



Enhanced measurement validation via ultra-precise spectral analysis

Manus Henry^{a,b,*}

^a *Fluids and Complex Systems Centre, University of Coventry, Priory Street, Coventry CV1 5FB, UK*

^b *Department of Engineering Science, University of Oxford, Parks Road, Oxford OX1 3PJ, UK*

ARTICLE INFO

Keywords:

Measurement validation
Prism signal processing
Spectral analysis

ABSTRACT

Validating real-time measurements from a sensor/instrument is a multifaceted challenge. One goal is the provision of a dynamic uncertainty analysis, ideally incorporating the influence of instrument faults and the local environment. Such an analysis requires a broader model of instrument behaviour, accommodating non-ideal operational conditions. It may also require the analysis of a wider range of transducer data than when ideal, fault-free operation is assumed. A companion presentation describes an ultra-precise Fast Fourier Transform (FFT) technique. In this presentation, the technique is applied to a Coriolis mass flow meter, a resonant sensor with rich spectral characteristics. Typically, the meter is driven in a single natural mode of mechanical vibration; the frequency of this mode varies with fluid density, while the flow rate and density calibration coefficients assume a fixed frequency ratio to an adjacent vibration mode. A prototype Coriolis meter can operate in two modes of vibration simultaneously. The new FFT technique exhibits high precision (mode frequencies from the two independent vibration sensors agree by up to 10^{-8} Hz), allowing precise tracking of the true frequency ratio for on-line calibration and measurement validation. Additional transducer signal components, such as mains noise and external vibration, may be identified and monitored.

Videos to this article can be found online at <https://doi.org/10.1016/j.sctalk.2022.100094>.

Figures and tables



Fig. 1. Industry 4.0 and the Industrial Internet of Things.

* Corresponding author at: Fluids and Complex Systems Centre, University of Coventry, Priory Street, Coventry CV1 5FB, UK.
E-mail addresses: manus.henry@coventry.ac.uk, manus.henry@eng.ox.ac.uk.

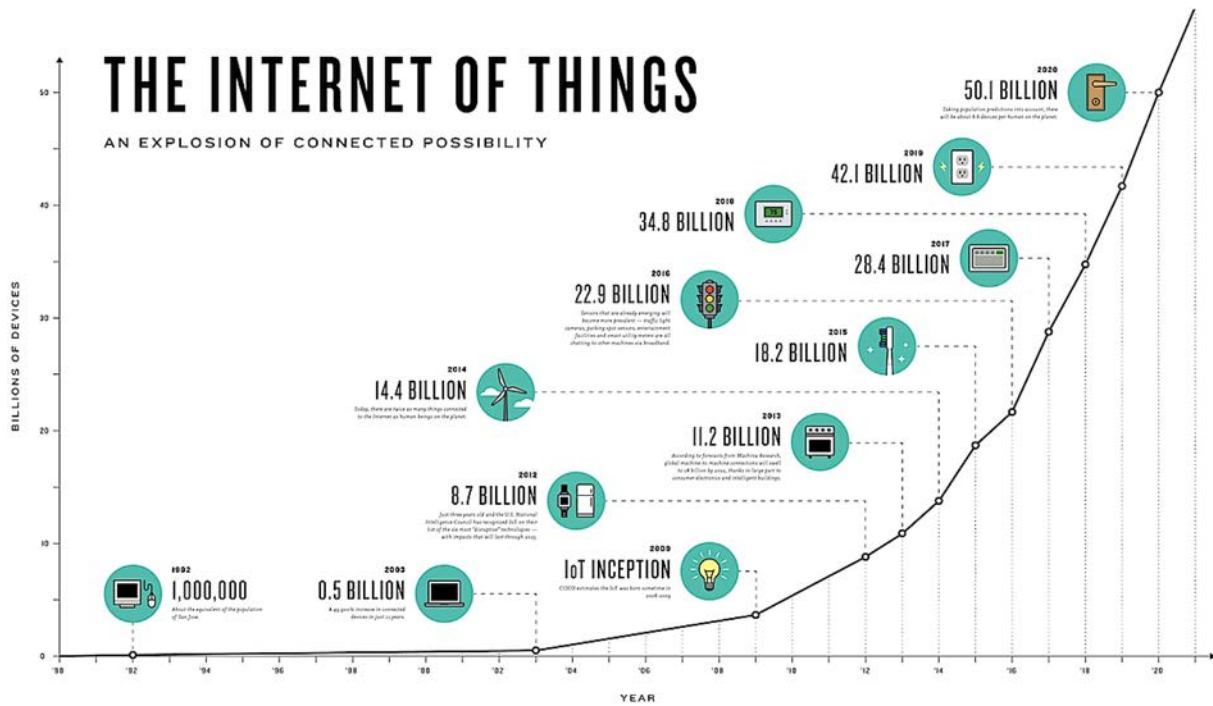


Fig. 2. The Internet of Things.
This plot illustrates the growth in volume of network-connected devices.

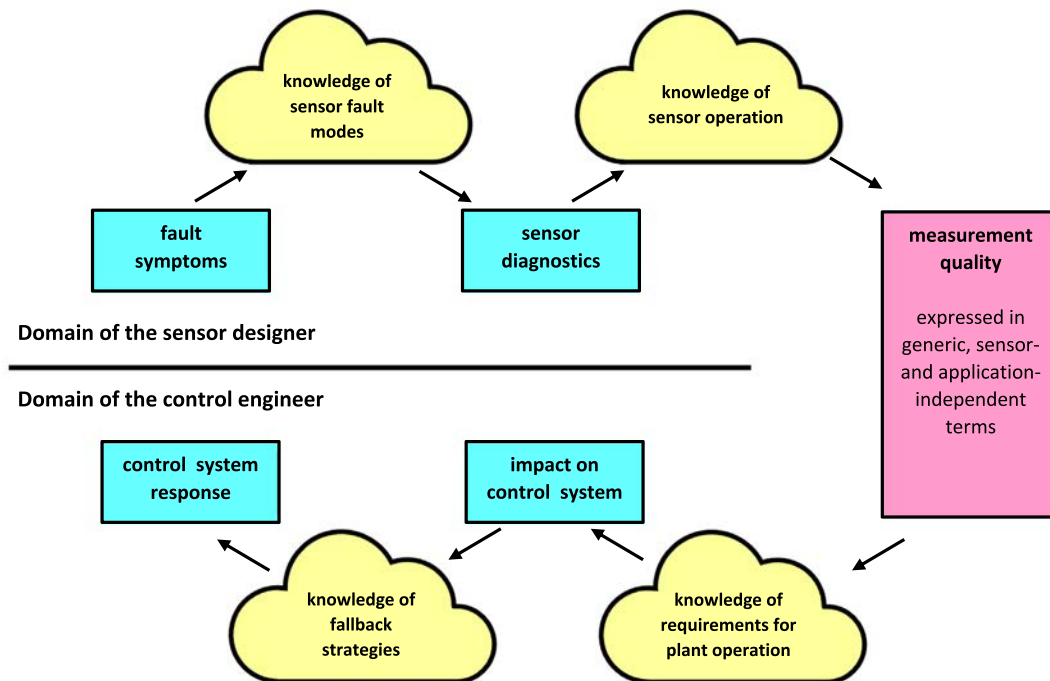


Fig. 3. Stages in Reasoning from Fault Symptoms to Control System Response [1].

There are several distinct knowledge sets required to interpret fault symptoms arising within an instrument through to the appropriate response of the control system within a particular application, partitioned between (at least) two domains of expertise: those of the sensor designer and of the control engineer. A description of measurement quality, independent of sensor and plant, may be a suitable metric for transmission between these two domains of expertise. Knowledge is required both from the sensor manufacturer (to determine what the fault is and how it affects the measurement) and from the operator or control system (to determine the impact of the loss of measurement quality on plant operation, and to select an appropriate operational response). It is generally understood that the sensor designer's knowledge is required to interpret fault symptoms to determine the sensor diagnostics (i.e. what faults have been detected). However, a further stage of interpretation is required to evaluate the resulting measurement quality. If expressed in generic, device-independent and application-independent terms, measurement quality is a suitable form of validity data to transfer from the domain of the sensor designer to that of the control engineer or operator.



Fig. 4. Examples of Sensor Validation Standards.
International Sensor Validation standards include British Standard BS-7986-2005 [2], Russian Standard GOST R 8.734-2011 [3], and VDI/VDE/ Richtlinien 2650-2006 (equivalent to NAMUR guideline 107 [4]).

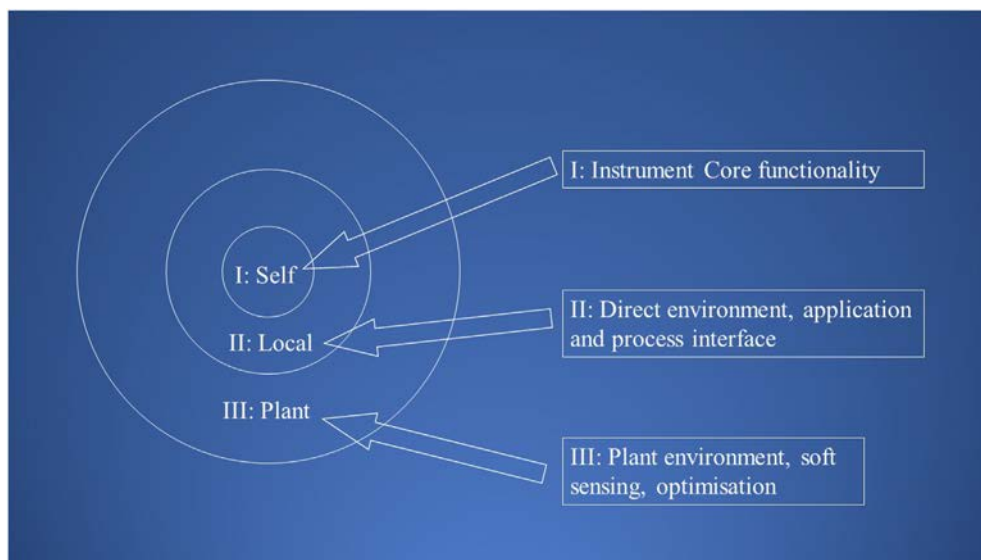


Fig. 5. VDI/VDE 2650 Layers.
The standard identifies three layers to be considered during diagnostic analysis: instrument core functionality; direct environment, including the application and process interface; and the plant environment, which may incorporate techniques such as soft sensing and optimisation.

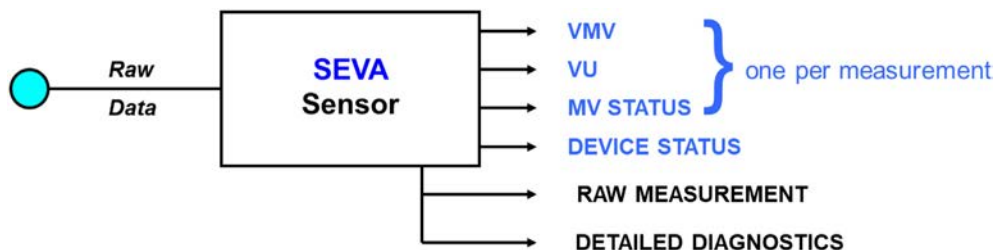


Fig. 6. Sensor Validation.
The self-validating or SEVA sensor [1] generates a standard set of metrics to describe the validity of each measurement value. These include the following parameters. The Validated Measurement Value (VMV) is the best estimate of the true process value: note that if a diagnosed fault has occurred the sensor is required to provide a corrected estimate. The Validated Uncertainty (VU) is a dynamic estimate of the uncertainty of the VMV, which should include the additional uncertainty introduced by any measurement correction. The Measurement Value Status (MV Status) is a generic indication of the diagnostic state of the measurement. The underlying philosophy and further details are explained in [1,5].

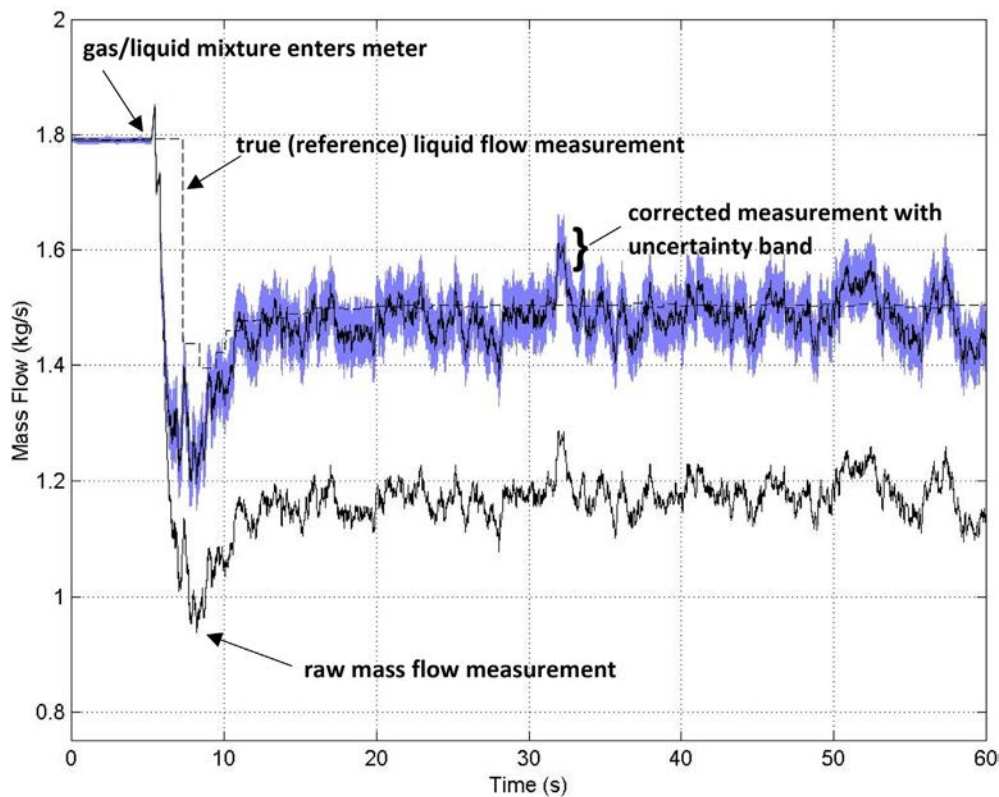


Fig. 7. Sensor Validation Applied to Coriolis meter with Two Phase flow.

Two phase (gas/liquid) flow is known to induce potentially large errors in the mass flow measurement generated by a Coriolis mass flow meter. This plot shows experimental data of a self-validating Coriolis meter responding to the onset of gas/liquid flow. The dashed line shows an independent reference measurement of the true liquid flow, which drops when the gas is added due to back pressure from the gas injection point. At the start of the sequence, before the gas is added, the Coriolis mass flow measurement is close to the reference measurement, and the blue uncertainty band around the measurement is narrow. The onset of the gas/liquid mixture induces a large negative error in the raw mass flow measurement, but a correction algorithm is applied which continues to provide a useful estimate of the true flow rate, with a significantly wider uncertainty band.

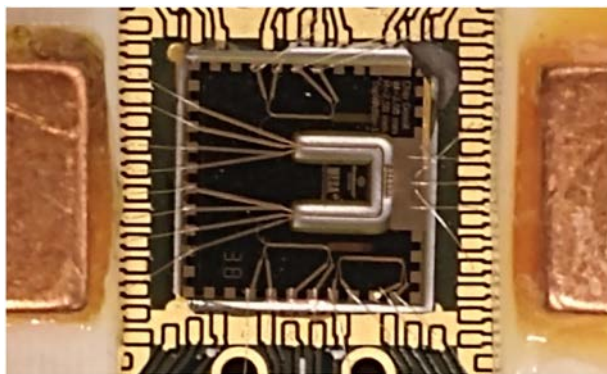


Fig. 8. Micromachined Coriolis flowtube.

A micromachined flow transducer operating using the Coriolis measurement principle.



Fig. 9. A large Coriolis meter.
A 400 mm diameter Coriolis flowtube, used to meter the supply of marine fuel.

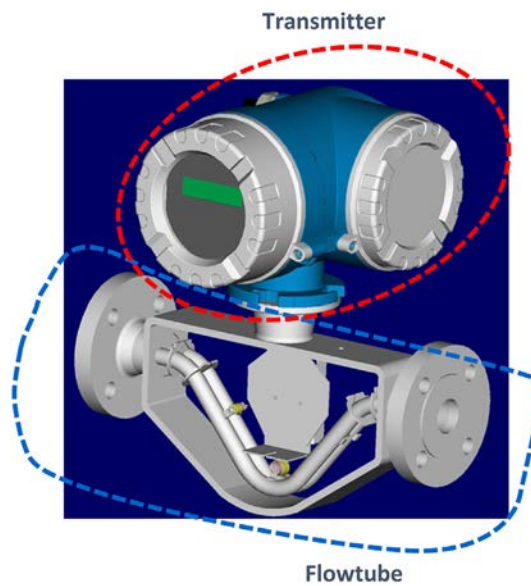


Fig. 10. Coriolis meter architecture.
A Coriolis meter consists of the mechanical flowtube through which the process fluid passes, and the electronic transmitter which drives the flowtube, performs measurement calculations, and performs diagnostics.



Fig. 11. An array of Coriolis meters in an industrial application.

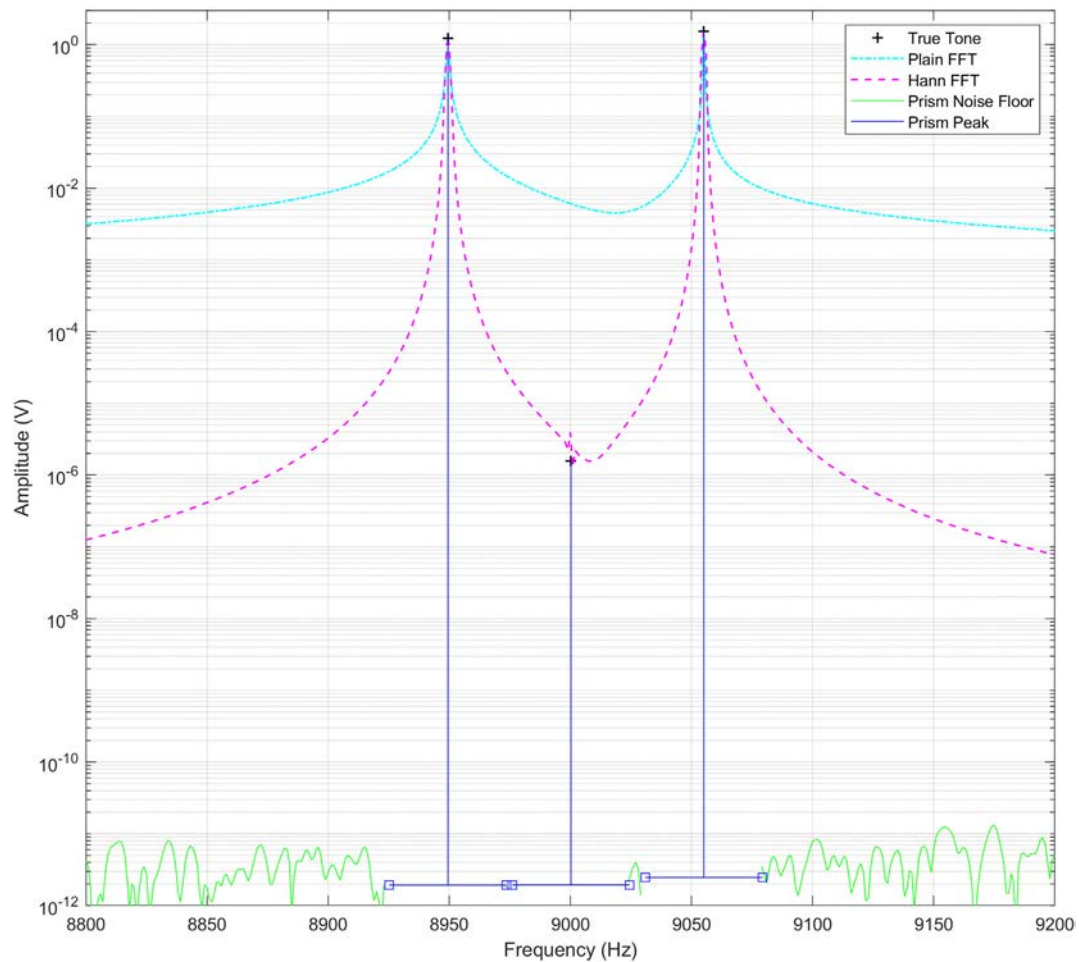


Fig. 12. New Prism Fast Fourier Transform (FFT) technique.

A companion presentation at MeSSAC 22 [6] describes a new FFT technique based on Prism Signal Processing [7], which provides ultra-precise spectral analysis. In the figure, a simulated signal with three true tones (marked with crosses '+') is analysed using three different FFT techniques. The conventional Plain FFT, and an FFT calculation applying the well-known Hann windowing function, are able to detect the high amplitude outer tones, but the middle, low amplitude tone is hidden. The Prism FFT technique is able to calculate the frequency and amplitude of the outer tones to 12 decimal places, and those of the middle tone to 6 decimal places. This example and the Prism FFT calculation are explained in detail in [6].

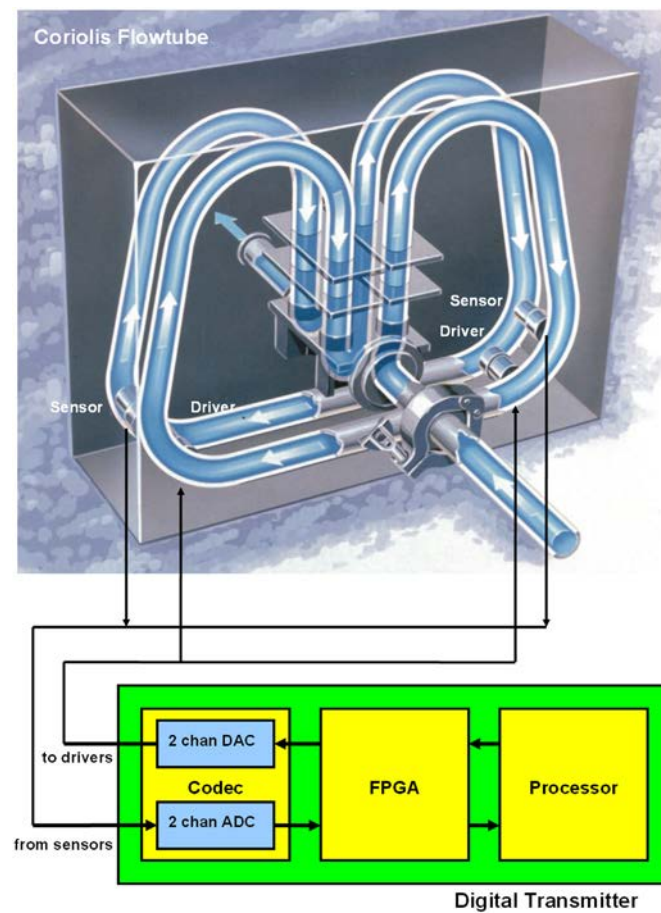


Fig. 13. Coriolis meter with digital transmitter architecture.

Modern Coriolis transmitters typically use audio quality digital components, for example 48 kHz dual channel analogue-to-digital (ADC) and digital-to-analog (DAC) channels [8]. With two independent sensing channels monitoring the same resonant flowtube, the Coriolis meter provides a useful example for evaluating the real-world performance of the new FFT technique. The tone frequencies of the FFT results from the two sensor channels should show good agreement.

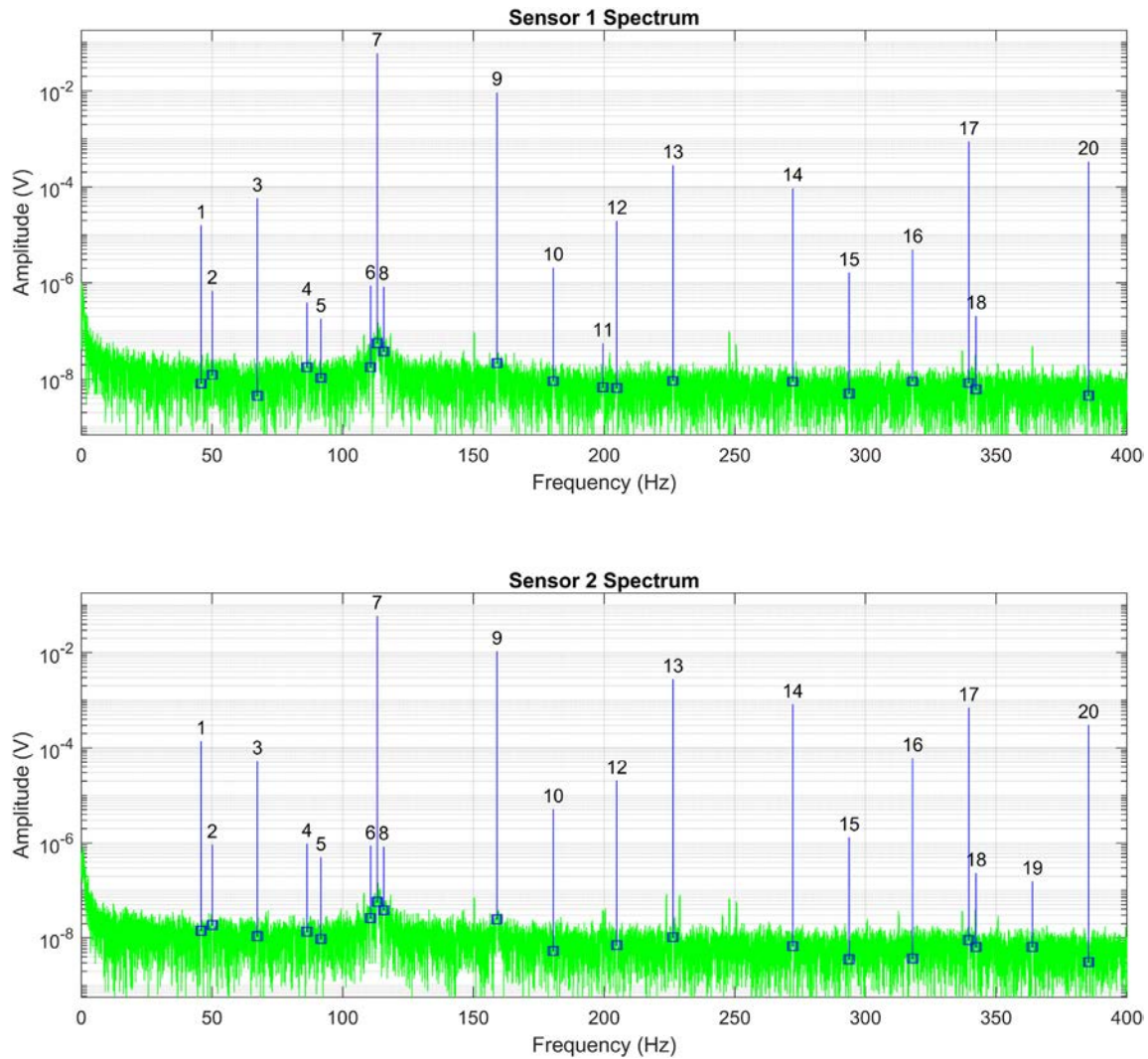


Fig. 14. Prism FFT spectra from Coriolis meter operating in two modes of vibration.

The plots show the Prism FFT spectra obtained from the two Coriolis meter vibration sensors (Fig. 13). The results are based on 24 bit, 48 kHz sampling over 21 s, yielding a data set of approximately 1 million samples collected simultaneously from each sensor. The identified tones (peaks) are numbered, so that the frequencies of the corresponding tones can be compared between the two sensor signals. Results are tabulated in Table 1. The Coriolis meter is being driven in two modes of vibration, labelled as tones 7 and 9.

Table 1
Prism FFT analysis of dual mode Coriolis meter operation.

Tone No.	Frequency (Hz)	Amplitude (V)	Repeatability (S1 v 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 table lists, for tones identified in both the sensor 1 and sensor 2 of the spectra shown in Fig. 14, the approximate frequency (to two decimal places only), the amplitude observed on Sensor 1, and the difference in frequency observed between sensor 1 and sensor 2. In all cases, the difference in frequency is less than 1e-3 Hz, even for low amplitude tones, while for the high amplitude tones such as Tones 7, 9 and 17, there is agreement to better than 1e-7 Hz.

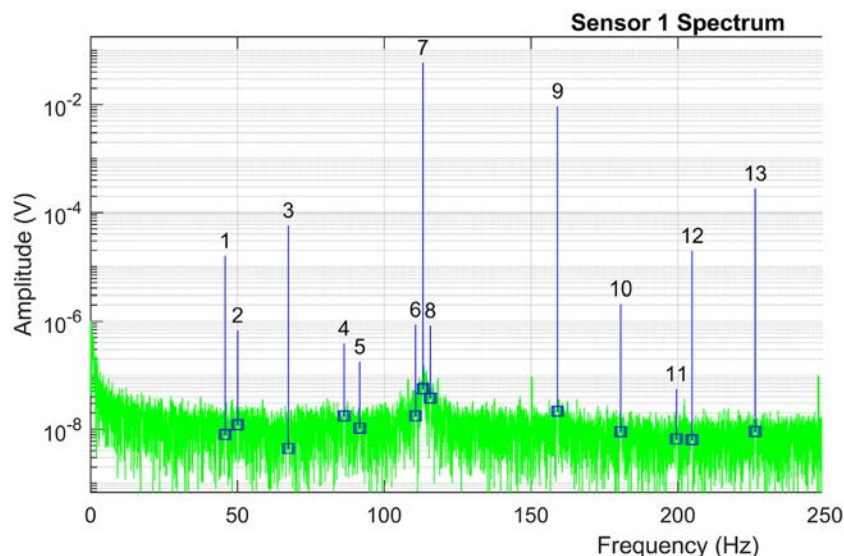


Fig. 15. Sensor 1 Spectrum detail.

The high precision with which tone frequencies are determined enables the identification of the source of each tone. All observed tones are sums of integer multiples of the two drive tones – Tones 7 and 9 – with two exceptions. Tone 2 is the mains frequency, at approximately 50.09 Hz, while Tone 4, at 86.35 Hz, is the resonant frequency of another Coriolis meter in the experimental rig. This demonstrates that the Prism FFT technique can be used not only to precisely monitor the operation of the meter itself (Level I in the NAMUR hierarchy of Fig. 5), but also its direct and plant environments (Levels II and III).

Manus Henry: all aspects.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

- [1] M.P. Henry, G.G. Wood, *Sensor Validation: Principles and Standards*, ATP International, October 2005 39–52.
- [2] British Standard Institute, “Specification for data quality metrics for industrial measurement and control systems”, BS 7886:2001, revised, 2005.
- [3] Russian Federal Agency for Technical Regulation and Metrology, “State system for ensuring the uniformity of measurements. Intelligent sensors and intelligent measuring systems. Methods of metrological self-checking” (in Russian), GOST R 8.734-2011, Russian Federal Agency for Technical Regulation and Metrology, 2011.
- [4] NAMUR, “Self-monitoring and diagnosis of field devices”, NE-107, User Association of Process Control Technology in Chemical and Pharmaceutical Industries, 2005 Revised 2017.
- [5] M.P. Henry, D.W. Clarke, The self-validating sensor: rationale, definitions and examples, *Control. Eng. Pract.* 1 (4) (1993) 585–610.
- [6] M.P. Henry, An Ultra-Precise Fast Fourier Transform (FFT), MeSSAC, 2022.
- [7] M.P. Henry, The prism: recursive FIR signal processing for instrumentation applications, *IEEE Trans. Instrum. Meas.* 69 (2020).
- [8] M.E. Zamora, M.P. Henry, Digital control of a coriolis mass flow meter, *IEEE Trans. Ind. Electron.* 55 (7) (July 2008).

Further Reading

- [1] Dimitris K. Iakovidis, Melanie Ooi, Ye Chow Kuang, Serge Demidenko, Alexandr Shestakov, Vladimir Sinitsin, Manus Henry, Andrea Sciacchitano, Stefano Discetti, Silvano Donati, et al., Roadmap on signal processing for next generation measurement systems, *Meas. Sci. Technol.* 33 (2022) 012002.
- [2] H.Y. Teh, A.W. Kempa-Liehr, K.I.K. Wang, Sensor data quality: a systematic review, *J. Big Data* 7 (2020) 11.
- [3] Taymanov, et al., Actual measuring technologies of Industry 4.0 and analysis of their realization experience, *J. Phys. Conf. Ser.* 1379 012049 (2019).
- [4] Y. Chen, D. Chen, T. Song, H. Lin, K. Song, Self-validating chemical sensor array and its application prospect in machine olfaction, 2020 IEEE 4th International Conference on Frontiers of Sensors Technologies (ICFST), 2020.
- [5] F. Sartori, R. Melen, F. Giudici, IoT data validation using spatial and temporal correlations, in: E. Garoufallou, F. Fallucchi, E. William De Luca (Eds.), *Metadata and Semantic Research. MTSR 2019. Communications in Computer and Information Science*, vol. 1057, Springer, Cham, 2019.



Manus Henry is Professor of Flow Measurement at the Centre for Fluid and Complex Systems, Coventry University and Director of the Advanced Instrumentation Research Group at the Department of Engineering Science, University of Oxford. He is the Editor-in-Chief of the *Flow Measurement and Instrumentation*. He is a member of the UK Government National Measurement System Programme Expert Groups for Flow Metrology and for Digital Metrology. He has over 130 granted patents, mostly in the field of Coriolis mass flow metering. He developed the Prism in pursuit of improved signal processing for instrumentation applications.