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Author post-print (accepted) deposited by Coventry University's Repository

Original citation & hyperlink:

Ibryaeva, O, Taranenko, P, Tombs, M, Zhou, F & Henry, M 2018, Matrix pencil method for coriolis metering with liquid/gas flow II: Experimental results. in 2018 IEEE Industrial Cyber-Physical Systems (ICPS). Proceedings - 2018 IEEE Industrial Cyber-Physical Systems, ICPS 2018, Institute of Electrical and Electronics Engineers Inc., pp. 434-439, 1st IEEE International Conference on Industrial Cyber-Physical Systems, ICPS 2018, Saint Petersburg, Russian Federation, 15/05/18.

<https://dx.doi.org/10.1109/ICPHYS.2018.8390744>

DOI 10.1109/ICPHYS.2018.8390744

ISBN 9781538665312

Publisher: IEEE

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Matrix Pencil Method for Coriolis Metering with Liquid/Gas Flow II: Experimental Results

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Abstract—Our companion conference paper describes the requirement for flexible, self-validating instrumentation to support the goals of Industrial Cyber-Physical Systems. For high-value instruments such as Coriolis Mass Flow (CMF) meters, this entails more sophisticated signal processing techniques to provide additional sources of diagnostic and measurement data, particularly in dealing with common, but difficult real-world conditions such as two-phase (gas/liquid) flow. A novel Matrix Pencil Method (MPM) was described, adapted to monitor two modes of vibration for the CMF flowtube, and its performance evaluated in simulation. In this paper, we present results from applying the MPM technique to experimental data.

Keywords— Industrial cyber-physical systems, measurement validation, oil and gas, Coriolis mass flow meter, signal processing, matrix pencil method, two-phase flow.

I. INTRODUCTION

The Coriolis mass flow (CMF) meter is a widely used industrial flow metering technology. Fig. 1 shows the main components – a mechanical flowtube through which the process fluid passes, and an electronic transmitter which is required to generate drive signals to maintain the oscillation of the flowtube at the natural frequency for one selected mode of vibration, while extracting from the sinusoidal sensor data the process measurement information. From a measurement perspective, the key parameters to be calculated are the resonant frequency (from which the density of the process fluid can be derived), and the phase difference between the two sensor signals, which yields the mass flow of the process fluid. Amplitude information is also required to facilitate control of the flowtube oscillation. A review of CMF developments over the last two decades is given in [1].

Our companion conference paper [2], describes the requirement for flexible, self-validating instrumentation to support the goals of Industrial Cyber-Physical Systems. For high-value instruments such as CMF meters, this entails more sophisticated signal processing techniques to provide additional sources of diagnostic and measurement data, particularly in dealing with common, but difficult real-world conditions such as two-phase (gas/liquid) flow. The classic Matrix Pencil Method (MPM), was adapted to match the characteristics of the CMF application to create a new technique Multi-Channel MPM (MCMPM), which showed improved performance over MPM in simulation. A key benefit

of all MPM methods is that, unlike conventional CMF signal processing techniques, they are able to track two or more modes of oscillation. This is potentially valuable in two-phase flow, where other natural modes of vibration may be excited by the high mechanical energy of the fluid mixture.

In this paper, we present results from experiments using a commercial flowtube and a research transmitter. Two types of experiment are performed. In the first, the flowtube is deliberately excited in two modes of vibration, in the absence of actual flow, to evaluate MCMPM tracking. In the second, experiments are carried out using air/water mixtures to compare the performance of MPM and MCMPM.

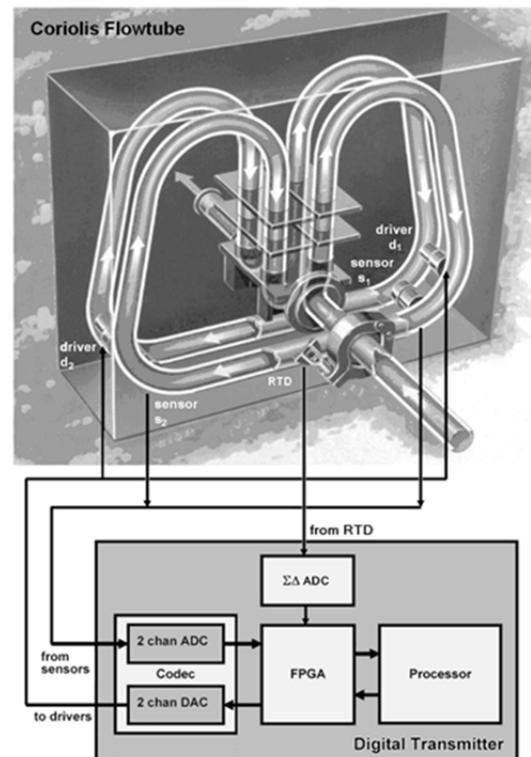


Fig. 1. Coriolis Mass Flow Meter (from [3]).

II. EXPERIMENTAL FACILITY

Experimental work was carried out at the Oxford flow laboratory. This has a water rig, into which a 15mm commercial flowtube (Fig. 2) was fitted. The rig has the capability of injecting air into the water flow ahead of the meter under test; traceable reference measurements for the mass flow rates of both water and injected air occur before the mixing point so that accurate values of the true mass flow rates of each phase are available. Pressure and temperature measurements at the inlet to the test flowtube enable the calculation of the water and air volumetric flow, and so the gas volumetric fraction (GVF) i.e. the percentage of gas by volume, can be calculated and controlled. The primary interest at this stage of the research is the ability of the MPM algorithms to track basic sensor signal properties (frequency, amplitude and phase difference) and so there is no assessment of flow measurement error associated with two phase flow. However, the liquid flow rate and GVF values reported for each experiment were controlled and recorded using traceable reference measurements.

The commercial flowtube is controlled using a new research transmitter developed at Oxford. Any CMF transmitter is required to perform two duties, acting as both a measurement and a control system: the flowtube must be supplied with a drive signal causing it to vibrate at its natural resonant frequency for the (at least one) selected mode of vibration; in addition the sensor signals must be analyzed to derive flow rate and density measurements, as well as to facilitate continuing flowtube control. An overview of a fully digital implementation of a Coriolis transmitter is given in [3].

The research transmitter used here has been developed to support next generation CMF metering techniques. For example [4], a commercial flowtube rated for high pressure (1000 bar) has been interfaced to the research transmitter in order to track diesel engine fuel injection pulses, as short as 1ms, by generating mass flow measurements at 48 kHz.

The transmitter is programmed by the research team. It includes two channels of 24 bit, 48 kHz ADC inputs to read the sensor signals, and two DAC channels with the same specification to generate flowtube drive signals. It has a large local memory and supports a web interface, so that detailed data records can be generated during experiments, including the raw sensor signals at the full sampling rate, which may subsequently be downloaded for off-line analysis.

As the CMF meter acts both as a control system and as a flow meter, there are particular difficulties in developing new measurement algorithms. Good flowtube control requires robust, accurate measurement of frequency, amplitude and phase; but without a well-controlled flowtube, developing and testing measurement algorithms is not possible. One common way of breaking the feedback loop is to use a signal generator to simulate flowtube sensor signals until both the new measurement algorithm and the corresponding drive signal generation are sufficiently reliable to operate directly with the flowtube. In this application, because the purpose is to compare MPM and MCMPM algorithms with sensor signals generated from experimental two-phase flow, a different

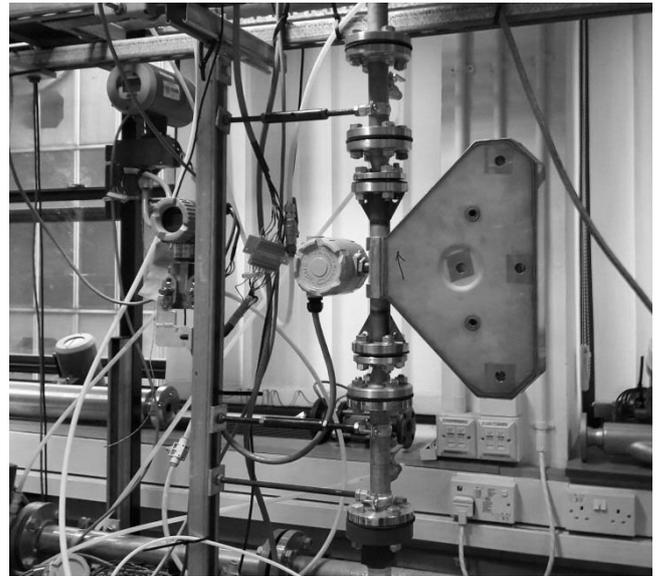


Fig. 2. Coriolis Mass Flow flowtube positioned in experimental rig

strategy has been adopted. The research transmitter has been programmed to monitor and drive the flowtube using a simple measurement algorithm, described below, which is sufficiently robust to maintain flowtube operation during two-phase flow. Sensor data generated during these conditions are recorded, and then analyzed off-line using the two MPM algorithms. At a future stage, once accuracy and robustness have been established, one or more MPM algorithms will be coded to run in real-time on the research transmitter.

The algorithm used to drive the flowtube during these experiments is one of the simplest techniques used for CFM: the sensor signals are bandpass filtered, allowing only the frequency range of the desired vibration mode to pass, and then the frequency and phase difference are calculated using zero-crossing (ZC) detection [5]. The amplitude is calculated using peak detection of the band-passed, and hence smoothed, sensor signal. The ZC method may be considered a basic benchmark against which other algorithms can be compared.

In the first experiment, the ZC algorithm is adapted to control two modes of vibration of the flowtube simultaneously. This is achieved by using separate bandpass filters to select the respective frequency ranges of the two different modes of vibration, followed by tracking of the frequency, phase and amplitude of each vibration mode in each sensor signal. The resulting drive signal is a combination of the desired control signal for each vibrational mode.

While this dual mode control [6] is performed only on a dry flowtube in this case, the application of dual mode control as a means of improving measurement performance in two phase flow is a major long-term goal for research; the natural affinity of the MPM family of techniques to handling multiple frequency components in a signal is one of the motivations for this particular work.

In the second and third experiments, the performance of classic MPM and MCMPM are compared in the case of low and medium GVF air/water mixtures.

III. EXPERIMENT 1: NO FLOW, DUAL MODE CONTROL

Figs. 3 – 6 show the results using a dry flowtube filled with air. The transmitter controlled the flowtube to operate with two modes of vibration simultaneously. In air, the first (and conventional) vibration mode is around 96.5 Hz; the controlled amplitude of oscillation was set at 0.2V. The second mode has a frequency of approximately 177.5 Hz, with the controlled amplitude of oscillation set to 10 mV.

Fig.3 shows a time series of data with its corresponding FFT. The time series is steady, while in the FFT peaks occur at the two modes, but also at their multiples. Specifically, the second harmonic of the lower mode (193 Hz) is close to the second mode of vibration (177.5 Hz). While this harmonic could also be tracked using the MCMPM techniques, here we use bandpass filtering to restrict analysis to the lowest harmonic of each of the two vibration modes. Fig. 4 shows both sensor signals in detail. These clearly display the modulation arising from the presence of the two modes of vibration.

Fig. 5 compares the parameter values calculated for the first mode of vibration by the ZC technique and the MCMPM technique. There is good agreement on the frequency measurement, with the MCMPM results showing lower noise. However, both techniques exhibit a significant oscillation in their phase difference measurement. These oscillations require further investigation and are most likely due to physical imbalances in the flowtube properties. Further adjustments to the MCMPM technique could be used to reduce or eliminate such oscillations. The amplitude results for the sensor 1 signal are broadly similar, but show a slight offset in mean value.

Figure 6 compares the parameter values calculated for the second mode of vibration, where the distinction between ZC and MCMPM is clear. While broadly agreeing on the mean value of each parameter and its change over time, the ZC technique shows a significantly higher level of measurement noise. The drift in amplitude over time is attributable in part to the action of the flowtube control. The large zero offset in the phase difference measurement is likely to be a function of the mechanical design and/or condition of the flowtube.

IV. EXPERIMENT 2: FLOW 0.3KG/S, 2.2% GVF

Figs. 7 – 10 compare the performance of classic MPM and MCMPM for a two-phase flow experiment with water mass flow 0.3 kg/s and GVF 2.2%. Sensor signal 1 (Fig. 7) shows amplitude variation over time and its FFT shows a low level of the second mode. Fig. 8 shows typical variation of the sensor signals in detail. Figs. 9 and 10 show the calculated parameter changes for the first and second modes respectively. Note that the ‘true’ mass flow and density of the water and air mixture passing through the flowtube varies over time and only the averaged value over a reasonable timespan (say 30s or more) is known (via the reference measurements). Thus the instantaneous variations shown in Fig. 9 are broadly plausible but cannot be verified directly. The MPM and MCMPM methods are mostly in good agreement, especially for amplitude, but with both frequency and phase difference the MPM method shows sporadic large deviations. For the second mode (Fig. 10), again there is broad agreement between the

two methods with spike occurring particularly on the amplitude measurement. However, the large swings in phase difference and frequency with either technique suggest the second mode measurements are subject to high levels of noise.

V. EXPERIMENT 3: FLOW 0.6KG/S, 15.6% GVF

Figs. 11 – 14 show the results with a higher liquid flow rate and higher GVF. The excited secondary mode has higher amplitude in the FFT (compare Figs 7 and 11), and this is reflected in the calculated value of amplitude (approximate 10 mV vs 1 mV, Fig. 14 vs Fig. 10). This in turn probably explains the more stable measurements of its frequency and phase difference. Again the classic MPM technique shows occasional spikes in the measurements, particularly for the second mode phase difference (Fig. 14), but otherwise there is broad agreement between the two methods.

VI. CONCLUSION

These early experiments demonstrate the potential for MPM-type algorithms to track multiple modes of CMF vibration during two-phase flow conditions, which could perhaps be combined with dual mode flowtube vibration control. The assumption of common poles in MCMPM appears to provide greater stability than the unconstrained classic MPM. While significant further theoretical and experimental work is needed to develop a robust algorithm, this work suggests a route for generating additional sources of diagnostic and measurement validation for this economically important flow metering technology, thus contributing to the requirements of Industrial Cyber-Physical Systems.

VII. ACKNOWLEDGEMENT

This work was conducted with the financial support of the Ministry of Education and Science of the Russian Federation of the Applied Scientific Research «Development of domestic mass Coriolis flow meter for oil and gas industry with the flow measurement function of multiphase flows», Agreement № 14.578.21.0191 from 03.10.2016. Unique identifier of the Applied Scientific Research is RFMEFI57816X0191.

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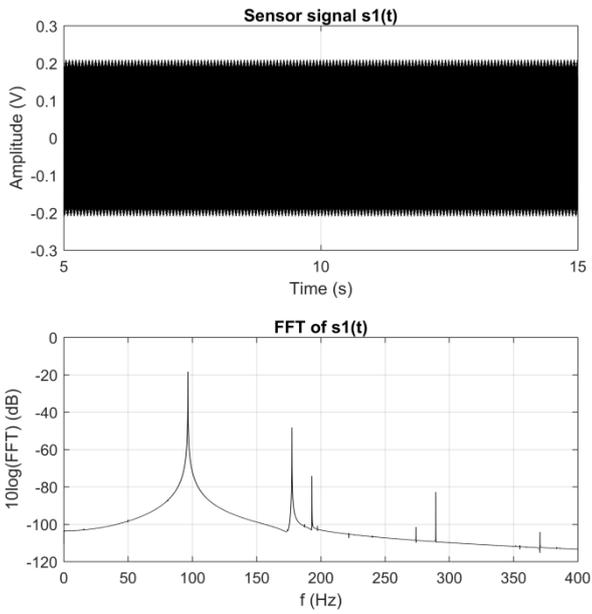


Fig 3. Sensor data and FFT for dual mode control, no flow

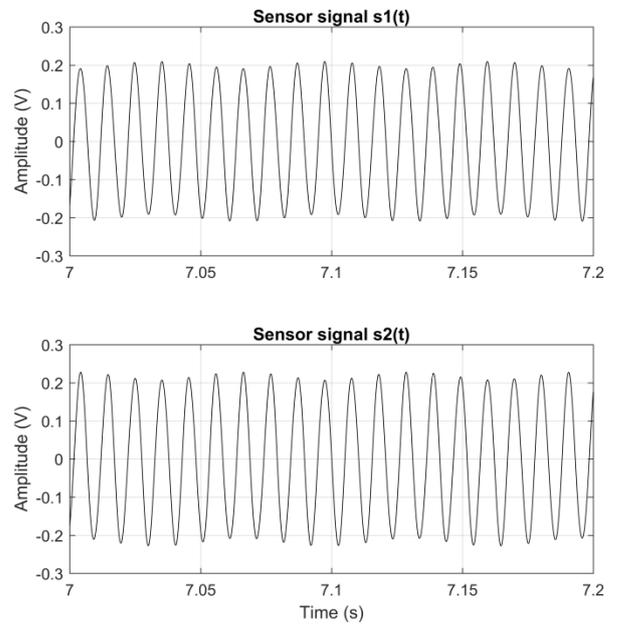


Fig. 4. Detailed sensor data for dual mode control, no flow

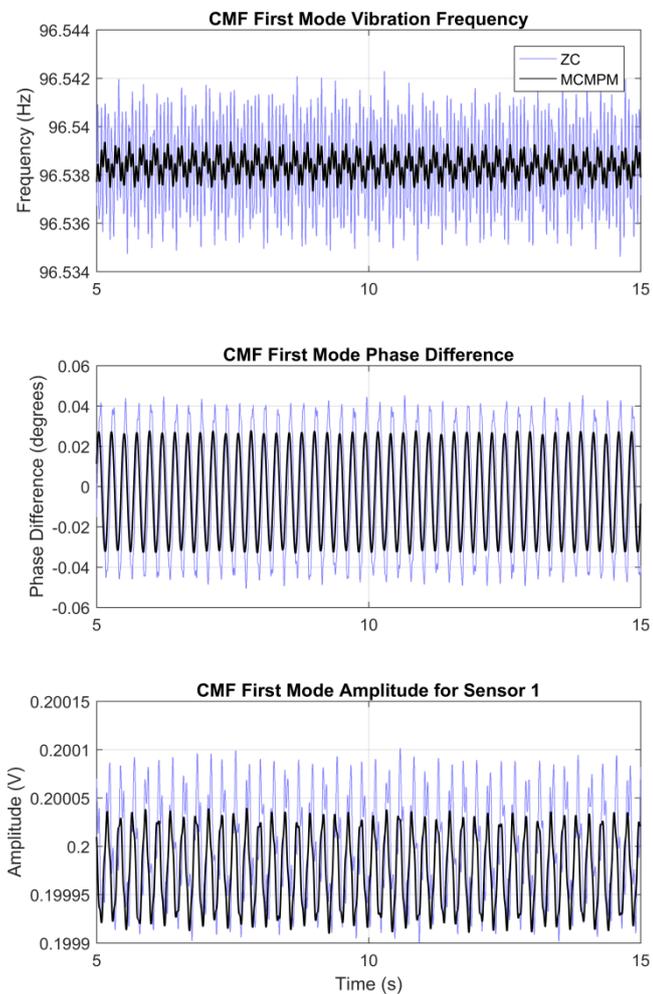


Fig. 5. First mode parameters for dual mode control, no flow

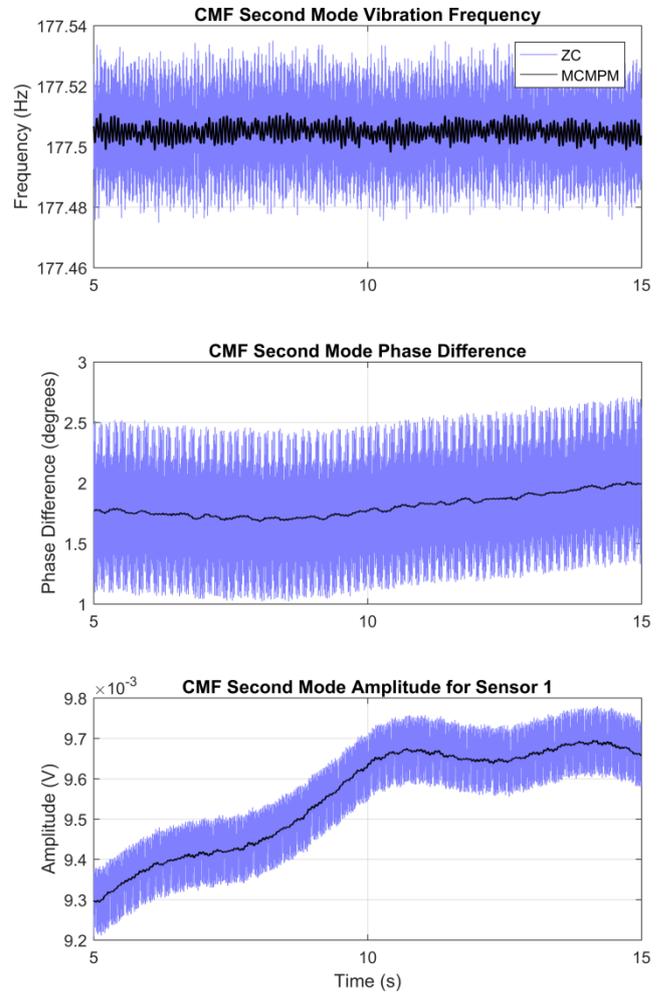


Fig. 6. Second mode parameters for dual mode control, no flow

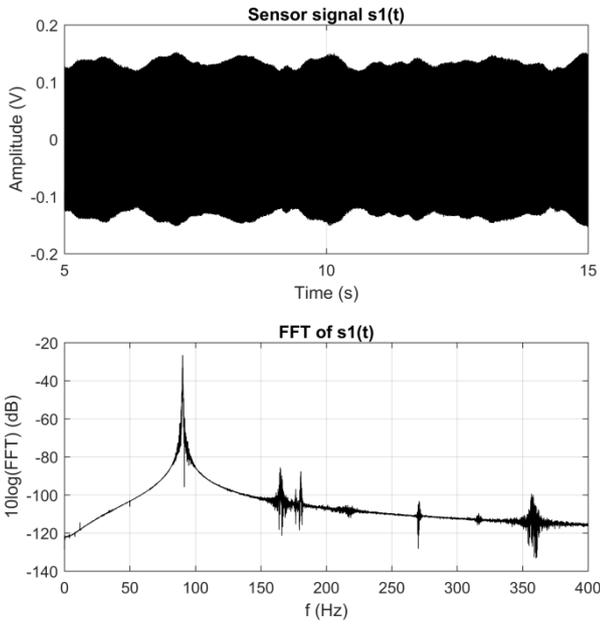


Fig. 7. Sensor data and FFT for water flow 0.3 kg/s, GVF 2.2%

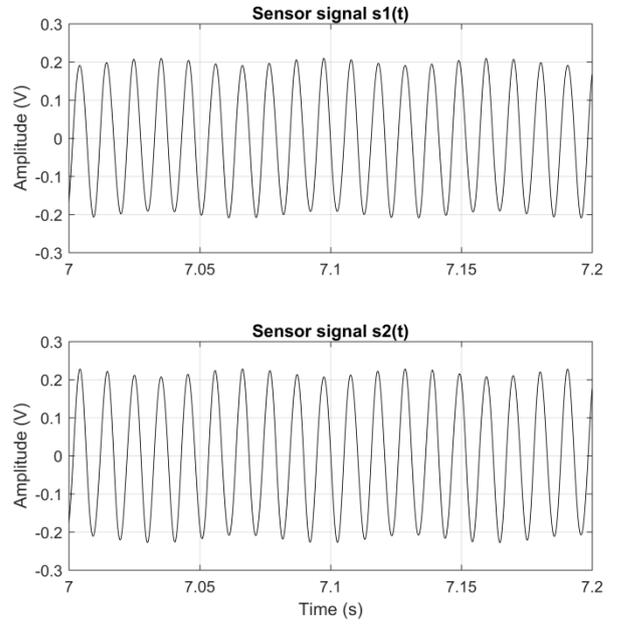


Fig. 8. Detailed sensor data for water flow 0.3 kg/s, GVF 2.2%

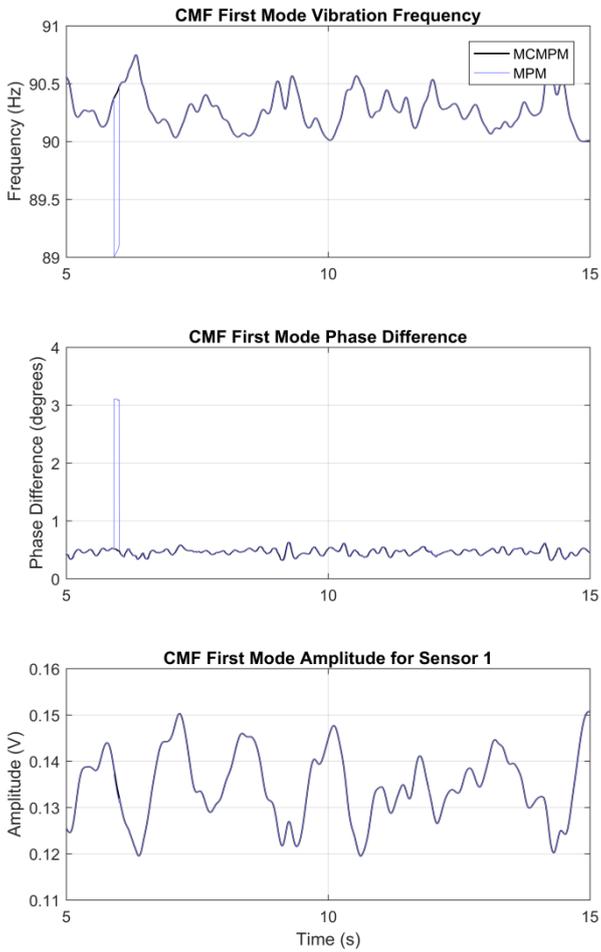


Fig. 9. First mode parameters for water flow 0.3 kg/s, GVF 2.2%

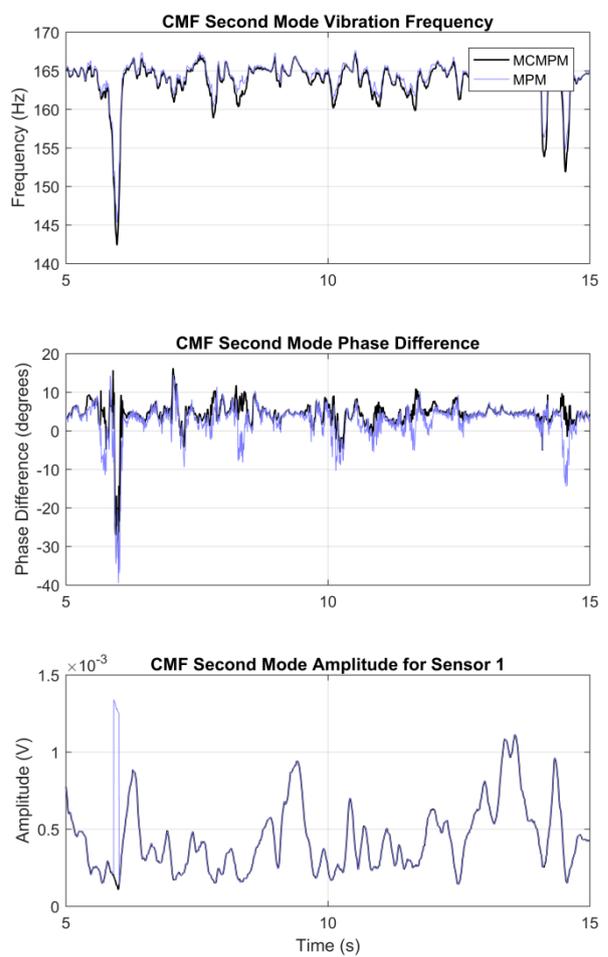


Fig. 10. Second mode parameters for water flow 0.3 kg/s, GVF 2.2%

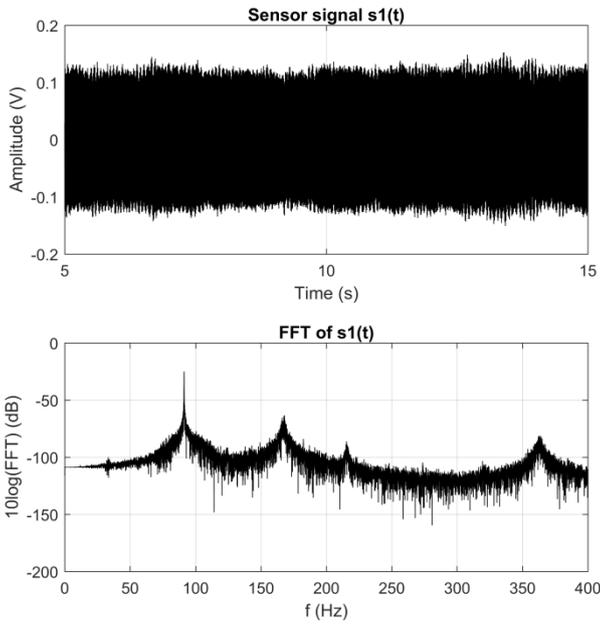


Fig. 11. Sensor data and FFT for water flow 0.6 kg/s, GVF 15.6%

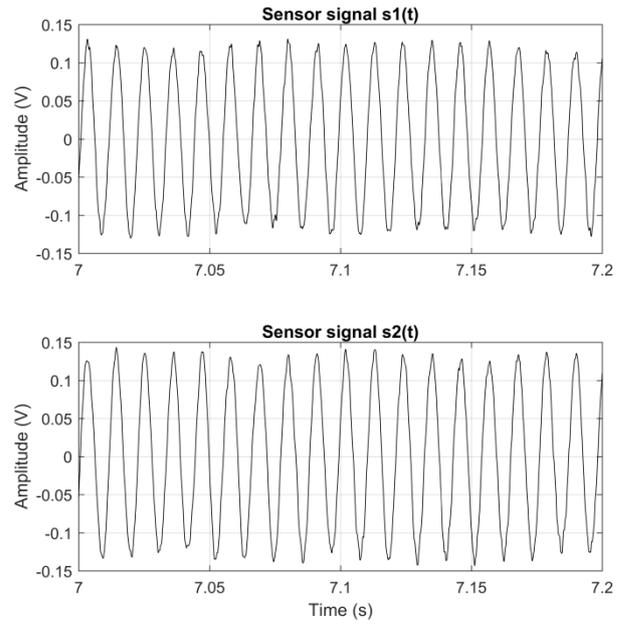


Fig. 12. Detailed sensor data for water flow 0.6 kg/s, GVF 15.6%

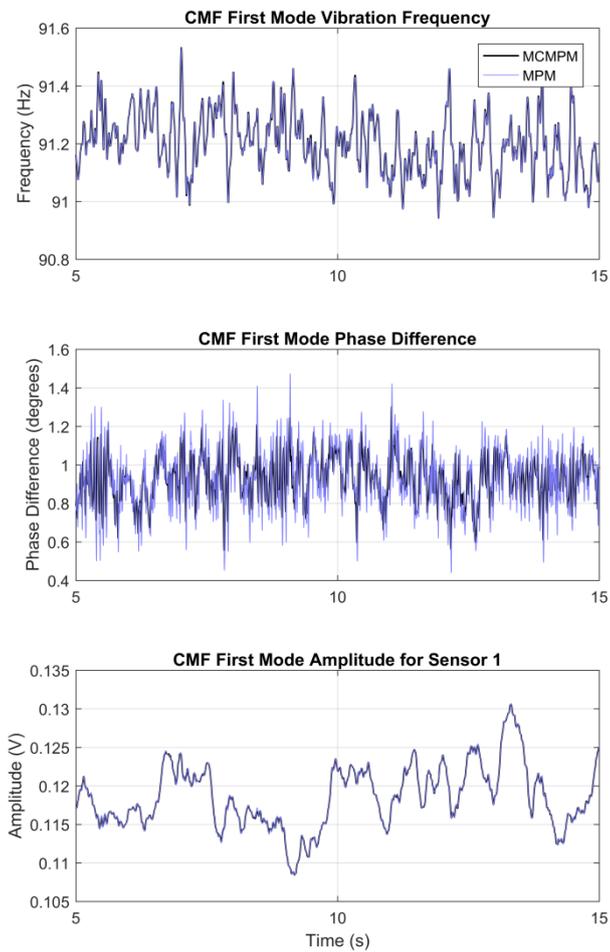


Fig. 13. First mode parameters for water flow 0.6 kg/s, GVF 15.6%

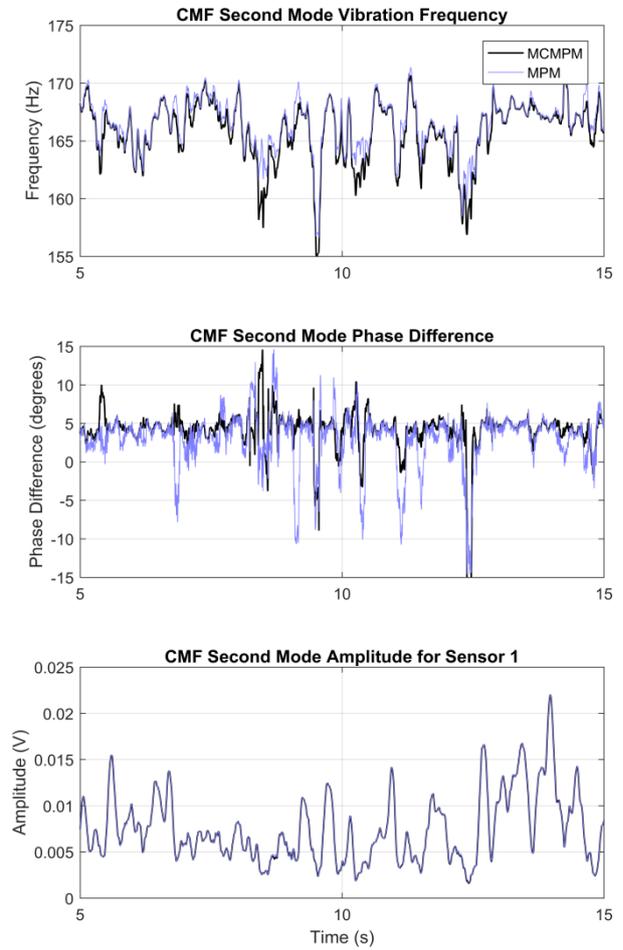


Fig. 14. Second mode parameters for water flow 0.6 kg/s, GVF 15.6%