indicating additional uncommanded motions in the T67, PA38, C152, C172, C182P and Safir in the cruise configuration, and in those plus the Easy Raider and Auster with the flaps down. In a few instances – the PA28, CTSW, Easy Raider and Auster in the cruise configuration, although only the CTSW and FR172 in the landing configuration, this recovery gave the least height loss in stall recovery whilst the aeroplane remained fully controllable. This could make a case, if not a strong one – given the alternative benefits of standardisation, for recommended stall recovery actions to be type dependent, as they often are for spin recoveries. However, considerable caution should be applied here – pilots often transfer between aircraft types and a pilot very well versed in a set of actions on one type may try to use those actions in another where they are inappropriate.

In particular, the PA28-161: which is one of a family of aircraft (the Piper Cherokees) commonly used within commercial flying training, responds well to a power only recovery. Anecdotally many commercial flying course graduates in recent years have apparently tended to "power out" of a stall without a leading or simultaneous pitch input, and this may be part of the reason for this perceived trend. This practice, as earlier noted being described as inappropriate by the UK CAA[14], has a negative training effect in the sense that this technique seem to work for one particular aeroplane type, but might be potentially hazardous in other aeroplane models.

The next observation, is that none of the CAA, FAA or power delayed recoveries gave rise to any subsequent further loss of control, or any delay in stall recovery. So, purely from the perspective of controllability, all of these are satisfactory sets of actions for stall recovery.

Within those however, it then becomes appropriate to consider the relative merits of these three sets of actions – which primarily comes down to height loss, with the recovery giving least height loss being most satisfactory. In particular, the recovery giving least height loss from the descending turn/landing configuration combination, which is the stall most likely to be experienced close to the ground.

Before considering this, it must be recalled that this investigation is based upon only a small number of test points per aeroplane/configuration/recovery – but nonetheless a comparison over the full data set is worthwhile and simple. In the least critical cruise/wings-level/idle set firstly, the mean height loss in recovery was little different between the FAA and power delayed recoveries at 153ft and 178ft respectively. However, the CAA recovery was substantially better at a mean of 105ft: 69% of the height lost flying the next-best FAA recovery.

The more safety critical wings-level/idle power/landing-configuration recoveries are similar in pattern: the mean height loss in recovery across the five aeroplanes for which data was obtained are for the CAA, FAA and power delayed recoveries: 102ft, 146ft and 173ft respectively. This gives a clear safety advantage to the CAA method: again 69% of the height loss of the nearest, FAA, method.

In the most safety critical landing case of 30º of bank, set to approach power and in the landing landing configuration, the height losses of the three aeroplanes tested showed a similar pattern:123ft, 142ft and 211ft. So, there is an advantage again, albeit a small one – the CAA method losing 88% of the height of the FAA method. In this case the effect of delaying use of power (power delayed versus FAA) is more marked than elsewhere with the FAA recovery losing only 67% of the mean altitude of the power delayed.

In all cases where the power was not applied after the pitch control, any tendency to lateral or directional excursions immediately ceased. This was not necessarily the case where pitch input was delayed.

THE RELATIONSHIP BETWEEN PITCH CHANGE WITH POWER AND STALL RECOVERY CHARACTERISTICS

Whilst intuitively one might expect aeroplane designs to vary in their pitch response with power – with the probable exception of the Thruster TST (which has an extremely high thrustline, but also for which the data quality is suspect), in practice every type tested reduced in trim speed with increased thrust (so $\Delta M_T>0$ and $\Delta U_T<0$), and required a stick push to maintain constant speed as power was increased. Apart from obviously giving the lie to the common layman's misbelief that to make an aeroplane fly faster one should increase the power in the first instance, this also presents an obvious explanation for the regular failure of "power first" mishandling to recover aeroplanes from the stall. Clearly, a net nose-up pitching moment when the aeroplane is about α_{crit} will not be helpful. It is suggested by the authors (two of whom are also flying instructors) that this presents a teaching opportunity – where demonstration of changes in trim speed with power may help emphasise to a student pilot the importance of not leading a stall recovery with the power alone.

In the flying training community VFR approaches to land have historically been taught on the basis of power for vertical speed and pitch for flight speed, yet IFR approaches and some VFR approaches are increasingly taught on the basis of power for speed, and pitch for rate of descent (often known as "point and power"; the interrelation of pitch, power and rate of descent – plus much flying experience, clearly show that both work. However, this suggests that a method currently being taught in IFR and VFR approaches may be creating more workload than is necessary for VFR pilots in piston singles, possibly because of a desire for common practice with multi-engine turbine aeroplanes where experience teaches that "point and power" is more appropriate. This shows potential for future study.

EFFECTS OF WING LOADING AND WING ASPECT RATIO

In evaluating the relationships between stall and stall recovery characteristics and aspect ratio (defined as AR=Span^2/Area), no significant relationship could be found.

In evaluating the relationships between stall and wing loading, a limited relationship was found between height loss during the stall recovery and wing loading. This is broadly consistent with both anecdotal experience and some previous research on microlight aeroplanes[16].

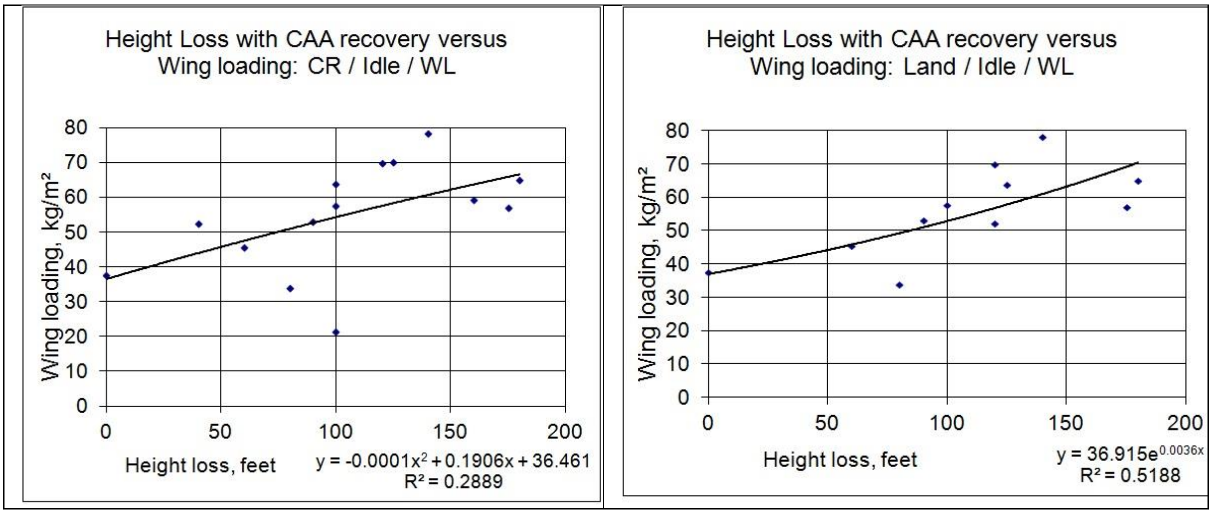


Figure 2, Height loss during stall recovery versus wing loading for CAA recovery, showing correlation

Figure 2 shows an attempt to find a relationship between wing loading and height loss using the CAA recovery – similar patterns were found with the other recovery techniques. A very limited pattern appears of increasing height loss with increasing wing loading; whilst this study is constrained to the SEP and microlight classes, this appears consistent for example between the known behaviour of low wing loading gliders which tend to enjoy very small height losses in stall recovery, and of heavy combat and transport aeroplanes, which suffer rather greater height losses. Across this data, although discounting the anomalous Thruster TST aircraft, one can tentatively offer a worst case height loss in recovery of δh_{max}=3ft ft/kg/m^2 in all configurations for a correctly executed CAA recovery, which may have some value for safety planning (including the Thruster this becomes δh_{max}=5 ft/kg/m^2). Reconsidering the data for the less favourable FAA stall recovery this becomes δh_{max}=4 ft/kg/m^2 (or δh_{max}=10 ft/kg/m^2 including the Thruster.)

It was noted that there were also significant differences in the consistencies of height loss between recoveries. Taking the cruise configuration recoveries, the standard deviation height loss for the CAA recovery was 50ft, compared to 61ft for the FAA, and 53ft again for the power delayed recovery. In landing configuration at idle with wings level these values were CAA: 34ft, FAA:77ft, power delayed:63ft. In the simulated base turn stall, these values were CAA:48ft , FAA:79ft , power delayed: 83ft. So the CAA recovery provides the most consistent value for height loss, as well as the lowest. Whilst the FAA does not provide the greatest mean height loss, it does provide the greatest variability – so the potential for height loss using the FAA recovery is greater than the mean results alone indicate.

CONSIDERATION OF ERRORS

It is well known that stall speeds and characteristics can change with weight and balance. This however was not explored during this study, which took each aeroplane at an available and typical set of conditions without seeking to explore the full weight or centre of gravity range. Results would certainly differ at different W&CG conditions. However, it was considered more important to assess a wide range of types.

Two Test Pilots were used for the flight tests. To address the issue of individual flight test technique, one test flight (C182P) was flown using both test pilots and test points repeated between them. There were no significant discrepancies in qualitative comments and recorded altitude losses were within 25% whilst more importantly also showing the same greatest/least height loss per recovery type.

Each pilot on several occasions repeated tests with the same aeroplane and showed similar variation – height losses within 25% of separate test points at similar conditions, handling comments were substantially the same and the same pattern of relative height loss per recovery type was seen.

All aircraft were flown in a condition approved for normal use, so airspeed indicators and altimeters were serviceable and of a consistent and acceptable standard. Every aircraft flown had an altimeter where readings could be resolved to 25ft or better.

CONCLUSIONS AND RECOMMENDATIONS

Delaying application of the pitch control in stall recovery can in a few cases (5 in cruise configuration, 2 in landing configuration, of 14 types tested) minimise or eliminate height loss, but in far more cases (6 and 8 in cruise and landing configurations respectively) gives a significant additional risk of loss of control – this supports recent authority assertions about the unacceptability of power-only stall recovery[14].

However, no evidence from this research shows that, for the range of types tested, delaying the increase in thrust, beyond the moment of initiation of the nose-down pitch input, provides any advantage – only resulting in an increased loss of height.

All other recoveries from the stall assessed: those published by the CAA and FAA, and the power delayed recovery, gave satisfactory <u>handling</u> in the stall recovery. However, the CAA method, using simultaneous power and pitch consistently gave about one third less height loss than that of the FAA's pitch then power recovery, which in turn gave slightly reduced height loss than the power delayed recovery.

It appears from these results, that where there are not good reasons otherwise, the universal best stall recovery for single engine piston aeroplanes is the simultaneous pitch and power method published by the United Kingdom Civil Aviation Authority – giving universally rapid and consistent recovery from the stall, and least height loss of all methods assessed. It is however cautioned that no set of actions for recovery from an aeroplane loss of control should be used without thorough evaluation on that aircraft type.

Describing this differently: the primacy should be given to the pitch control, which is always what will recover an aircraft from the stall. The sooner full power is applied, the less the height loss. However, whilst simultaneous use is acceptable, power should never be applied before the pitch control.

It was found that from the data available, the worst case height loss from a correctly flown CAA stall recovery should not exceed 3 ft/kg /m^2 [height per mass per wing area], and for a correctly flown FAA stall recovery 4 ft/kg /m^2.

It should be emphasised that this study has only considered single engine piston light and 3-axis microlight aeroplanes, and conclusions should not automatically be applied to multi-engine and/or turbine powered aeroplanes, or to weightshift controlled microlight aeroplanes, for which the characteristics may be different. It is also likely that this research may not apply to some unusually configured aeroplanes: for example no canard aircraft were tested in the course of this study.

Some of the aeroplanes flown had relatively high power (e.g. 230 HP in the C182P), but greater power aeroplanes than these do certainly exist. It is interesting to note that the aeroplanes with highest power:weight in the group (C182P, T67M and Safir) all exhibited an uncomfortable pitch-up with application of power using the pitch delayed method, further underlining the importance of correctly using the pitch control in the recovery. It is on the basis of the potential destabilizing effect of power, at or near the stall, Roberts has advocated the power delayed method[10], and it may potentially be the case that should very high power: weight aeroplane be tested, these do require a delay in throttle advance; however, this remains unproven.

QUESTIONS FOR REGULATORY AUTHORITIES

The authors invite regulatory authorities worldwide to consider these conclusions in the context of their current regulated or encouraged practices. Whilst the conclusions of this paper appear compelling, there are potentially further questions to be considered before taking action. These are offered to be:-

(1) Is minimum height loss with controllability the best criterion for deciding the set of stall recovery actions in use? The power delayed recovery by comparison was consistently the most comfortable for pilots to use, with one action following the other in a sensible order, although height loss was greatest.
(2) It is the view of the authors of this paper that single engine light aeroplanes should be flown as such, and given that only a very small proportion of SEP pilots will progress to MEP or turbine aeroplanes, there is little grounds for co-inciding SEP stall recovery actions with those for larger aeroplanes for which later specialist training can be provided. Is this view correct?
(3) Is it appropriate that the UK (and much of Europe) is teaching one set of stall recovery actions, whilst the USA uses another?

(4) Is it likely that aircraft assessed in Europe or the USA against one set of stall recovery actions, are then being certified in the other where the alternate stall recovery actions may be used, without any re-testing?

ACKNOWLEDGMENTS

The authors would like to thank Rob Thomasson, Mike Grunwell, Mike Boxill and the aircraft syndicate represented by Graham Lund for their generosity in allowing their aeroplanes to be used to gather data for this study without cost to the project.

CONDUCT OF, AND CONTRIBUTIONS TO, THE RESEARCH

This research was led by Brunel Flight Safety Laboratory, part of the School of Engineering and Design at Brunel University. Flight hours were internally or self funded by researchers or donated by aircraft owners. Several expanded test programmes were also produced and managed by undergraduate students at Brunel University for their third year dissertations on the BEng or MEng degrees in Aviation Engineering with Pilot Studies – those students are co-authors of this paper. Project management and primary paper drafting was by Gratton; Gratton and Hoff flew as Test Pilots; all other co-authors flew as Flight Test Observers, all authors contributed to and approved the text.

The approach, first used here, of an openly available research flight test plan[28] hoping to create a collaborative piece of research with multiple new research collaborators was less fruitful than had been hoped, but did not in any way damage the project and will be repeated with future projects.

AVAILABILITY OF DATA

All of the data from this study will, post publication, be made freely available to other researchers via the Brunel University Research Archive at http://bura.brunel.ac.uk .

APPENDIX

A – OUTLINE DETAILS OF THE AEROPLANES USED IN THIS STUDY

Type	**MTOW (kg.f)**[1]	**Test Weight (kg.f)**	**Test CG condition** (within range)	**Engine power** (hp)	**Configuration** *(All fixed gear and fixed pitch propeller unless stated otherwise)*	V_{S1} (As tested)	V_{S0}	**Aircraft registration**
Auster J5L Aiglet	1020	901-836	Mid-Aft	150	 High wing, mid-tailplane, tractor, tailwheel	40	36	G-AMYD
Cessna C152	758	676	Mid-fwd	110	 High wing, low tailplane, nosegear, tractor.	40	36	G-BMTJ
Cessna C172P	1089	862	Mid-Fwd	160	 High wing, low tailplane, nosegear, tractor.	45	34	G-BOJS
Cessna C182P	1338	1125	Mid-fwd	230	 High wing, low tailplane, nosegear, tractor.	52	57	G-BMMK
Easy Raider J2.2(2)	450	337-327	Mid-fwd	80	 High wing, mid-tailplane, tractor, tailwheel	35	32	G-CBXF
Flightdesign CTSW	450	378 - 370	Mid-fwd	80	 High wing, mid-tailplane, tractor, nosegear	40	34	G-CEKT
Grumman AA5a Cheetah	998	940-910	Fwd	150	 Low wing, low tailplane, tractor, nosegear	54	48	G-RATE
Piper PA28-161 Warrior II	1052	850	Mid-fwd	160	 Low wing, low tailplane, tractor, nosegear	50	45	G-BUFY

[1] Please note that for many of these aircraft types the MTOW varies with airframe modification state, and the values given are for the test airframes at the time of test only.

Type	**MTOW (kg.f)**[1]	**Test Weight (kg.f)**	**Test CG condition** (within range)	**Engine power** (hp)	**Configuration** *(All fixed gear and fixed pitch propeller unless stated otherwise)*	**V_{S1}** (As tested)	**V_{S0}**	**Aircraft registration**
Piper PA38-112 Tomahawk	759	664	Mid-aft	112	 Low wing, high tailplane, tractor, nosegear	45	45	G-BNPM
Reims-Cessna FR172J	1157	960	Mid-aft	210	 High wing, low tailplane, tractor, nosegear, variable pitch propeller.	43	33	G-BARC
Saab Safir	1165	1,067 – 970	Mid	190	 Low wing, low tailplane, nosegear, tractor, fixed pitch propeller	55	52	LN-SAO
Slingsby T67M200 Firefly	975	829 – 790	Mid-fwd	200	 Low wing, mid tailplane, nosegear, tractor, variable pitch propeller.	58	52	LN-TFF
Thruster TST	380	332 – 320	Mid-Aft	50	 High wing, high-tailplane, tractor, tailwheel	37		G-MTPT
Vans RV8	862	705-685	Mid-Fwd	180	 Low wing, mid tailplane, tailwheel, tractor, variable pitch propeller	58	52	LN-SMB

Notes:

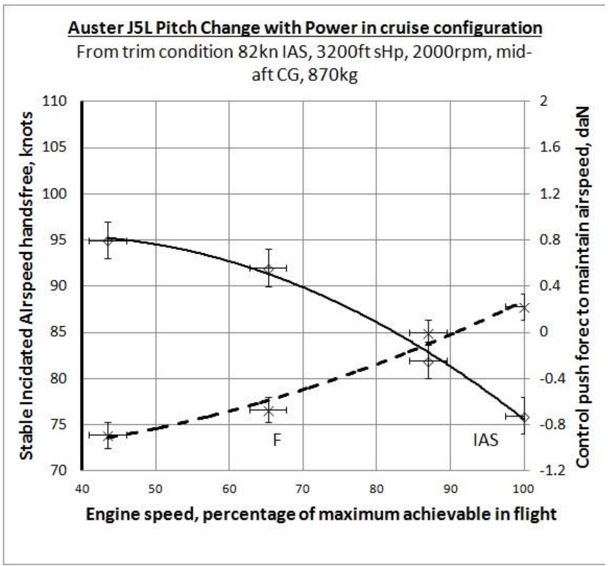
(1) Where available, speeds are quoted in knots CAS, but more commonly in knots IAS (even if the ASI was in mph). In certified aeroplanes these should be within 5% in any case, but the errors are probably larger in the Thruster TST, which was permitted to a standard which did not mandate minimum airspeed measurement accuracies.

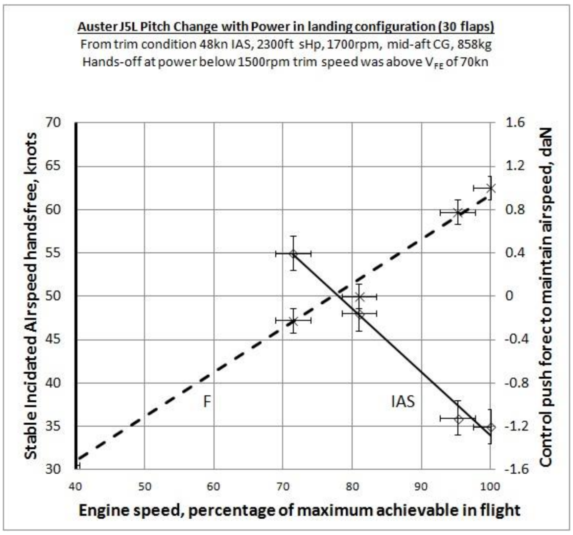
(2) Registrations of aircraft in the illustrations do not necessarily correspond to the registrations of the aeroplanes flown in the research programme.

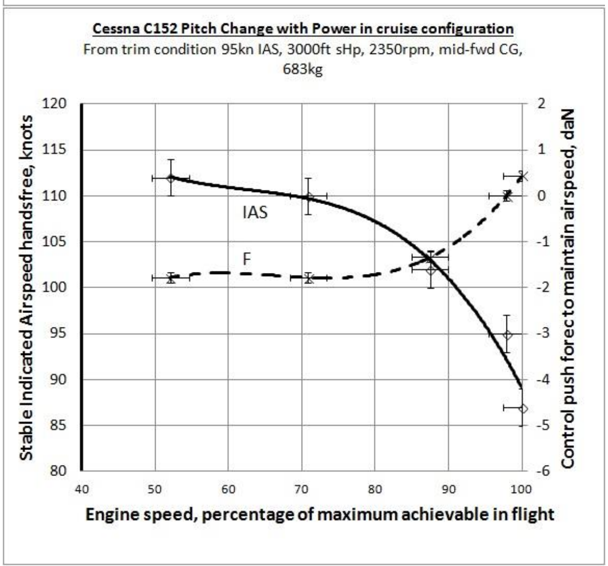
APPENDIX

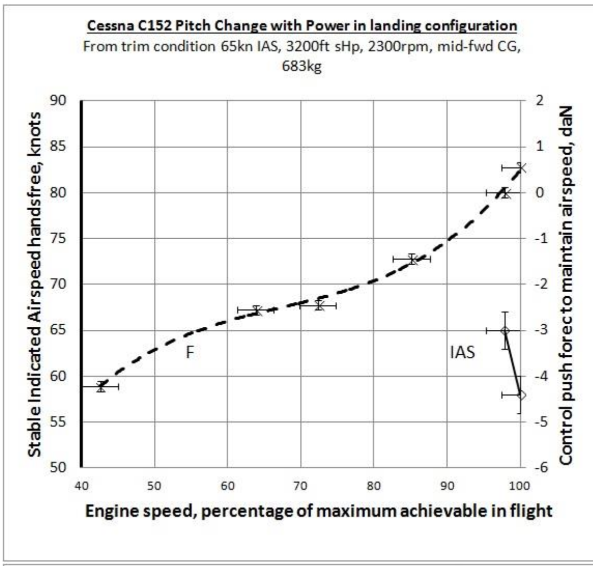
B – RESULTS FOR PITCH STABILITY EVALUATION

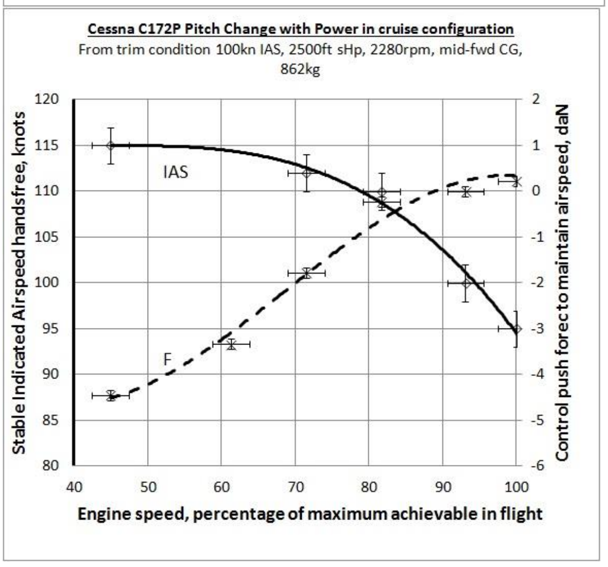
Error bars based upon instrument display resolution.

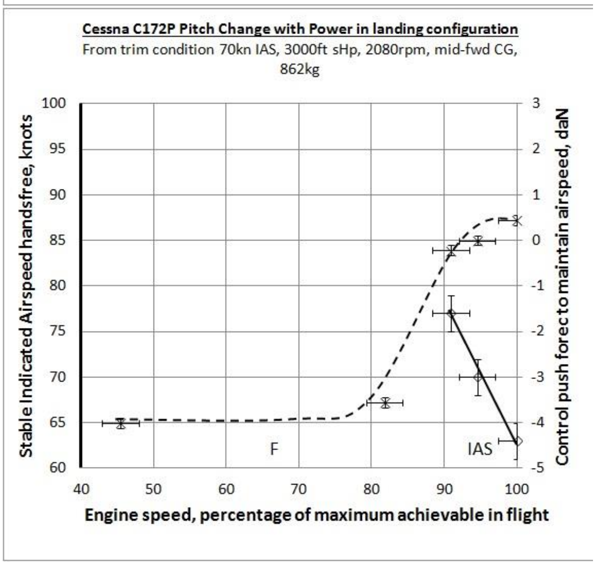


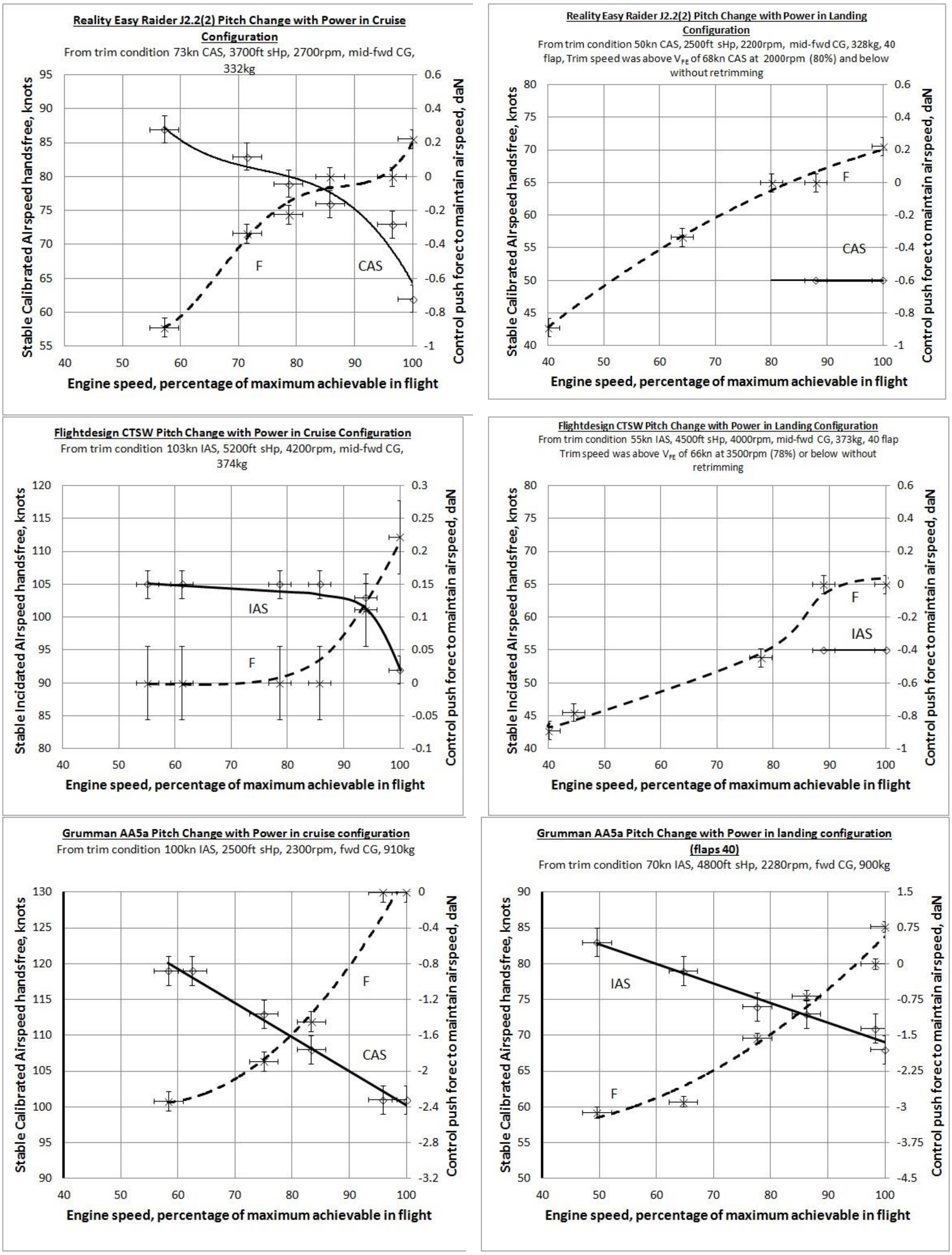


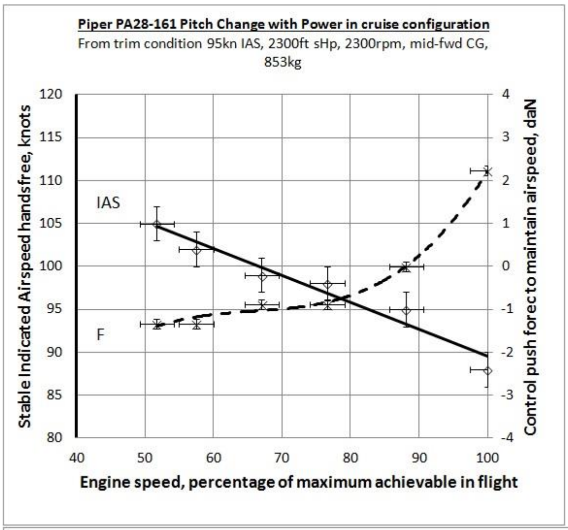


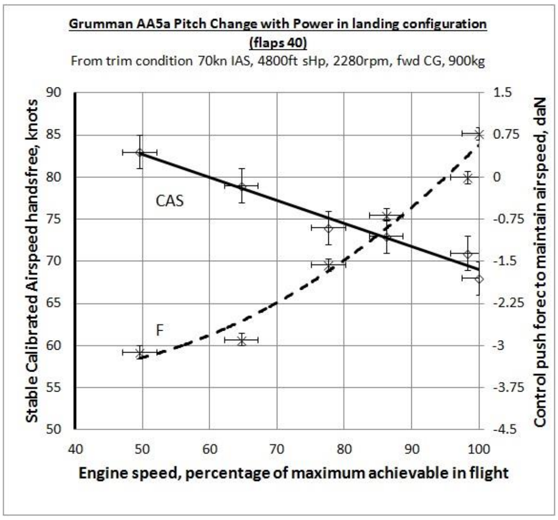


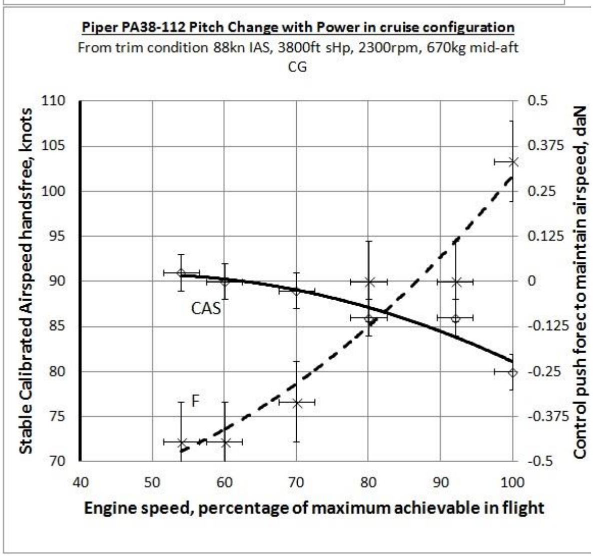


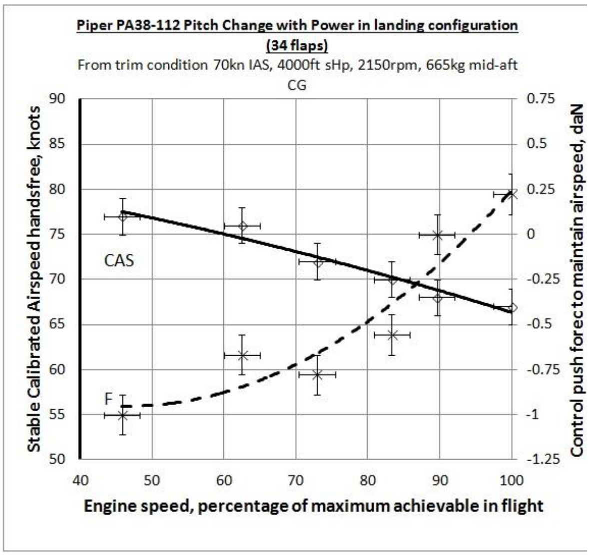


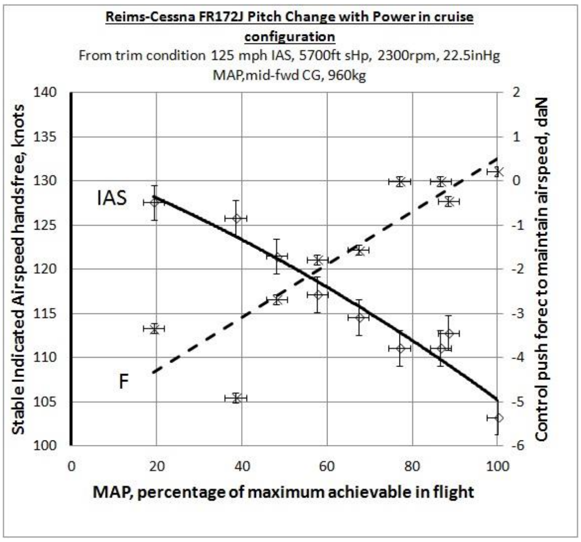

Reality Easy Raider J2.2(2) Pitch Change with Power in Cruise Configuration
From trim condition 73kn CAS, 3700ft sHp, 2700rpm, mid-fwd CG, 332kg
Stable Calibrated Airspeed handsfree, knots
Control push forec to maintain airspeed, daN
Engine speed, percentage of maximum achievable in flight
F
CAS
95
90
85
80
75
70
65
60
55
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
40
50
60
70
80
90
100
Reality Easy Raider J2.2(2) Pitch Change with Power in Landing Configuration
From trim condition 50kn CAS, 2500ft sHp, 2200rpm, mid-fwd CG, 328kg, 40 flap, Trim speed was above V_FE of 68kn CAS at 2000rpm (80%) and below without retrimming
Stable Calibrated Airspeed handsfree, knots
Control push forec to maintain airspeed, daN
Engine speed, percentage of maximum achievable in flight
F
CAS
80
75
70
65
60
55
50
45
40
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
40
50
60
70
80
90
100
Flightdesign CTSW Pitch Change with Power in Cruise Configuration
From trim condition 103kn IAS, 5200ft sHp, 4200rpm, mid-fwd CG, 374kg
Stable Incidated Airspeed handsfree, knots
Control push forec to maintain airspeed, daN
Engine speed, percentage of maximum achievable in flight
IAS
F
120
115
110
105
100
95
90
85
80
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
40
50
60
70
80
90
100
Flightdesign CTSW Pitch Change with Power in Landing Configuration
From trim condition 55kn IAS, 4500ft sHp, 4000rpm, mid-fwd CG, 373kg, 40 flap
Trim speed was above V_FE of 66kn at 3500rpm (78%) or below without retrimming
Stable Incidated Airspeed handsfree, knots
Control push forec to maintain airspeed, daN
Engine speed, percentage of maximum achievable in flight
F
IAS
80
75
70
65
60
55
50
45
40
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
40
50
60
70
80
90
100
Grumman AA5a Pitch Change with Power in cruise configuration
From trim condition 100kn IAS, 2500ft sHp, 2300rpm, fwd CG, 910kg
Stable Calibrated Airspeed handsfree, knots
Control push forec to maintain airspeed, daN
Engine speed, percentage of maximum achievable in flight
F
CAS
130
125
120
115
110
105
100
95
90
0
-0.4
-0.8
-1.2
-1.6
-2
-2.4
-2.8
-3.2
40
50
60
70
80
90
100
Grumman AA5a Pitch Change with Power in landing configuration (flaps 40)
From trim condition 70kn IAS, 4800ft sHp, 2280rpm, fwd CG, 900kg
Stable Calibrated Airspeed handsfree, knots
Control push forec to maintain airspeed, daN
Engine speed, percentage of maximum achievable in flight
IAS
F
90
85
80
75
70
65
60
55
50
1.5
0.75
0
-0.75
-1.5
-2.25
-3
-3.75
-4.5
40
50
60
70
80
90
100

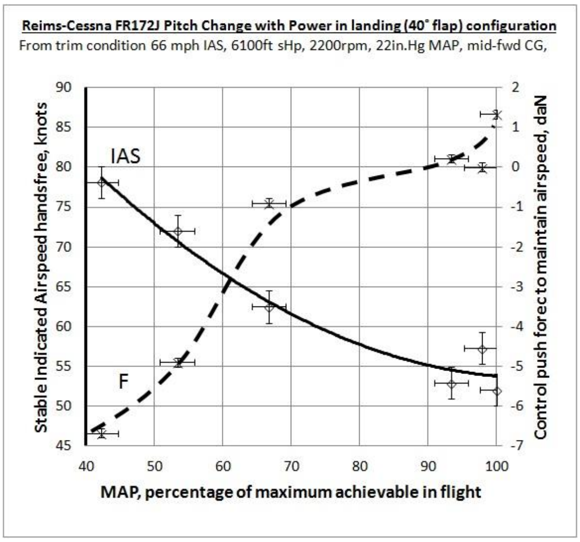

Piper PA28-161 Pitch Change with Power in cruise configuration
From trim condition 95kn IAS, 2300ft sHp, 2300rpm, mid-fwd CG, 853kg
Stable Indicated Airspeed handsfree, knots
Control push forec to maintain airspeed, daN
IAS
F
Engine speed, percentage of maximum achievable in flight

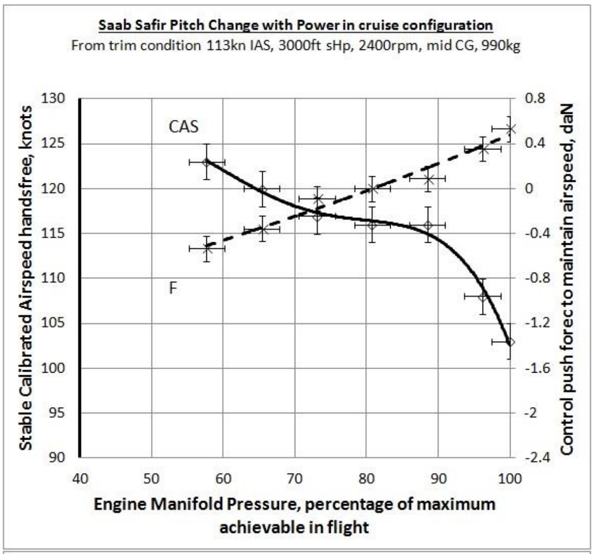

Grumman AA5a Pitch Change with Power in landing configuration (flaps 40)
From trim condition 70kn IAS, 4800ft sHp, 2280rpm, fwd CG, 900kg
Stable Calibrated Airspeed handsfree, knots
Control push forec to maintain airspeed, daN
CAS
F
Engine speed, percentage of maximum achievable in flight

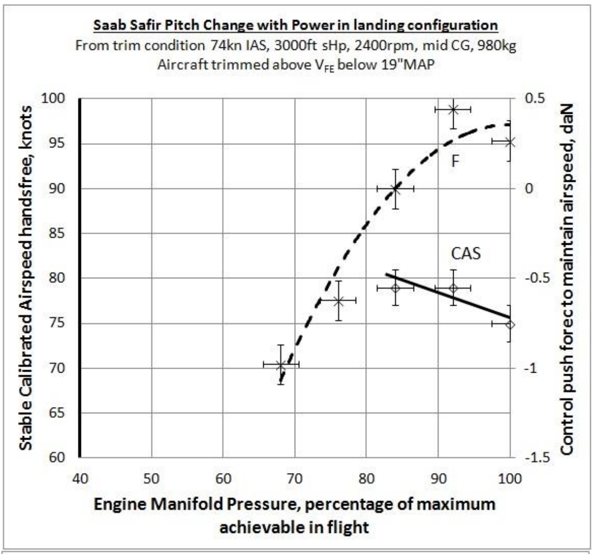

Piper PA38-112 Pitch Change with Power in cruise configuration
From trim condition 88kn IAS, 3800ft sHp, 2300rpm, 670kg mid-aft CG
Stable Calibrated Airspeed handsfree, knots
Control push forec to maintain airspeed, daN
CAS
F
Engine speed, percentage of maximum achievable in flight

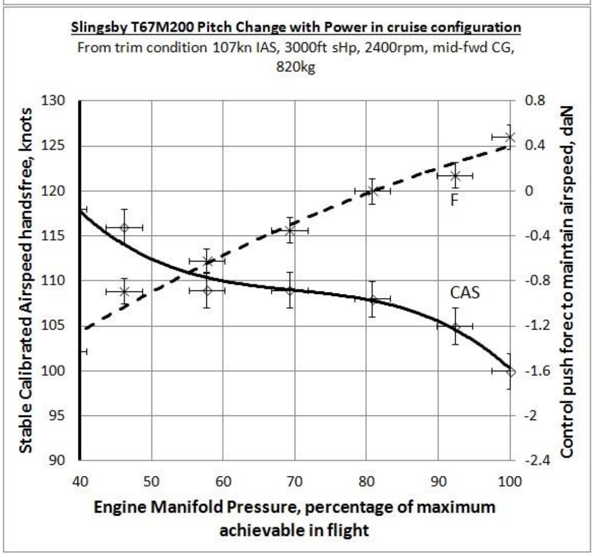

Piper PA38-112 Pitch Change with Power in landing configuration (34 flaps)
From trim condition 70kn IAS, 4000ft sHp, 2150rpm, 665kg mid-aft CG
Stable Calibrated Airspeed handsfree, knots
Control push forec to maintain airspeed, daN
CAS
F
Engine speed, percentage of maximum achievable in flight

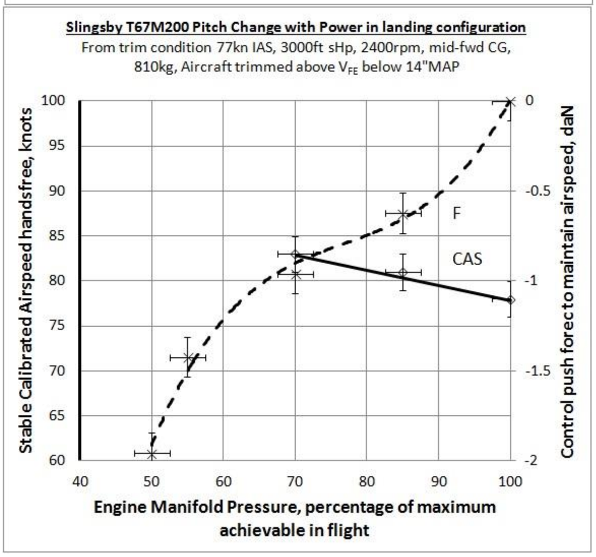

Reims-Cessna FR172J Pitch Change with Power in cruise configuration
From trim condition 125 mph IAS, 5700ft sHp, 2300rpm, 22.5inHg MAP,mid-fwd CG, 960kg
Stable Indicated Airspeed handsfree, knots
Control push forec to maintain airspeed, daN
IAS
F
MAP, percentage of maximum achievable in flight

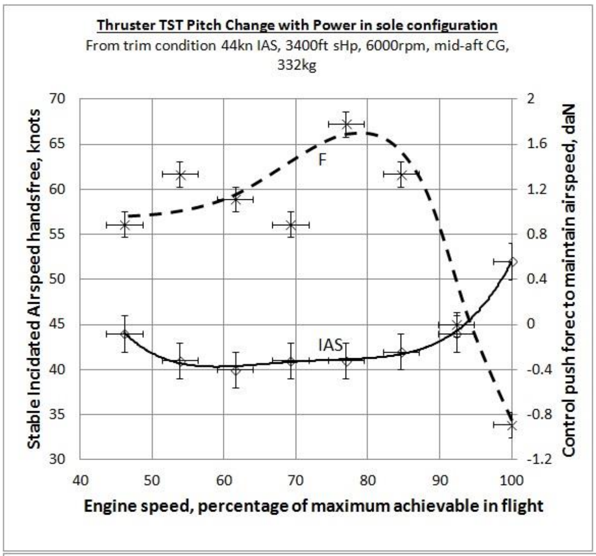

Reims-Cessna FR172J Pitch Change with Power in landing (40° flap) configuration
From trim condition 66 mph IAS, 6100ft sHp, 2200rpm, 22in.Hg MAP, mid-fwd CG,
Stable Indicated Airspeed handsfree, knots
Control push forec to maintain airspeed, daN
IAS
F
MAP, percentage of maximum achievable in flight


Saab Safir Pitch Change with Power in cruise configuration
From trim condition 113kn IAS, 3000ft sHp, 2400rpm, mid CG, 990kg
CAS
F
Stable Calibrated Airspeed handsfree, knots
Control push forec to maintain airspeed, daN
Engine Manifold Pressure, percentage of maximum achievable in flight


Saab Safir Pitch Change with Power in landing configuration
From trim condition 74kn IAS, 3000ft sHp, 2400rpm, mid CG, 980kg
Aircraft trimmed above V_{FE} below 19"MAP
F
CAS
Stable Calibrated Airspeed handsfree, knots
Control push forec to maintain airspeed, daN
Engine Manifold Pressure, percentage of maximum achievable in flight

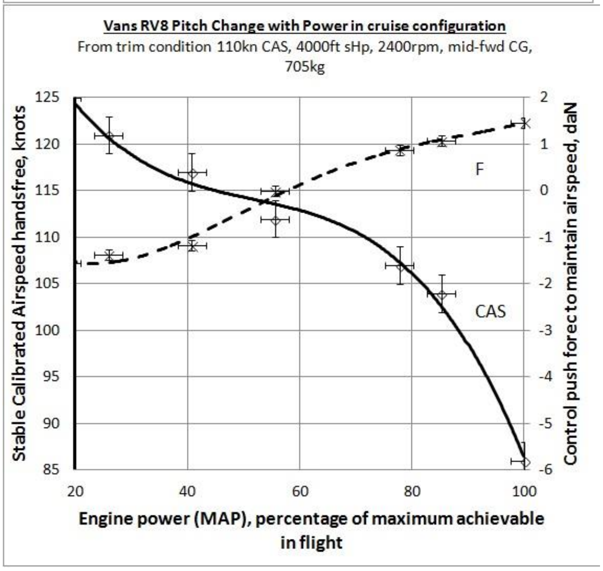

Slingsby T67M200 Pitch Change with Power in cruise configuration
From trim condition 107kn IAS, 3000ft sHp, 2400rpm, mid-fwd CG, 820kg
F
CAS
Stable Calibrated Airspeed handsfree, knots
Control push forec to maintain airspeed, daN
Engine Manifold Pressure, percentage of maximum achievable in flight


Slingsby T67M200 Pitch Change with Power in landing configuration
From trim condition 77kn IAS, 3000ft sHp, 2400rpm, mid-fwd CG, 810kg, Aircraft trimmed above V_{FE} below 14"MAP
F
CAS
Stable Calibrated Airspeed handsfree, knots
Control push forec to maintain airspeed, daN
Engine Manifold Pressure, percentage of maximum achievable in flight



The graph to the left is considered potentially untrustworthy. However, the test airframe has subsequently been removed from service so re-testing is impossible and it was elected to retain the data.

This data is retained for completeness, and other data for this airframe is considered trustworthy.



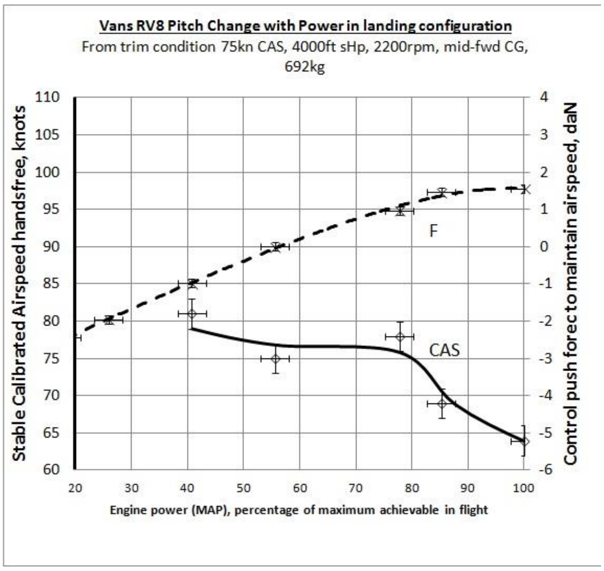


Figure 3, Trim change with power for aeroplanes investigated
(CAS used where available and significantly different from IAS, IAS otherwise, note that control force scales vary between graphs; best fit curves showed where reasonably achievable, linear points-join where not; lowest power shown is always with throttle fully closed, highest power shown is always with throttle fully open; trim condition is always at zero stick force. For variable pitch propellers, RPM control was not changed from trim condition.)
Numeric pitch data was not obtained for the Cessna 182, but its characteristics were qualitatively similar to those of the Cessna C172.

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