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Technical Paper

Operation and verification of a dual-mode Coriolis meter using Prism Signal Processing

Manus Henry, University of Oxford, Coventry University
Michael Tombs, University of Oxford
Feibiao Zhou, University of Oxford
Sakethraman Mahalingam, Aramco Overseas Company

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1 INTRODUCTION

Conventionally, the Coriolis meter flowtube is driven by its electronic transmitter to oscillate at the natural resonant frequency of a specific mode of mechanical vibration. However, the mapping (calibration) from the observed phase difference/time delay to the corresponding mass flow rate depends upon the ratio of this frequency to that of an adjacent mode of vibration, which is typically not directly measured. This frequency ratio issue is an important constraint on flowtube design and manufacture, whereby it is often a goal to ensure that the ratio is kept approximately constant over the range of resonant frequencies corresponding to the operating range of fluid densities for the meter. During actual meter operation, this frequency ratio is assumed rather than measured, as only one of the modes is actively stimulated and observed, so that measurement accuracy depends (in part) on how well the frequency ratio behaves in accordance with the presumed model. A variety of environmental factors, including dynamic changes in temperature, pressure, fluid properties (including gas entrainment) may in practice impact this assumed frequency ratio, which can therefore become an important source of measurement error.

In more recent developments, prototype meters have been developed which operate in more than one mode of vibration, offering the possibility of actively tracking the frequency ratio. There are many potential benefits, including active correction of the meter calibration based on the actual frequency ratio, but also meter diagnostics, and perhaps in the longer term a relaxation of flowmeter design constraints, enabling lower cost and/or lower pressure drop. The main challenge is the need for signal processing capable of separating and tracking the two or more modes of vibration in a way that is fast enough for real-time flowtube control, while also providing sufficient measurement accuracy.

This paper describes recent developments in Prism signal processing applied to Coriolis metering. A prototype transmitter drives a commercial Rheonik flowtube in two modes of vibration simultaneously, where the modes are only 15 Hz apart. Good precision and linearity is observed in the phase difference for both modes against flow rate, supporting measurement validation. A new Prism-based FFT calculation provides a precise spectral analysis of the meter operation and of its environment. Mode frequencies from the two independent vibration sensors agree by up to 1e-8 Hz, allowing precise tracking of the true frequency ratio for the purposes of on-line calibration and measurement validation. Additional sensor signal components, such as mains noise and the vibration mode of another Coriolis meter, may also be identified and monitored, without loss of measurement quality, demonstrating the potential of using the meter as a 'window on the plant'.

2 PRISM SIGNAL PROCESSING

Prism Signal Processing (PSP) was developed by the Advanced Instrumentation Research Group at Oxford, based on the experience of developing prototype instrumentation, primarily Coriolis metering, over the previous three decades. The Prism [1] is a signal processing block that performs Finite Impulse Response (FIR) filtering with a recursive calculation, significantly reducing computational cost compared with conventional, convoutional-based FIR filtering. Networks of Prisms can be used to perform a variety of signal processing tasks, including bandpass, lowpass and notch filtering, and 'tracking' i.e. the calculation of frequency, phase and/or amplitude of an isolated sinusoid.

PSP has been used to implement novel applications of Coriolis metering. For example, a prototype system has demonstrated the tracking of 1ms fuel injection pulses when installed in an internal combustion engine lab test facility [2,3], despite fast flow transients, the low flowtube oscillation frequency, and the high levels of mechanical noise. A key to achieving this performance is the use of Prism-based Dynamic Notch Filtering (DNF) [4,3], which removes unwanted signal components, where the notched frequencies can be selected in real time.

A more recent development has been the use of PSP as a design tool for convolutional filters. Prisms are computationally efficient when providing sample-by-sample updates, but if a reduced update rate is acceptable, then a convolutional form may offer further significant reductions in computing requirements. Section 3 describes how this low-cost method has been used on a prototype transmitter to drive a Rheonik Coriolis flowtube in two modes of vibration simultaneously. The convolutional form also supports the novel FFT calculation, which may be used to verify proper flowtube operation and implement condition monitoring more broadly; this is described in Section 4.

3 DUAL MODE FLOW MEASUREMENT

A 60mm diameter Rheonik flowtube has been coupled to a prototype transmitter which drives the flowtube in two oscillation modes simultaneously while calculating independent mass flow measurements using the data from each mode. The two modes are close to one another: the oscillation frequencies are approximately 83 Hz & 95 Hz when the flowtube filled with air, and 75 Hz & 86 Hz with the flowtube filled with water. Having vibration modes in such close proximity results in large phase differences with flow rate (so the 'measurement signal' is strong), but the signal processing challenges of separating the two modes are significant. As discussed in [2,3], there are also tradeoffs between noise rejection and dynamic response to be considered. As the Coriolis meter acts as a control system, the measurement of frequency, phase and amplitude must be fast enough to enable the control system to maintain stable flowtube oscillation. Conventionally, these parameters are tracked using a signal processing technique with a suitably fast dynamic response, while (perhaps filtered) averages of the same values are used to provide process measurements at a slower rate.

In the approach adopted here, different measurement techniques are used for flowtube control and process measurement. Figure 1 shows the frequency response of a Prism-based narrowband lowpass filter suitable for process measurement for this flowtube. The filter is 'lowpass', as frequencies above 11 Hz

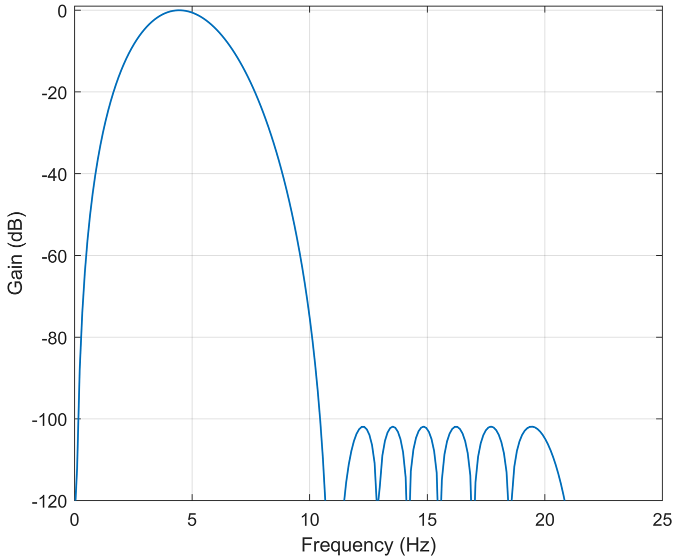

Fig. 1 - Prism Low Pass filter for process measurement

are attenuated by more than 100 dB, however all Prism-based filters have zero gain at 0 Hz.

The filter peak is at approximately 4.5 Hz, where the gain is unity. After the analog sensor signals have been digitized via twin analog-to-digital converters, heterodyning is used to shift the frequency of each mode into the filter passband. As the passband is narrow, when one mode is shifted to the filter peak then the other mode falls into the filter stop band, ensuring there is no modal interference. Figure 1 shows the low pass filtering stage; to calculate the frequency, phase and amplitude parameters an additional Prism tracking layer is used (similar to the scheme described in [5]). Filters are implemented in convolutional form using 12 kHz sampling with a filter duration of approximately 1s (resulting in 0.5s measurement delay). Measurement results can be generated at higher frequency by running multiple versions of the filter in parallel, with staggered starts and ends. In the implementation described here, measurement updates are provided at 10 Hz.

Figures 2 and 3 shows experimental results for dual mode operation. In Fig. 2, the observed phase difference is plotted against water flowrate. Each point is based on approximately 1 minute of data, and each flowrate experiment is repeated three times. The zero offsets are stable and have been removed. Good linearity is observed for both vibration modes. The phase difference values are high (up to 4.6 degrees), as expected given the close proximity of the mode frequencies. Even these initial results suggest the potential for meter self-validation: independent estimates of the process mass flow rate may be generated from each vibration mode for cross-checking and verification. Figure 3 shows the vibration frequency of each mode for the same flow experiments. These results simply demonstrate that the modal frequencies are stable with

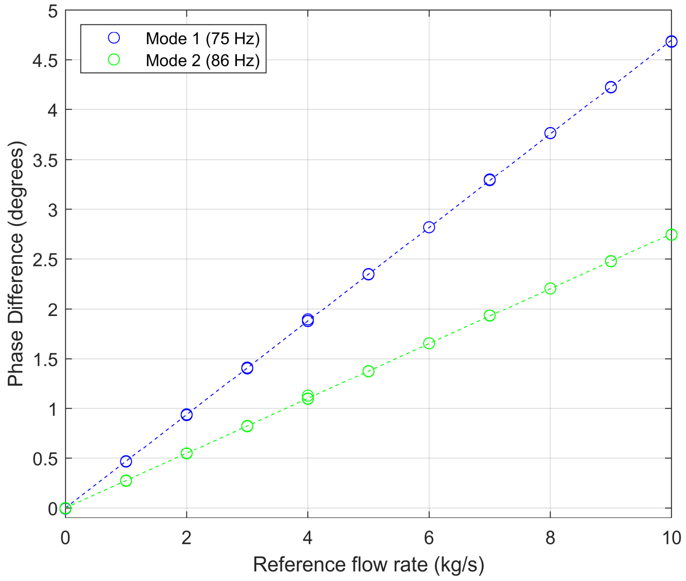

Fig. 2 – Mass flow calibration for dual mode operation

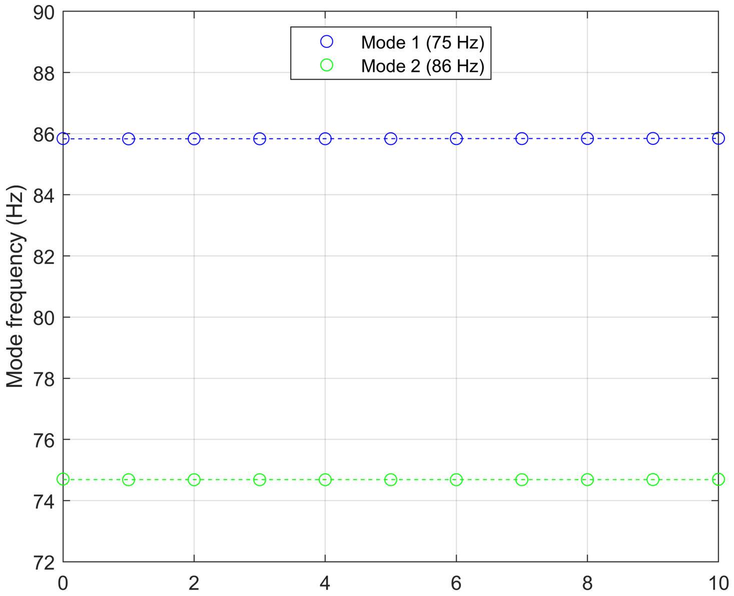

Fig. 3 – Mode frequencies against flow rate for dual mode operation

flowrate. Developing density and temperature calibrations for the dual mode meter will follow. Nevertheless, these initial results show the basic feasibility of a dual mode Coriolis meter with the potential for cross-checking measurement results between modes.

While this signal processing scheme can successfully separate and derive measurement data, from each of the two modes, its dynamic response is too slow to enable stable control of the flowtube operating in dual mode. Accordingly, an alternative Prism-based scheme may be used to generate parameter values with a faster dynamic response, but with poorer noise suppression. This filter structure combines the same Prism low pass filter shown in Fig. 1, with a wider pass band, together with a dynamic notch filtering layer [4]. Instead of using heterodyning and a narrow passband to separate the modes, dynamic notching is used, whereby a suitably weighted linear combination of parallel filter outputs can notch out one unwanted node. In a parallel path, a different linear combination is used to notch out the other mode. Weightings can be selected in real time to match the current oscillating frequencies of the flowtube, so that a fixed set of filters can provide notching across the full operating range of the flowmeter.

Figure 4 shows how this filtering scheme can provide different frequency responses to match the current oscillation modes. In the upper plot, frequencies corresponding to air density are shown: one filter weighting (in green) notches the lower mode frequency at 83 Hz, while provides unity gain for the high mode frequency at 95 Hz. The blue curve uses a different weighting to notch the higher mode and provide unity gain at the lower mode. In the lower plot the same mode separation is achieved for the frequencies associated with water density, through the use of appropriately selected weightings.

The filter of Fig. 4 includes the same low pass filter structure of Fig. 1, but there are clear differences. In Fig 4 the passband is wider, so that the stop band begins at approximately 187 Hz. This ensures the full range of oscillation frequences for both modes fall within the high gain region of the filter. Notching succeeds in separating the two modes, but this comes at the cost of reduced attenuation in the stop band: the -100 dB attenuation in Fig. 1 is reduced to around -80 dB in Fig. 4. An implementation of the filter structure in Fig. 4 results in a window length of approx. 66ms, with a measurement delay of 33ms: this combination of higher noise and faster dynamic response is suitable for dual mode oscillation control of this flowtube.

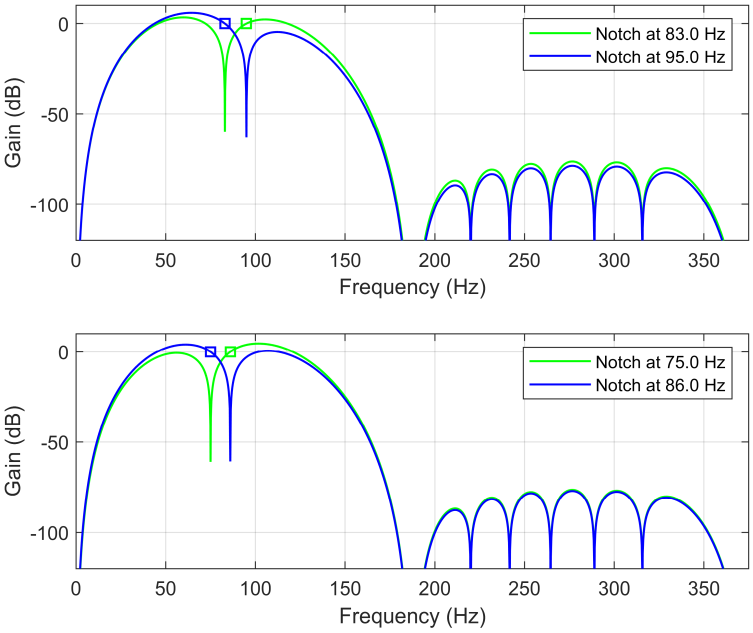

Fig. 4 - Prism Dynamic Notch filtering for flowtube control: (top) frequencies in air; (below) frequencies in water

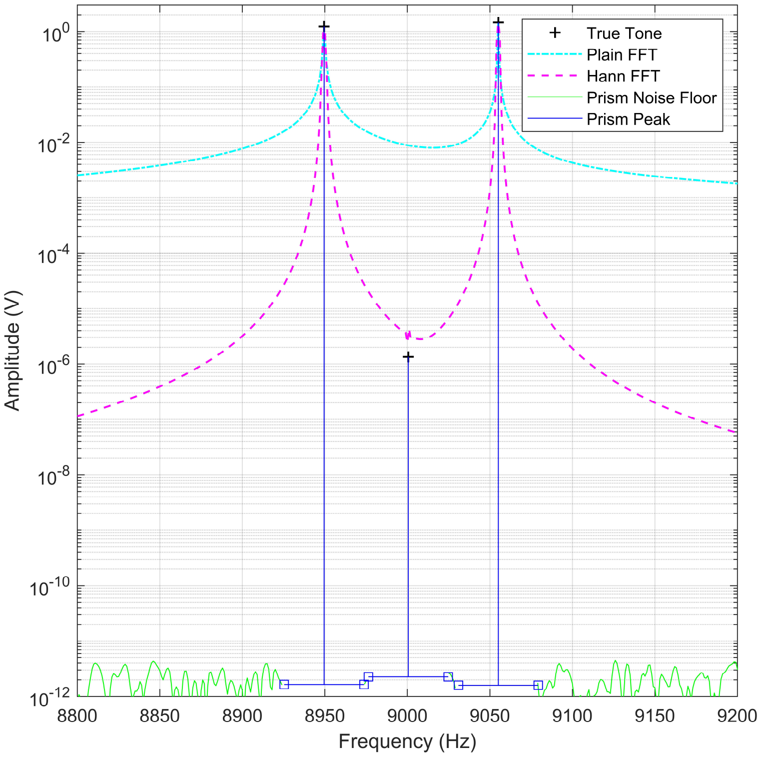

Fig. 5 - New Prism Fast Fourier Transform (FFT) technique (from [5])

4 CONDITION MONITORING VIA PRISM FFT

While the techniques discussed in Section 3 are appropriate for tracking specific modes of vibration for measurement and control, it is also desirable to monitor the operation of the flowtube more broadly across the whole frequency spectrum for the purposes of condition monitoring, whether to identifies potential issues in the instrument itself (e.g. wiring faults, erosion or corrosion), its interface to the processs (e.g. gas entrainment), or the wider environment (e.g. externally-induced vibration).

As discussed in [5], Prism-derived convolutional filters may also be used as windowing functions to provide ultra-precise spectral analysis via the Fast Fourier Transform (FFT). For example, Fig. 5 compares FFT results obtained in a simulated data set consisting of two high amplitude peaks with a low amplitude peak positioned between them on the frequency axis. The 'Plain' and 'Hann' FFT spectra are derived from conventional FFT analyses which can approximately locate and size the two outer peaks, but are unable to locate the middle peak. The Prism analysis generates a much lower noise floor, locates all three peaks, and, as detailed in [5], provides estimates of peak frequency, amplitude and phase correct to 12 significant places for the outer peaks and 6 decimal places for the low amplitude middle peak.

While such high precision results may be achievable with simulated, low-noise data, a further question is what may be achieved in a real measurement system. The Coriolis meter provides a useful test case for several reasons: (1) it is a resonant mechanical system with multiple modes of vibration, providing a rich spectrum to analyse; (2) precise spectral analysis may prove useful for validation of meter performance; (3) the Coriolis meter uses two sensors to monitor the (same) vibrating flowtube: spectral analyses of the two sensor data channels should therefore have identical peak frequencies; note that the amplitudes and phase values for each peak are likely to have different values for each sensor signal.

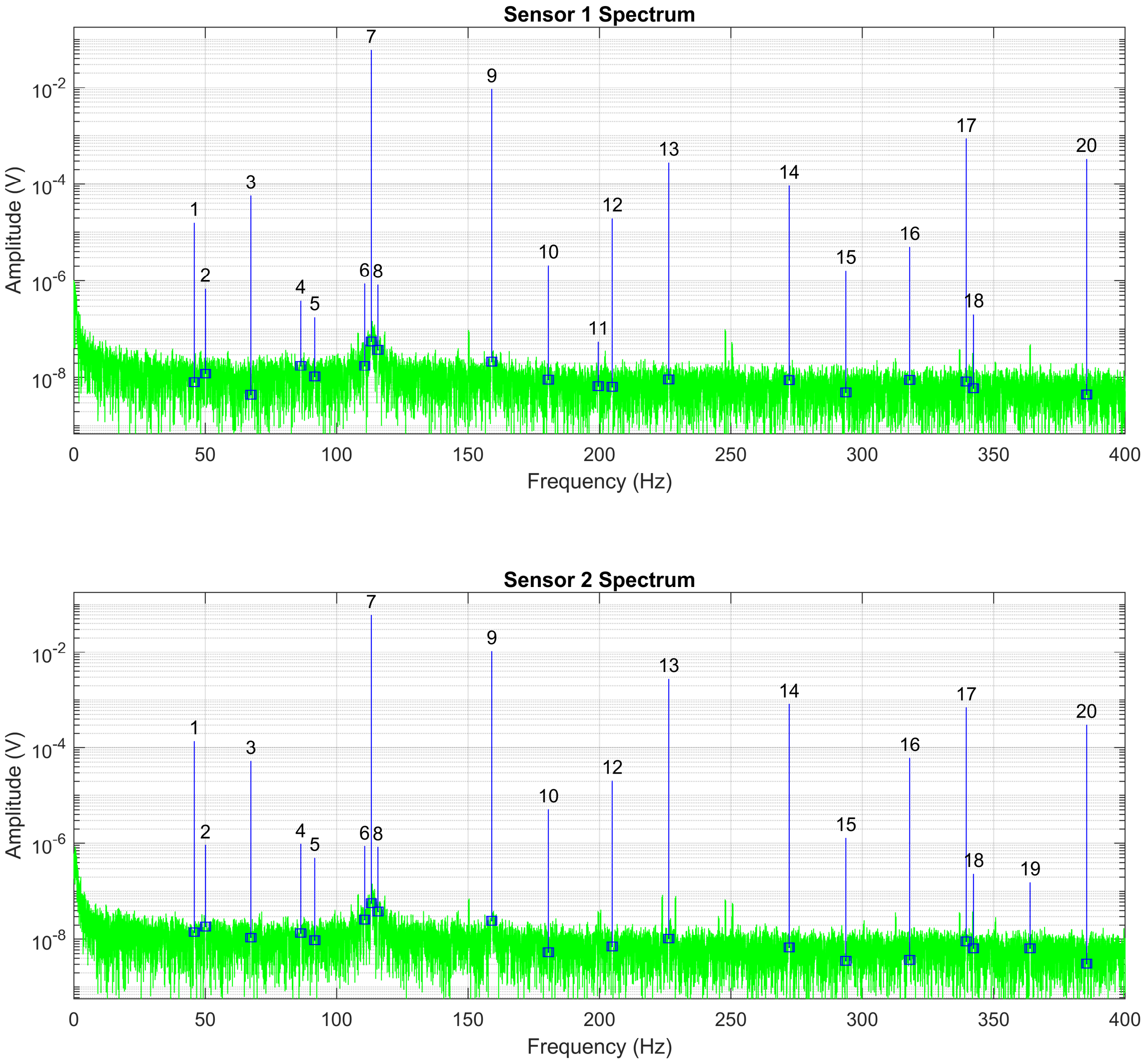

Fig. 6 - Prism FFT spectra from Coriolis meter operating in two modes of vibration (from [6])

Figure 6 shows the Prism FFT spectra obtained from the two vibration sensors of a 25mm diameter Rheonik flowtube, which is being driven to oscillate in two modes, at 113 Hz and 159 Hz respectively. During data collection the meter is filled with water, but the flowrate is zero. Sensor data is collected at 48 kHz for 21s, so that approximately 1 million samples are used to produce each spectrum. Corresponding peaks in the two spectra are given the same numerical label. Table 1 lists parameter values for a set of peaks identified in the spectra of the two sensor signals, which includes the two drive frequencies, labelled 7 and 9.

These parameters include the mode frequency, the amplitude for sensor 1, and the repeatability of the estimated frequency, defined as the difference in peak frequency calculated from the two sensor data sets.

The amplitude values of the detected modes vary from 60 mV down to 180 nV. Good repeatability is observed between the two spectra, with peak frequencies agreeing to better than 1 mHz in all cases. The two drive modes at peaks 7 and 9 agree to within 10 nHz. This high level of agreement suggests the Prism FFT can provide very precise assessment of spectral peak frequency for an operating Coriolis meter, as well as a useful means of cross-validating results between the two sensor signals.

Table 1 - Prism FFT analysis of dual mode Coriolis meter operation (from [6])

Tone no.	Frequency (Hz)	S1 Amplitude (V)	Repeatability (S1 - S2) (Hz)
1	45.82	1.59e-5	1.4e-5
2	50.09	6.79e-7	1.8e-4
3	67.36	5.78e-5	1.7e-6
4	86.35	3.87e-7	5.5e-4
5	91.65	1.79e-7	3.8e-4
6	110.66	8.69e-7	3.0e-4
7	113.18	6.00e-2	9.4e-9
8	115.70	8.26e-7	2.8e-4
9	159.01	9.32e-3	9.1e-9
10	180.54	2.07e-6	7.0e-6
12	204.83	1.95e-5	4.4e-6
13	226.37	2.80e-4	2.0e-7
14	272.19	9.31e-5	2.9e-6
17	339.55	8.75e-4	6.3e-8

The precision with which the peak frequencies are located can also assist in determining the likely source of each mode. Analysis has shown that most of the peak frequencies match, to less than 1 mHz, the sum of whole multiples of the drive frequencies 7 and 9. In other words, most peaks are beat frequencies or harmonics arising from the two drive modes. Peaks 6 and 8 are equidistantly spaced 2.52 Hz above and below the drive frequency 7. This suggests a low frequency beat around the drive frequency, possibly arising from the amplitude control system. Mode 2 is the mains frequency at 50 Hz. Finally, mode 4 was identified as being the resonant frequency of a separate Coriolis meter mounted in the same flow rig; its detection demonstrates the potential for using the high sensitivity of the meter as a 'window on the plant' when spectral analysis is performed using the Prism FFT technique.

The detection, cross-validation and source identification of spectral peaks provides a useful technique for performing condition monitoring, whether of the flowtube itself (e.g. drive modes, their beat modes, and other undriven flowtube modes – relative positions and amplitudes), the meter's local interface to the plant (e.g. supplied mains frequency) or of the wider environment, including other plant components (e.g. adjacent meters, pumps, etc).

5 CONCLUSION

This paper provides initial results demonstrating the feasibility of deriving flow measurement parameters simultaneously from each of two modes of vibration of a Coriolis mass flow meter, with potential application in meter verification and auto-correction. It has also demonstrated that precise spectral analysis of flowtube sensor data can support condition monitoring of the meter itself, its process interface and the plant environment. The improved measurement and spectral analysis capabilities are implemented using Prism Signal Processing.

The most significant technical challenge to overcome in the demonstrator is the close proximity of the two modes of vibration which are less than 15 Hz apart. For other flowtube designs, with wider mode separation, similar PSP schemes could be implemented providing, for example, a faster measurement response.

PSP generally, and the Prism FFT technique in particular, have broad potential for measurement and condition monitoring beyond Coriolis mass flow metering; new applications are currently under development.

6 REFERENCES

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