CORIOLIS MASS FLOW METERING TRACKING RAPID FUEL INJECTION PULSE TRAINS IN INTERNAL COMBUSTION ENGINES

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ABSTRACT

A previous MFHS presentation described the tracking of rapid fuel injections (as short as 1 ms) in a diesel internal combustion engine laboratory rig using Coriolis mass flow metering and Prism Signal Processing (PSP). This presentation provides an update on this work. Petrol/gasoline engines operate at lower pressures, but may be subject to higher levels of mechanical noise. Additional PSP filtering techniques are required to remove unwanted noise sources to reveal the fuel pulses. Where fuel pulses are significantly shorter than the resonant frequency of the Coriolis flowtube, flow measurements are subject to systematic distortions that require further investigation.

KEYWORDS

Coriolis mass flow metering; Prism Signal Processing; Internal combustion engine; fuel injection; Coriolis dynamic response.

INTRODUCTION

A presentation at MFHS 2017 [1] outlined the application of Prism Signal Processing (PSP) [2, 3] to the tracking of Coriolis meter signals for fast fuel injection monitoring in internal combustion engine laboratory rigs [4]. PSP is an alternative approach to FIR filtering, replacing the conventional convolution calculation with a set of Fourier-style double integrations that can be performed recursively. The resulting technique offers the benefits of FIR calculation – numerical stability and a linear phase response – combined with the low computational burden normally associated with IIR filtering. In addition, the Fourier-style calculation means that the equivalent of filter coefficients are simply linearly-spaced sine and cosine values so that design costs are negligible. Overall, PSP offers a fast and flexible toolset for instrumentation in the era of the Internet of Things [2].

In this paper, we report our experimental findings working with fuel injection systems for petrol (gasoline) powertrains. Basic challenges include high pressure requirements (30 MPa or more), high levels of mechanical noise, and fuel injection events as short as 1 ms. While PSP enables 48 kHz real-time flow measurement updates using modest computational resources, greater challenges arise with transducer operation and the need for traceable calibration facilities.

Firstly, the design of a PSP notch filtering scheme is described which enables the successful tracking of 1ms fuel pulses, despite the high levels of mechanical noise in the experimental system. Secondly, more detailed results are presented which show that where the fluid pulse length is shorter than the resonant period of the flowtube, the observed phase difference (related to the mass flow rate) is not repeatable. It is conjectured that the instantaneous phase of the flowtube oscillation is influential on the observed phase difference in these circumstances. Finally, further steps are proposed for improving measurement quality through higher resonant frequencies for flowtubes and developing a traceable calibration facility for short injection events.

NOTCH FILTER DESIGN

Coriolis mass flow metering entails passing the fluid to be measured through a flowtube, which oscillates at the resonant frequency of a natural mode of vibration. Two sensors monitor the flowtube vibration, whereby the phase difference between the sensor signals at the resonant frequency is proportional to the mass flow rate of the fluid.

Typically, Coriolis flowtubes have a high Q factor, resulting in sharp spectral peaks at the resonant frequency and its harmonics. Other modes of vibration of the flowtube may be excited by external mechanical noise, but these effects are usually small, and a number of mechanical and signal processing techniques have been developed to minimize the effect of off-resonance noise on the flow measurement in conventional circumstances.

In the case of the fuel injection process, exceptionally high levels of noise are present in one of the sensor signals (note that both sensor signals have similar properties and here are subject to the same filter design). Figure 1 shows two spectra. The green spectra shows the unfiltered sensor data. The peak at around 150 Hz corresponds to the resonant mode of vibration of the flowtube. All the other peaks represent undesired modes of vibration belonging either to the flowtube itself (and excited by system vibration) or the external experimental system. Here 1 ms fuel pulses are being supplied at intervals of 40.15 ms.

The signal processing problem is two-fold. One the one hand, all spectral peaks other than the desired mode of vibration must be suppressed in order to obtain the desired phase difference measurement. On the other hand, the dynamic response of the signals must be preserved sufficiently to detect the 1ms fuel injection events. This requirement rules out simply applying a narrow bandpass filter around the desired vibration mode, for example.

A cascaded set of Prism-based Dynamic Notch Filters (DNF) [2] has been used to target each of the spectral peaks marked with a circle. The resulting filtered signal is shown in blue in Figure 1, where the desired peak is preserved while all other peaks have been attenuated. Figure 2 shows the Prism-based notch filter design, which targets eight frequency peaks. The conference presentation will explain the design of this filter, and a more detailed explanation will be provided in a future journal publication.

Figures 3 and 4 show the corresponding phase difference measurement calculated from the two sensor signals, with and without the notch filtering, respectively. In Figure 3, with the unfiltered sensor data, the presence of high levels of noise masks the pattern of fuel impulses. In Figure 4, the sharp and regular flow peaks corresponding to the fuel pulse train are clearly observed. Note that the peak values in Fig 4, of around 0.35 degrees, are significantly lower than the noise amplitude in Figure 3, which is around ± 2 degrees: without filtering, it would not be possible to discern the peaks within the noise.

Although Figure 4 represents a significant improvement over Figure 3, there are still many issues to be resolved. A more detailed plot of an individual pulse would show that each 1 ms injection has been extended in duration to around 10 ms – this is believed to be due to the filtering action of both the signal processing and the flowtube. However, yet more significant difficulties arise, as discussed in the next section.

EXPERIMENTAL RESULTS

Further measurement problems may occur when, as in this case, the duration of a flow 'batch' is significantly shorter that the period of oscillation of the Coriolis flowtube. The problem is illustrated by the different behaviours shown in figures 5 and 7 (with details of each in figures 6 and 8 respectively). Both sets of results were obtained from the same Coriolis meter installed in a petrol/gasoline injection test rig (as described in [5]). The system uses a commercial Coriolis flowtube, rated for high pressure, oscillating at approximately 150Hz, and working with a prototype transmitter. The transmitter provides real-time PSP-based tracking of the amplitude of each sensor signal (among other parameters) and the phase difference between them.

In Figure 5 (with details shown in Figure 7), the pulse duration is 1.5 ms while the interval between the pulses is 40.15 ms, corresponding to exactly 6 periods of oscillation of the flowtube. The individual fuel pulses are clearly distinguishable via the phase difference measurement and show good repeatability. As Figure 7 shows, the peak height of each pulse is approximately constant, and the phase difference between pulses settles towards zero degrees, as would be expected. Around t = 15.5 s in Figure 5, a disruption in the phase difference measurement occurs: this corresponded to an audible 'misfiring' of the fuel injector during the experiment. Accordingly, this is interpreted as the system correctly detecting a true change in the flow behaviour. Note that the sensor amplitudes also adopt a specific and repeatable pattern of behavior, reflecting the response of the flowtube oscillation to the regular series of short fuel pulses.

The pattern of behavior shown Figure 6 (with details given in Figure 8) is very different to that of Figure 5, but experimentally, the only difference is that the time between pulses has been slightly increased to 40.3ms, so that it is no longer an integral number of flow tube periods. The repeatable behavior of Figure 5 is replaced with complex, essentially sinusoidal, variation for the observed amplitudes and phase difference, where pulse-to-pulse repeatability is poor. Note in particular in Figure 8 that the 'zero offset' of the phase difference measurement varies by ± 0.5 degrees, while the relative height of each flow pulse also varies over the sinusoidal trend. Analysis suggests the variations observed are a function of the flowtube phase when each fluid pulse arrives. In the case of Figure 5, as the interval between pulses is a whole number of flowtube resonant periods, repeatable behavior is observed. However, requiring such pulse intervals would place an unrealistic constraint on the operation of an engine. For the more general case, as shown in Figure 6, poor repeatability is observed due to flowtube phase shifts between fuel injections.

NEXT STEPS

Modelling and optimization of flowtube dynamics with short flow pulses may yield improved measurements techniques for this and similar applications.

However, a clear way to improve repeatability over arbitrary pulse intervals is to increase the resonant frequency of the flowtube. We have commissioned the construction of a high frequency flowtube suited for this application, and hope to report on experimental results obtained with this system in due course. We see great potential for micro-machined, high frequency, Coriolis transducers, if the pressure and vibration

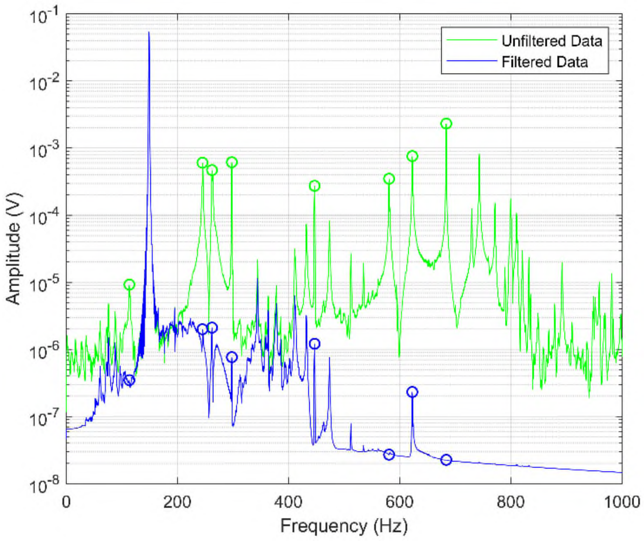

Figure 1: Coriolis sensor data frequency spectrum with and without Prism notch filtering. Notched frequencies are marked with a circle

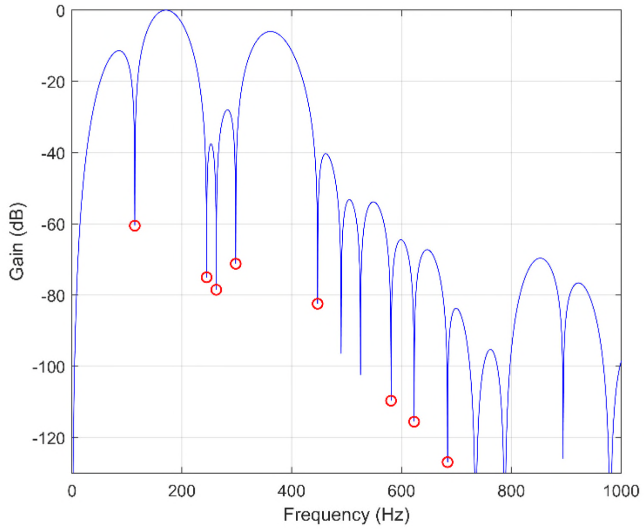

Figure 2: Design of Prism-based notch filter.

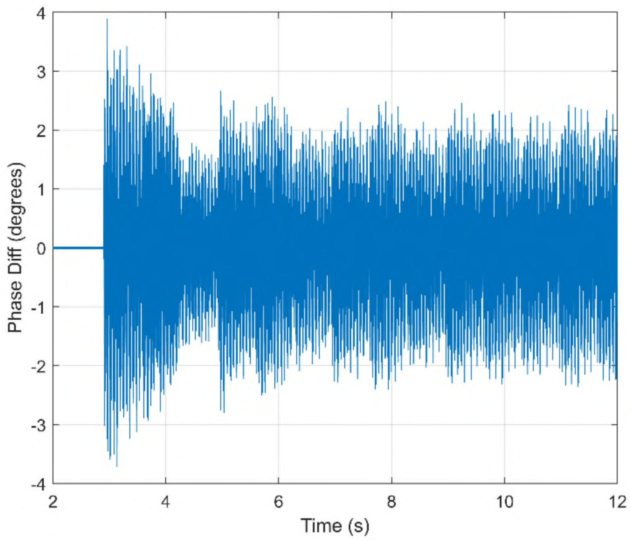

Figure 3: Phase difference measurement based on unfiltered sensor data.

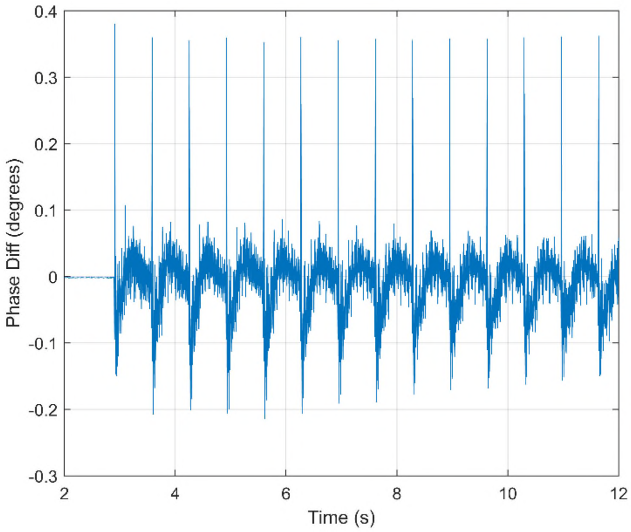

Figure 4: Phase difference measurement based on filtered sensor data.

challenges can be addressed. With, say, a resonant frequency exceeding 10 kHz, measurement updates can be provided at 100 kHz or higher using PSP. It is likely that with a higher resonant frequency, a simpler signal processing scheme could be used, as most noise sources would be far from the resonant frequency of the flowtube. However, even if a signal processing scheme of similar complexity is required, both the flowtube and signal processing dynamics would be scaled by the resonant frequency of the flowtube, so that the non-repeatability issue illustrated here would be significantly reduced or eliminated.

A further challenge to the development of Coriolis metering for fast injection applications is the provision of traceable mass flow measurement standards for instrument calibration.

The authors have completing a survey on behalf of TUV-NEL to gauge industry requirements for calibration in this domain, and will provide a brief summary of the findings at the conference.

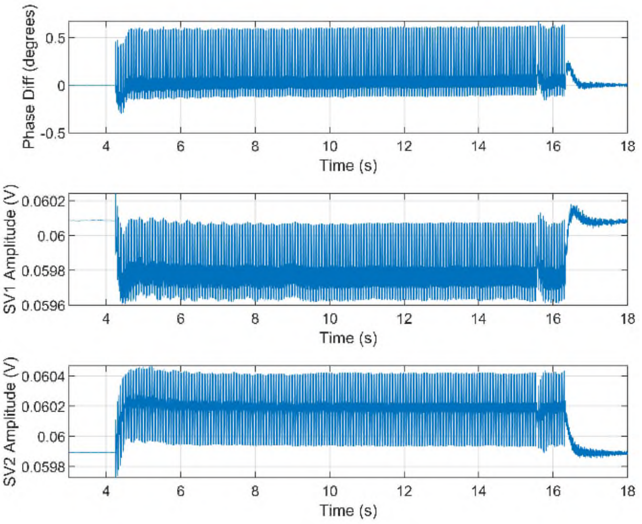

Figure 5: Phase difference and sensor amplitudes for fuel injection pulse train where the injection interval is set to 40.15 ms i.e. exactly 6 flowtube oscillation periods.

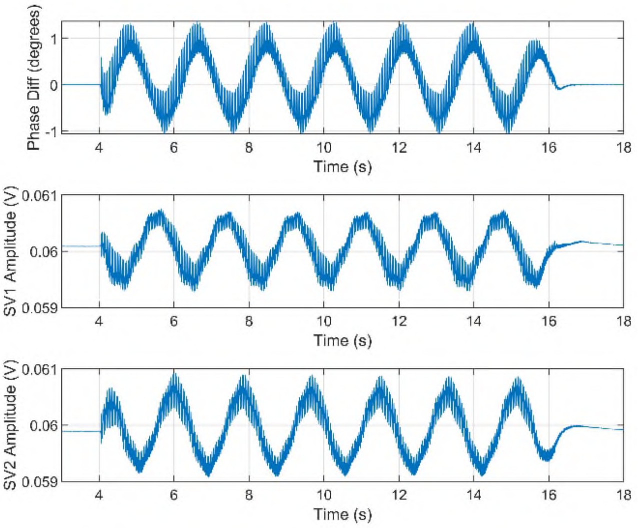

Figure 6: Results where the injection interval is 40.3 ms i.e. not a whole number of flowtube oscillation periods.

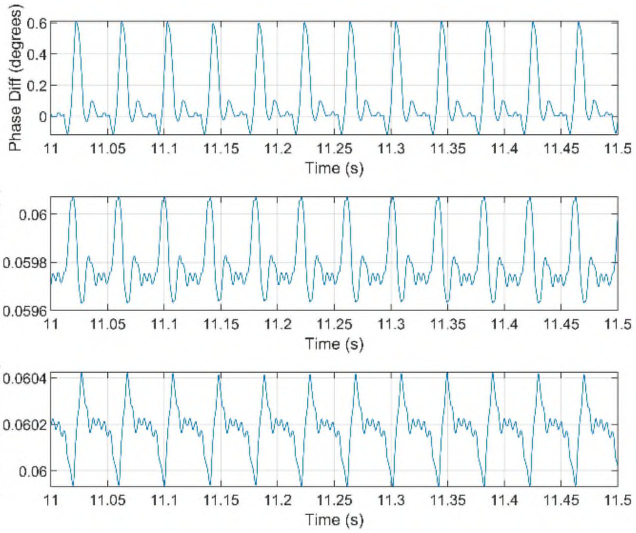

Figure 7: Detail from Figure 5, with reduced timescale.

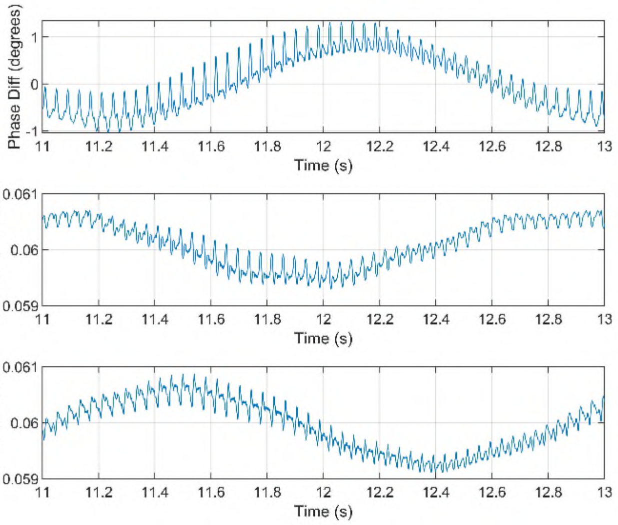

Figure 8: Detail from Figure 6, with reduced timescale.

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