3RD INTERNATIONAL CONFERENCE ON MICROFLUIDIC HANDLING SYSTEMS PRISM SIGNAL PROCESSING: A RECURSIVE FIR TECHNIQUE APPLIED TO THE EFFICIENT TRACKING OF RESONANT SENSOR SYSTEMS

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ABSTRACT

A new technique called Prism signal processing has been developed which offers an FIR response, including a linear phase characteristic, while being a fully recursive calculation. The Prism signal processing block accepts a time series input and generate either one output or two orthogonal outputs, where the computational requirement is low and independent of data window length. A Coriolis flow metering example is used to illustrate that Prism signal processing is suited to a wide range of resonant sensor systems, and can be used to provide a step change in measurement update rates compared with conventional FIR techniques.

KEYWORDS

FIR filtering, recursive filtering, resonant systems, Coriolis mass flow metering, automotive fuel injection monitoring.

INTRODUCTION

A longstanding research issue for interfaces to sensors such as Coriolis mass flow meters [1] is the development of efficient signal processing techniques for tracking sinusoidal signals. This is particularly important for microfluidic devices where resonant frequencies may be high and where batch times can be short, requiring high measurement update rates. For robust industrial systems, FIR techniques (for example in filtering and/or sinusoidal tracking) are widely preferred over IIR techniques, due to their numerical stability and linear phase characteristics. However, FIR calculations are typically non-recursive, and hence computationally expensive, thus restricting measurement update rates, particularly in intrinsically safe (i.e. low power) devices. A new technique called Prism signal processing has been developed which offers an FIR response and a linear phase characteristic while being a fully recursive calculation.

THE PRISM

Given a noise-free sinusoidal signal $s(t)$:

$$s(t) = A\sin(2\pi ft + \phi), \tag{1}$$

where t is time, A is the amplitude, f is the frequency in Hertz and ϕ is the phase offset at time t=0, we consider integrals of the following form:

$$I^h_{[s|c][s|c]} = \tag{2}$$

$$m^2 \int_{-\frac{1}{m}}^{0} [\sin|\cos](2\pi hmt + q)\left(\int_{t-\frac{1}{m}}^{t} [\sin|\cos](2\pi hmt + q)\cdot s(t)dt\right) dt$$

The subscript notation [s | c] indicates the selection of one alternative between s and c. The superscript h is the harmonic number, a positive integer, usually small. m is the characteristic frequency, where, in any digital implementation, its period must be a whole number of sample durations. q is an arbitrary initial phase of the modulation function. Analytically, groups from this integral family can be combined to form simple results. Specifically:

$$G^h_s = I^h_{ss} + I^h_{cc} = A\,\mathrm{sinc}^2(r)\frac{r^2}{r^2 - h^2}\sin(\phi - 2\pi r) \tag{3}$$

$$G^h_c = I^h_{cs} + I^h_{sc} = A\,\mathrm{sinc}^2(r)\frac{hr}{r^2 - h^2}\cos(\phi - 2\pi r) \tag{4}$$

Here r is the frequency ratio of the input sinusoid, defined as:

$$r = f/m, \tag{5}$$

so that $r = 0$ when $f = 0$ Hz and $r = 1$ when $f = m$ Hz.

While the numerical evaluation of double integrals is expensive, these particular groups can be evaluated recursively as follows. Equations (3) and (4) remain true irrespective of the initial phase q of the modulation function in (2). Accordingly, it is possible to evaluate each integral in a 'sliding window' arrangement whereby only the oldest product value (data x modulation function) is removed and the newest value computed and included in the updated integral value. Using this approach, it is possible to evaluate G^h_s and G^h_c efficiently, so that the computational cost is low and independent of the window length in samples.

Figure 1 illustrates the structure of the Prism, implemented as two layers of integration blocks. It accepts an input signal $s(t)$ and generates up to two outputs G^h_s and/or G^h_c. The symbol on the right may be used to represent the Prism in diagrams of more complex signal processing arrangements. It will be noted that the two outputs of the Prism (3) and (4) are orthogonal, facilitating the calculation of frequency,

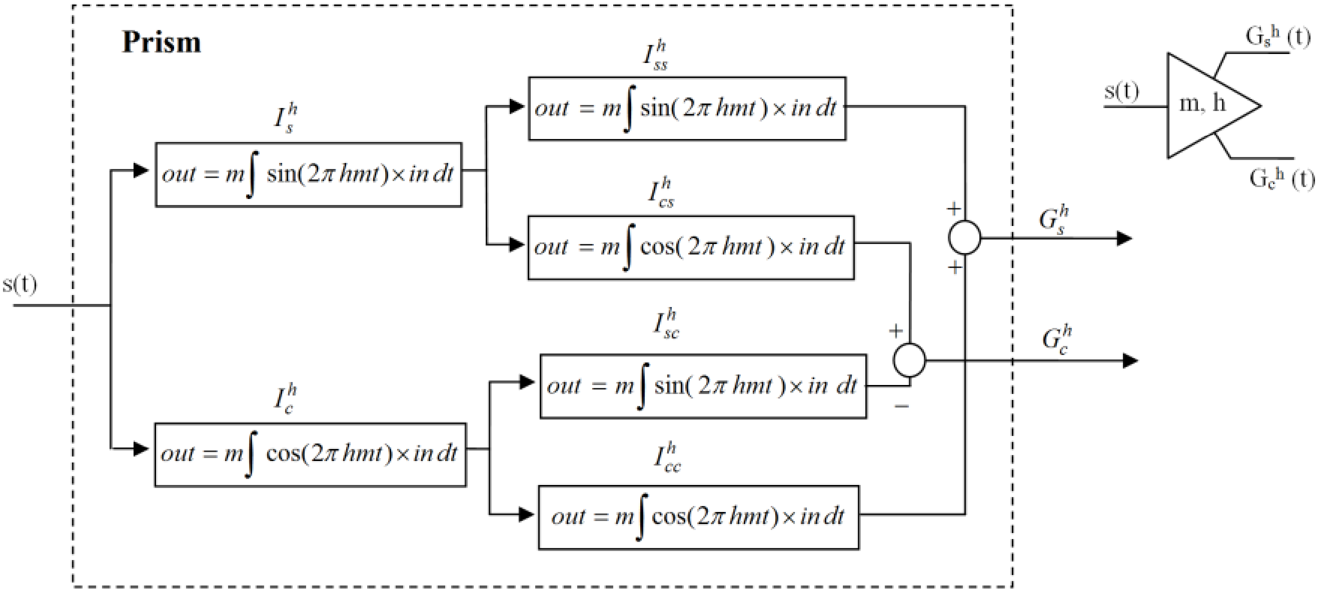

Figure 1: Prism Implementation and Symbol.

phase and/or amplitude information of the underlying signal. Figure 2 shows how the gains of G_s^h and G_c^h vary with frequency for h = 1. Notches occur at every multiple of m Hz, including DC. Note also that there is no conventional 'pass band' where the gain is constant. The linear phase and varying gain characteristics of the Prism outputs facilitate a variety of techniques such as low pass, bandpass and notch filtering. Several trackers have been developed to calculate the frequency, amplitude and/or phase of a sinusoidal signal. For example, the Recursive Signal Tracker (RST) has a tracking performance close to the Cramer-Rao Lower Bound [1] despite its low computational load. A conference paper [2] outlines some Prism signal processing techniques, and their use for tracking frequency components in ultrasonic pulses for a pressure sensor validation application.

FUEL INJECTION MONITORING

Prism signal processing has been used to develop an application of Coriolis mass flow metering for tracking fuel injection in a laboratory diesel engine. Here, fuel pulses as short as 1 ms are injected into a test cylinder at pressures of up to 100 MPa in a noisy mechanical environment (Figure 3). Working with a conventional commercial flowtube (Rheonik RHM 015, rated to 110 MPa), a new prototype transmitter has been built based around the Zynq-7000 chip [3], in which one of the two ARM Cortex-A9 processors is dedicated to measurement calculation, and where sensor data is sampled and flow measurement values are generated, at 48 kHz. This measurement update rate represents a significant advance on previous 'fast' Coriolis meter transmitters (e.g. 1.5 kHz [4]).

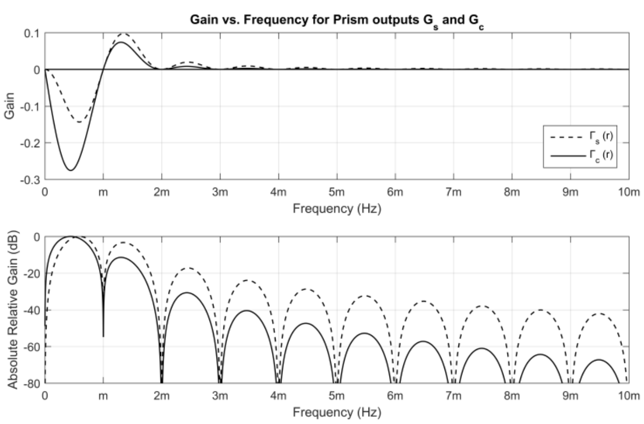

Figure 2: gains of Prism outputs G_s^h and G_c^h for h = 1.

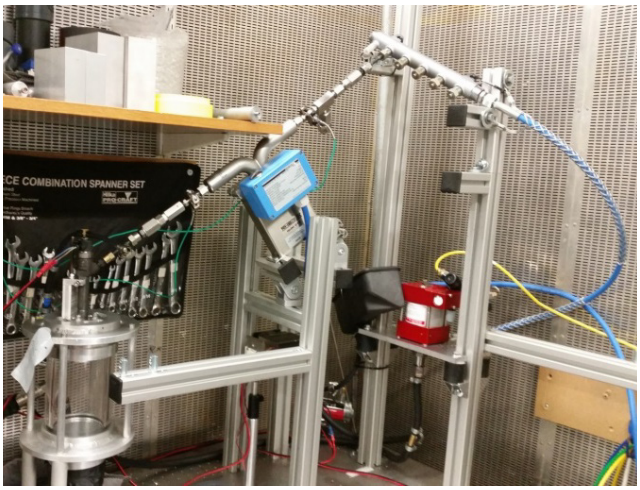

Figure 3: Experimental set up: high pressure diesel fuel line, Coriolis flowtube, injector, cylinder.

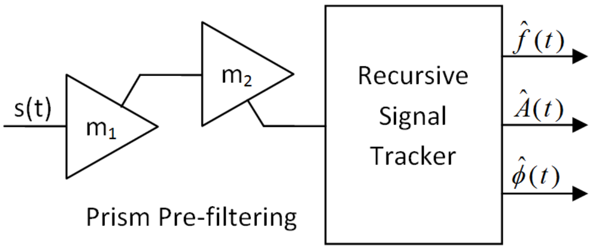

Figure 4. Signal processing scheme for one sensor chamnel of a Coriolis meter, including notch filtering and a Recursive Signal Tracker.

A Prism-based signal processing scheme for the Coriolis meter (Figure 4) includes a tracker for each sensor signal and notch filtering to remove undesired modes of oscillation excited by external mechanical noise. The flow measurement is derived from the difference in the instantaneous phases measured on the two sensor signals. This system is able to detect 1ms fuel pulses distinctly at engine speeds of up to 4000 RPM. Figure 5 shows the effectiveness of notching out the undesired frequency components by comparing the phase difference measurements obtained on the same raw sensor data set with and without the notch filtering.

Figure 6 shows the same flow pulse train in detail, with the noisy data removed. While each pulse is detected distinctly, there remain significant further challenges to overcome in order to obtain precise and accurate flow measurements. A limiting factor on the current system is the relatively low flowtube oscillation frequency (around 150 Hz). This leads to a 'smearing' of each 1ms flow pulse over an extended period of time (typically 16 ms). It is expected that the use of higher frequency flowtubes (say towards 1 kHz) would result in better measurement tracking of the fuel injection pulses. A consortium of interested parties is currently preparing a research project to develop new laboratory instrumentation for the automotive industry based on this approach.

As the Coriolis example illustrates, Prism signal processing is suited to a wide range of resonant sensor systems, and can be used to provide a step change in measurement update rates compared with conventional FIR techniques for a given computational budget.

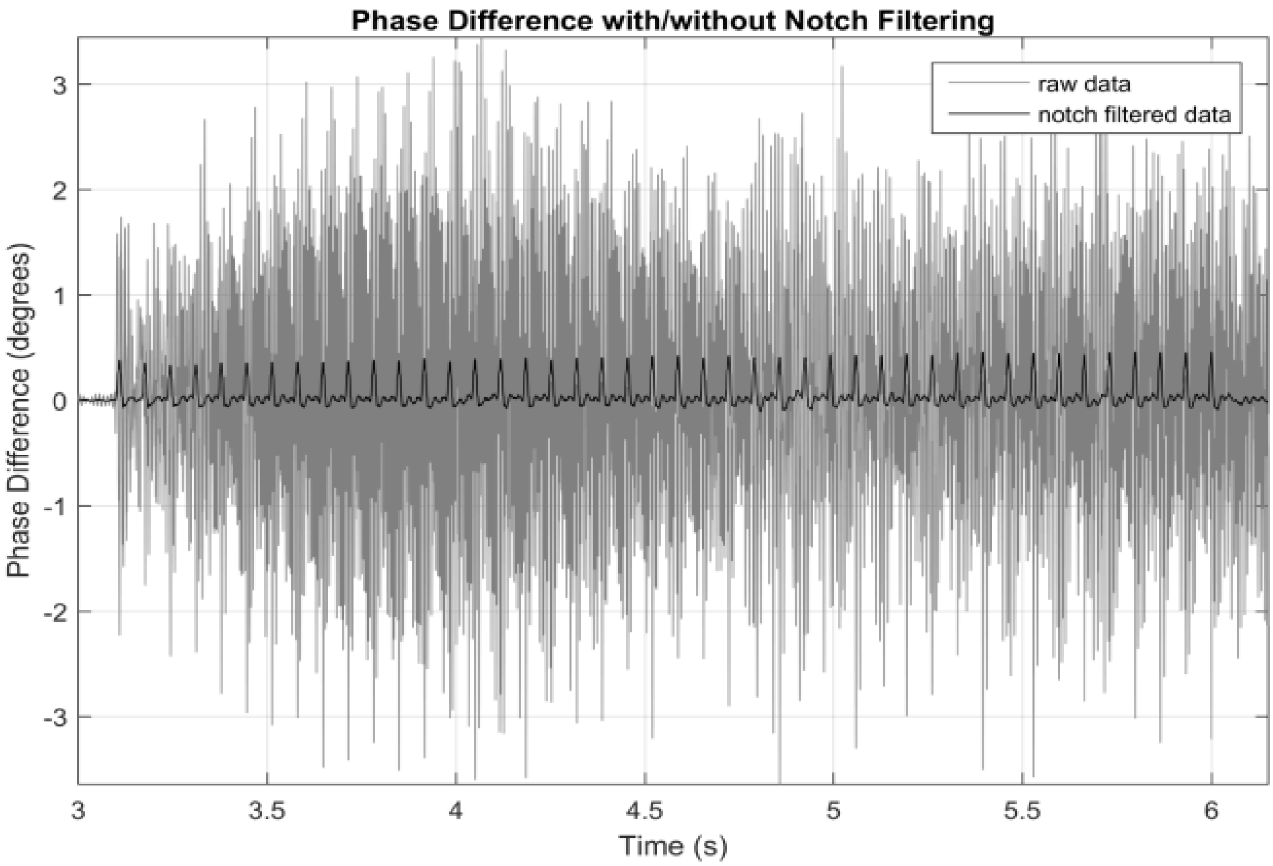

Figure 5. Phase difference measurement from a prototype Coriolis mass flow meter in response to a sequence of 1 ms fuel pulses: wth and without Prism-based notch filtering.

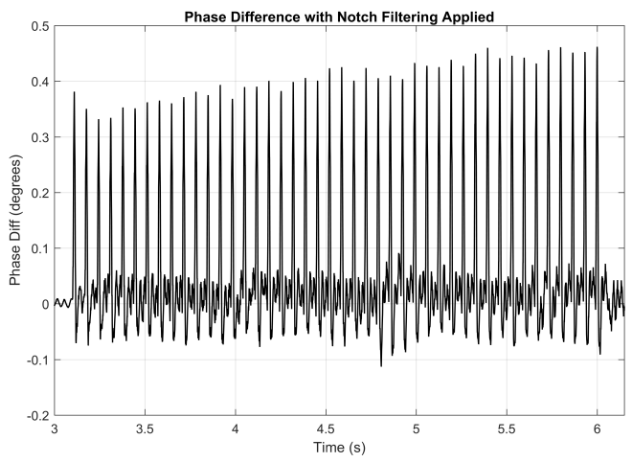

Figure 6. Phase difference measurement (detail).

CONCLUSIONS

Prism signal processing is a new FIR filtering technique which, by providing a recursive calculation with orthogonal outputs, facilitates rapid and flexible signal processing. Note also that as the filter 'coefficients' of the Prism are linearly spaced sine and cosine values, Prism reconfiguration (for example to adjust the frequency range over which it operates) is straightforward, and as a general rule of thumb, any device capable of running a Prism should be able to design one. This offers a significant advantage over conventional FIR filtering, where filter design is computationally expensive and almost invariably an offline task.

The Prism is suited to a wide range of applications, particularly those entailing signals with one or more discrete frequency components, even where these frequencies vary with time. For a given computational budget, Prism signal processing may afford a substantial increase in measurement update rate: in the Coriolis example, the update rate increased by a factor of over 100 times compared with conventional commercial devices. These capabilities match the signal processing requirements for high frequency resonant devices used in microfluidic applications.

A patent on Prism signal processing techniques has been filed by Oxford University [5]. We would welcome interest from potential partners in the microfluidic community to develop new applications.

REFERENCES

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