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Method for direction diagnosis of multiple fluctuation sources on the flow standard facility

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Abstract

Extra uncertainty is introduced to the result of flowmeter calibration by flow fluctuations in the flow standard facility. Identifying sources of fluctuations is important for the location and elimination of the fluctuation sources in the flow standard facility, however it is difficult to diagnose the direction of fluctuation source when multiple sources exist. A correlation analysis method based on Empirical Mode Decomposition (EMD) utilizing the signals of pressure sensor and flowmeter is proposed to diagnose the directions of different fluctuation sources. The proposed method could separate the superposition signal of multiple fluctuation sources and effectively diagnose the directions of multiple fluctuation sources at one time and provide accurate information for the location and elimination of the fluctuation sources. Experiment platform was built based on a water flow standard facility and the direction diagnosis experiment of double fluctuation sources was conducted to verify the effectiveness of the proposed method. The experiment results shows that the directions of multiple fluctuation sources could be accurately diagnosed by the proposed method.

Key word：flow standard facility; multiple fluctuation sources; direction diagnosis; correlation analysis; Empirical Mode Decomposition (EMD)

1. Introduction

The flow standard facility is used to measure or calibrate the metering performance of the flowmeter in an experimental manner, and the flow rate value provided by the flow standard facility should be accurate and stable. Fluctuation of the flow is used to represent the degree of flow instability, and it may bring greater uncertainty to the result of flowmeter calibration[1,2], especially in the low flow range, the uncertainty introduced by the fluctuation even exceeds 10% due to the non-linearity of the instrument coefficient [3].

And the flow fluctuation itself will also affect the measurement of the flowmeter[4-7], such as differential pressure flowmeter[4], ultrasonic flowmeter[5] and other traditional flowmeter, as well as some new flowmeter[6,7]. Therefore, it is necessary to locate the fluctuation source of the flow standard facility accurately and eliminate or suppress the fluctuation source. Previous studies have reported on the direction diagnosis of single flow fluctuation source, and the method has achieved good results[8]. However, there are more than one fluctuation source in the flow standard facility in most cases, such as the rotation of pumps, the trembling of valves, the pressure regulating valve, the pipe and the valve, and so on[8-10]. Therefore, obtained fluctuation signal by sensor may be a superposition singal of multiple fluctuation sources, and it is difficult to diagnose the direction of multiple fluctuation sources using fluctuation superposition signal compared with the direction diagnosis of single fluctuation source. Moreover, there are few reports about this aspect of research.

In this paper, a correlation analysis method based on Empirical Mode Decomposition (EMD) utilizing the signals of pressure sensor and flowmeter is proposed to diagnose the direction of fluctuation sources. By separating the superposition signal of multiple fluctuation sources, the proposed method could effectively diagnose the direction of multiple fluctuation sources at one time and provide accurate information for the location and elimination of the fluctuation sources. The experiment platform was built based on a water flow standard facility and the direction diagnosis experiment of double fluctuation sources was conducted to verify the effectiveness of the proposed method.

2. Principle of direction diagnosis method based on EMD

2.1 Relationship between pipeline pressure and flow rate

The flow standard facility studied in this paper is a complete set of water flow standard facility. The simplified schematic diagram is shown in Fig.1.

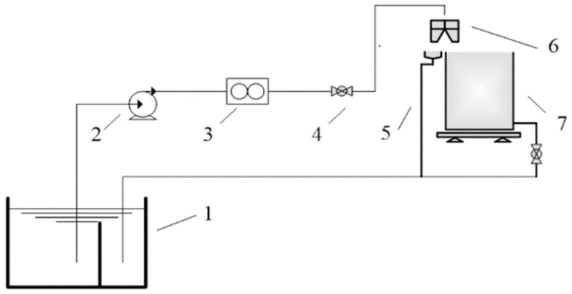


Figure 1: Schematic diagram of the flow standard facility.

Each number in Fig.1 represents a composition: 1 - water tank, 2 - water pump, 3 - flowmeter under test, 4 - control valve, 5 – bypass line, 6 - diverter, 7 - weighing system. Among them, the water pump is the power source of the facility, and it pumps water from the water tank to the pipeline system. And the water flows through the measured flowmeter to the pipeline outlet. The water is finally returned to the water tank through the diverter or the weighing container. When the facility is in a stable working condition, it can be known from Bernoulli's principle that the relative relationship between pressure and flow rate at each position in the facility is stable.

According to the derivation of the relationship between pipeline pressure and flow rate, when there is a single fluctuation source located at the upstream of the measurement point, the relationship between pressure and flow rate in the pipeline of the flow standard facility can be obtained[8]

$$\frac{p_T}{\rho g} = \Delta H_1 + K_D q^2 . \qquad (1)$$

In the formula, p_T is the pipeline pressure at the measuring point, ΔH_1 is the height difference between the pipeline outlet and the measuring point, and $K_D > 0$ is the pipeline resistance synthesis parameter, and q is the flow rate. Therefore, when the fluctuation source is located at the upstream of the measurement point, p_T is positive correlation to q^2 at the measurement point.

When there is a single fluctuation source downstream of the measurement point, the relationship between pipeline pressure and flow rate can be obtained[8]

$$\frac{p_T}{rg} = \Delta H_2 + \frac{p_U}{rg} + K_U q^2 . \qquad (2)$$

where ΔH_2 is the height difference between the pump outlet and the measuring point. p_U is the pump outlet pressure. $K_U < 0$ is the pipeline resistance synthesis parameter. Therefore, p_T is negative correlation to q^2 at the measurement point.

2.2 Empirical Mode Decomposition (EMD) method

When there is only one fluctuation source in the facility, the direction of the fluctuation source can be obtained according to the correlation between p_T and q^2. However, when there are multiple fluctuation sources, the signals obtained by the pressure sensor and the flowmeter may be superimposed signal of multiple fluctuation signals, and it is difficult to diagnose the directions of multiple fluctuation sources using the method dealing with single fluctuation source. Empirical Mode Decomposition (EMD) method is used to separate the fluctuations with different frequencies from the superimposed signal in this paper.

The change of flow q and pressure p_T with time appears as a wave signal in time series. Therefore, the change of the output of flowmeter and the change of the output of pressure sensor are all complex, and each signal appears as a complex superimposed signal, which is an irregular signal. The essence of EMD is to decompose an irregular frequency wave into multiple residual waves with single frequency[11]. Since most of the data to be analyzed does not always conform to intrinsic mode function, and the data may contain multiple fluctuation patterns at time[12]. Therefore, the original data needs to be decomposed to obtain the intrinsic mode function by using the EMD method. The decomposition process is as follows[13].

(1) Let $x_{i,l}(n) = x(n)$, $i = 1$, $l = 1$; (2) Find all local pole values of $x_{i,l}(n)$; (3) Using cubic spline interpolation to combine the local maximum and minimum sequences with the upper envelope $e_u(n)$ and the lower envelope $e_d(n)$ separately; (4) Calculate the envelope $m_{i,l}(n) = \left(e_u(n) + e_d(n)\right)/2$; (5) Pick up the components $h_{i,l}(n) = x_{i,l}(n) - m_{i,l}(n)$; (6) If the screening stop criterion is satisfied, $c_i(n) = h_{i,l}(n)$ is regarded as an intrinsic mode function (IMF) , $i = i + 1$, $l = 1$. Then transfer to the step (8); (7) If the screening stop criterion isn't satisfied, $x_i(n) = h_{i,l}(n)$, $l = l + 1$, and repeat the step (2) to (5); (8) Record the residue value as $r_i(n) = x(n) - \sum c_i(n)$. Let $x_{i,l}(n) = r_i(n)$ and repeat the step (2) to (6) to get the next IMF.

If $r_i(n)$ is a trend component, the algorithm terminates. Otherwise, the above steps are repeated until the end condition is satisfied. The above process can express the original signal as the sum of an IMF component and a trend component. Its expression is

$$x(n) = \sum c_i(n) + r_i(n). \tag{3}$$

In the process of signal acquisition, the flowmeter, pressure sensor, etc. are high sensitive, and are also subject to various factors such as power frequency interference, environmental random vibration and so on. These interference factors can be reduced during the analysis procedure by the self-adaptive filtering characteristics of the EMD method that can generate basis function.

According to the EMD method, the corresponding formulas can be affirmed through spectrum analysis of each IMF component. These IMF components are the original signals that compose the pressure signal $p_1, p_2 \cdots p_n$ and the corresponding flow rate signal. We can obtain the corresponding formulas through spectrum analysis of each IMF component, as shown in Eq. (4). The various formulas represent that p_i is proportional to $q_i^2\,(i=1,2,\ldots,n)$. According to Eq. (1) and Eq. (2), it can be found that plus-minus of $K_i\,(i=1,2,\ldots n)$ related to the direction of fluctuation source represents the correlation between p_i and $q_i^2\,(i=1,2,\ldots,n)$. Therefore, it could determine the direction of the fluctuation source by the correlation coefficient of p_i and q^2 after decomposition by the EMD method.

$$\begin{cases} \dfrac{p_1}{\rho g} = K_1 {q_1}^2 \\ \dfrac{p_2}{\rho g} = K_2 {q_2}^2 \\ \quad\vdots \\ \dfrac{p_n}{\rho g} = K_n {q_n}^2 \end{cases}. \tag{4}$$

2.3 Direction diagnostic method of Fluctuation sources

Differential pressure sensor was installed in Venturi tube to measure the flow rate q, by differential pressure Δp. The correlation relationship between Δp and q is shown in formula (5)[16].

$$q = CA_2\sqrt{\frac{2\Delta p}{\rho(1-A_2^2/A_1^2)}}. \tag{5}$$

where C is the Correction factor. A_1 is Venturi expansion section area, and A_2 is Venturi tube contraction section area. $\Delta p \propto q^2$ can be obtained from Eq.(5), and $\Delta p \propto p_T$ from Eq. (1). So, when the fluctuating source is at upstream, the differential pressure measured is linearly positively correlated with the pressure. Also, $\Delta p \propto -p_T$ obtain from Eq. (2). So, when the fluctuating source is at downstream, the differential pressure measured is linearly negatively correlated with the pressure.

The direction of the fluctuation source can be determined by calculating the Pearson correlation coefficient $r_{p-\Delta p}$ between the flow (differential pressure same, same below) signal and the pressure signal.

$$r_{p-\Delta p} = \frac{\sum_{n=1}^{N} p(n)\Delta p(n+m)}{\sigma_p \sigma_{\Delta p}}. \tag{6}$$

where $p(n)$ is the n*th* measurement point in the pressure signal and $\Delta p(n)$ is the n*th* measurement point of the flow signal. σ_p and $\sigma_{\Delta p}$ are the standard deviation of the pressure signal and the flow signal in the n measurement points. The response times of pressure sensor and the flowmeter are different in the actual measurement process, and in order to accurately capture the time difference, the actual calculation takes multiple sets of time differences in the possible delay time horizon for correlation analysis. If T_S is the sampling time, $m \cdot T_S$ is the delay time between physical signals from sensors at the same time.

When $r_{p-\Delta p}$ is significantly greater than zero ($r_{p-\Delta p}$ > 0.3) which indicates flow fluctuation signal and pressure fluctuation signal are positively correlated, and it can be determined that the fluctuation source is located at the upstream of the measurement point. Conversely, if $r_{p-\Delta p}$ is significantly less than zero ($r_{p-\Delta p}$ <-0.3), the flow fluctuation signal and pressure fluctuation signal are negatively correlated, and it can be diagnosed that the fluctuation source is located at the downstream of the measurement point.

3. Experiment platform

The water pump provides flow for the water flow standard facility, which flows through a pressure sensor, a Venturi flowmeter (differential pressure type flowmeter) and a simulative fluctuation source in turn. The schematic diagram of main composition in the water flow standard facility is shown in Fig. 2, and the photos of the experimental platform is shown in Fig. 3. The sampling frequency of the pressure sensor and the differential pressure sensor is 5000 Hz. And the sampling signal could be displayed in real time, and the sampling frequency could also be compressed according to an averaging method. The acquisition system interface is shown in Fig. 4.

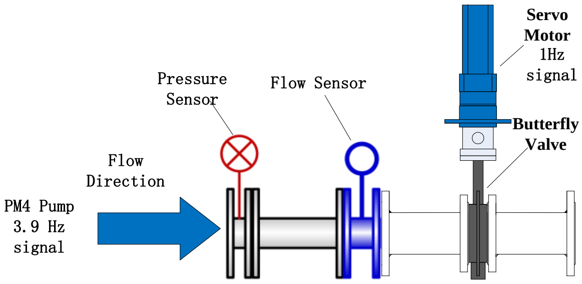


Figure 2: Schematic diagram of main composition in the water flow standard facility.

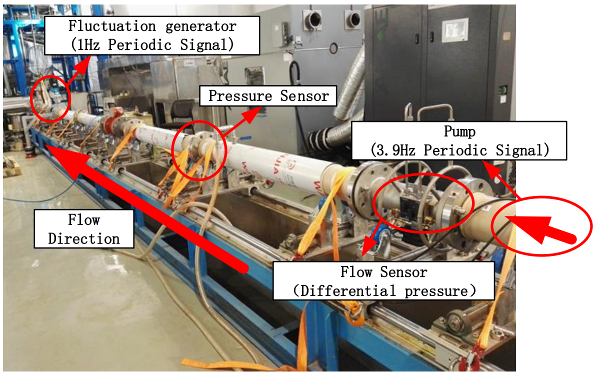


Figure 3: Main composition of water flow standard facility

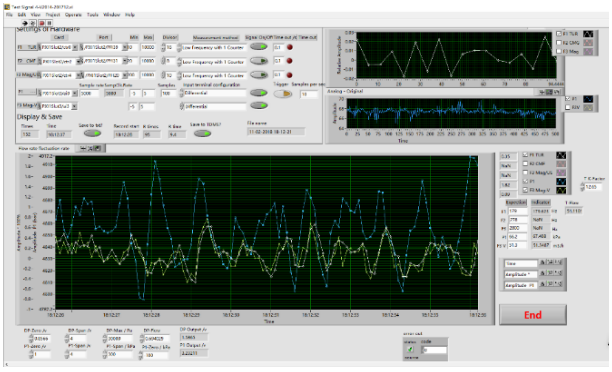


Figure 4: Display of acquisition system interface.

For this water flow standard facility, there is a buffer tank to eliminate the fluctuations. The buffer tank can eliminate the high-frequency fluctuations[15,16], however it could not effectively eliminate the low-frequency fluctuation. In this paper, the simulated fluctuation sources can generate low-frequency fluctuation. After the buffer tank eliminated the high-frequency fluctuations, a flow fluctuation of about 3.9 Hz by a poor pump (named PM4) from upstream still existed in pipe which was labeled by Fluctuation Source 1#. A fluctuation generator was added at the downstream in the experiment. In the fluctuation generator, the servo-driven motor controlled was used to drive the swing of the butterfly valve to generate simulative oscillations of 1 Hz, ±5° and set as Fluctuation Source 2#. The fluctuation of Fluctuation Source 2# simulated the fluctuations that might occur in the flow standard facility. So, the entire set of experiment facility had fluctuations from the upstream and downstream with frequencies of 1 Hz and 3.9 Hz respectively. The information of the fluctuation sources is shown in Table 1.

Table 1: Parameter of fluctuation sources

Source	location	Frequency	Property
PM4 Pump (Fluctuation Source 1#)	upstream	3.9 Hz	Periodicity
Simulative Fluctuation (Fluctuation Source 2#)	downstream	1.0 Hz	Periodicity

4. Direction diagnosis experiment of double fluctuation sources

The specific process using the EMD method to perform double fluctuation sources extraction and the locations judgment is as Fig. 5.

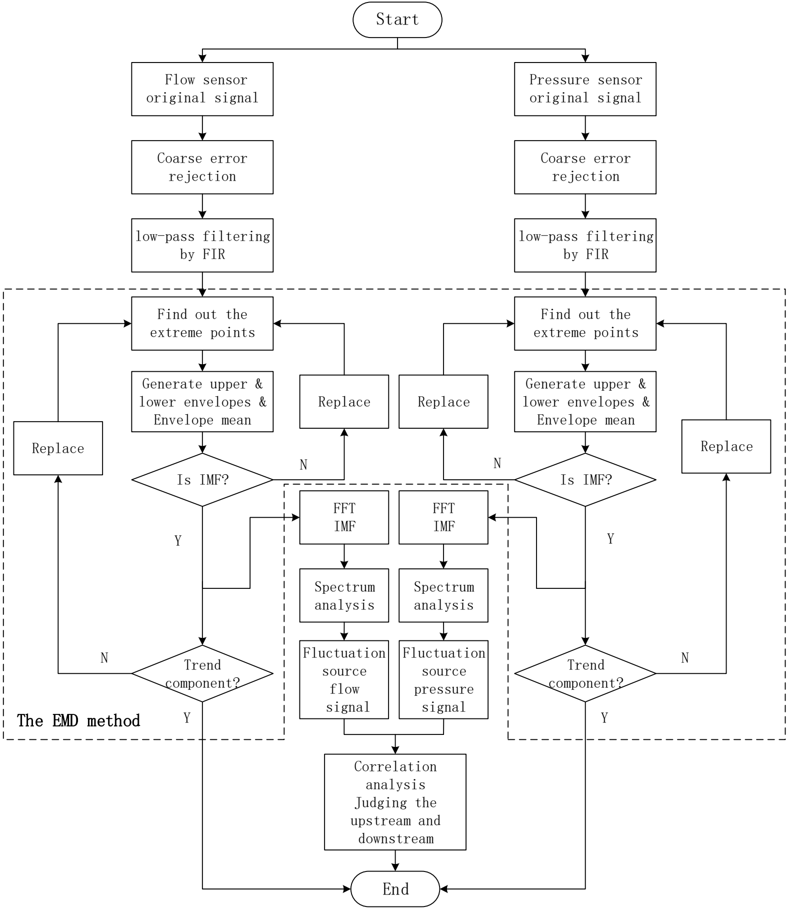
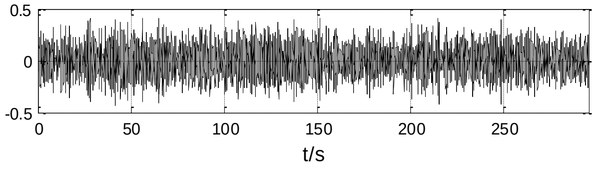


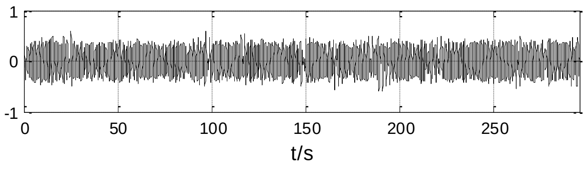
Figure 5: Simplified model of fluctuating source direction diagnosis based on EMD.

In order to provide a concise and precise description of the experiment results, this section is divided by subheadings as: (1) The extreme abnormal values of the pressure signal and flow signal were discarded, and then the Pauta criterion was used to eliminate the abnormal signal; (2) The pressure sensor and differential pressure sensor were easily disturbed by high-frequency noise in environment. Therefore, the FIR filter was used to low-pass filter the signal; (3) Sampling frequency is compressed; (4) signal was processed using the EMD method to obtain multiple IMF components; (5) Spectrum analysis of individual IMF components was done to distinguish and determine signals from different sensors for the same fluctuation source; (6) By correlating the IMF components of two sensors, the position of the fluctuating source was diagnosed from the upstream or the downstream of measurement point.

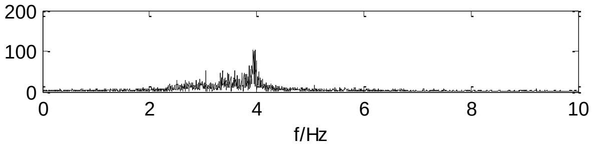
In the experiment, two signals of flow and pressure were both collected at 5 kHz respectively. The abnormal signal was processed first, and the FIR low-pass filter was used to filter the interference signal above 50 Hz. EMD decomposition was performed on the two signals respectively. The fluctuation and frequency spectrum of the resulting flow sensor are shown in Fig. 6 (a)~(d).



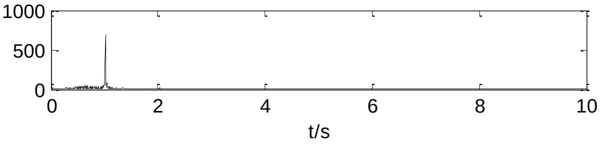
(a): IMF1 from flow signal after EMD



(b): IMF2 from flow signal after EMD



(c): Frequency spectrum 1 from flow signal after EMD

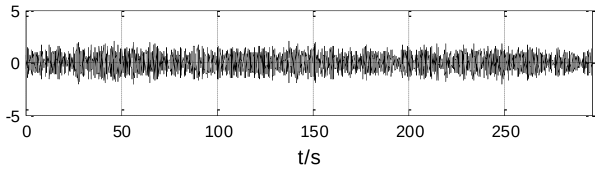


(d): Frequency spectrum 2 from flow signal after EMD.

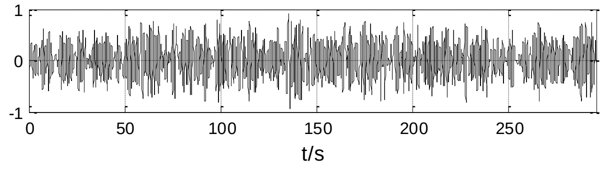
Figure 6: The IMFs and their frequency spectrums of flow signal

According to the spectrum analysis of Fig. 6 (c) and Fig. 6 (d), the IMF1 of waveform represents the flow fluctuation of the Fluctuation Source 1# about 3.9Hz, and the IMF2 of the waveform represents the 1Hz flow fluctuation of the Fluctuation Source 2#. It can be seen that the main IMF component is clear with less interference after the decomposition.

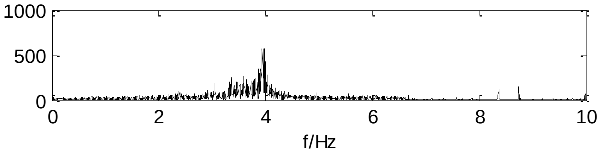
Fig. 7 (a)~(d) show the pre-processed waveform and frequency spectrum of the pressure sensor.



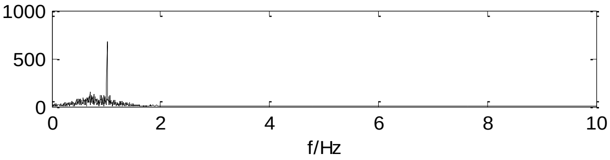
(a): IMF3 from pressure signal after EMD



(b): IMF4 from pressure signal after EMD



(c): Frequency spectrum1 from pressure signal IMF3 after EMD



(d): Frequency spectrum 2 from pressure signal IMF4 after EMD.

Figure 7: The IMFs and their frequency spectrums of pressure signal

According to the spectrum analysis of Fig. 7 (c) and Fig. 7 (d), the IMF3 of waveform represents the flow fluctuation of the Fluctuation Source 1# about 3.9Hz, and the IMF4 of the waveform represents the 1Hz flow fluctuation of the Fluctuation Source 2#. It can be seen that the main IMF component is clear with less interference after the decomposition.

There is a certain delay time between pressure signal and flow signal caused by different response time of pressure sensor and flowmeter. If it is negative, the pressure signal is faster than the flow signal. The actual calculation takes multiple sets of time differences in the possible delay time horizon for correlation analysis. Because the fluctuation signal is periodic, the change of the correlation coefficient with time delay also shows a clear periodicity. The correlation analysis is performed on IFM1 and IFM3 to obtain a correlation curve of the Fluctuation Source 1# as shown in Fig. 8. The correlation analysis of IFM2 and IFM4 for Fluctuation Source 2# as shown in Fig. 9. The correlation periodic signals will be negatively correlated when the two signals differ by an odd number of times of half cycle phase, and positively correlated when they have no phase difference or full cycle phase difference.

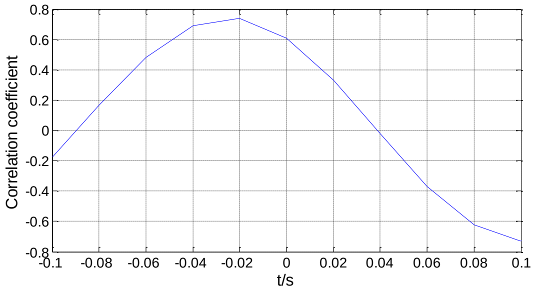


Figure 8: Pressure - flow correlation curve for Fluctuation Source 1#.

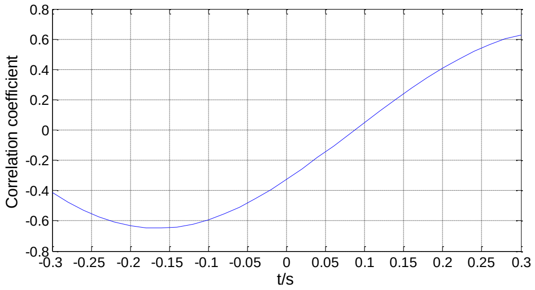


Figure 9: Pressure - flow correlation curve for Fluctuation Source 2#.

There is a certain delay time between pressure signal and flow signal caused by different response time of pressure sensor and flowmeter. Since the experiment fluctuation is a periodic signal, the correlation coefficient curve is also periodic. Therefore, it is necessary to determine the delay time between pressure signal and flow signal at first. The delay time is obtained by the calibration experiment with generating fluctuations when the corresponding sensors are located at the same measurement point. And through the calibration experiment, it could be found that the pressure signal responds faster than the flow signal within 0.06 s. So, it could be considered that the time delay is within the range -0.06 s ~ 0 s.

In Fig. 8, when the delay time is-0.06 s ~ 0 s, the correlation coefficient $r_{p-\Delta p}$ between pressure signal and flow signal is in the range of 0.48 ~ 0.70, which is significant positive correlation ($r_{p-\Delta p}$ > 0.3), so the Fluctuation Source 1# is located at upstream. In Fig. 9，when the delay time is -0.06 s ~ 0 s，the correlation coefficient $r_{p-\Delta p}$ between pressure signal and flow signal is in the range of -0.51 ~ -0.39, which is significant negative correlation($r_{p-\Delta p}$ < -0.3), so it is determined that the Fluctuation Source 2# is located at downstream.

In summary, the proposed method based on EMD method to determine the direction of the multiple fluctuation sources is consistent with the actual setting of the experiment. The experiment results shows that the directions of multiple fluctuation sources could be accurately diagnosed by the proposed method.

5. Conclusion

A correlation analysis method based on Empirical Mode Decomposition (EMD) utilizing the pressure sensor and flowmeter is proposed and could effectively diagnose the direction of multiple fluctuation sources at one time and provide accurate information for the location of the fluctuation sources. Experiment platform was built on a flow standard facility and the direction diagnosis experiment of double fluctuation sources was conducted to verify the effectiveness of the proposed method.
The results are as follows:

1) The EMD method could separate the superposition signal of multiple fluctuation sources obtained by pressure sensor and flowmeter respectively, and could accurately extract the fluctuation signals with different frequencies produced by multiple fluctuation sources.

2) The proposed method based on the EMD method could accurately diagnose the direction of fluctuation sources in the direction diagnosis experiment of double fluctuation sources.

Acknowledgment

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References

[1] W. Poschel, “The Concept of a New Primary Standard for Liquid Flow Measurement at PTB Braunschweig,” in *Proc.int.conf on Flow Measurement*, Lund, Sweden, 15-17, June, 1998.

[2] ISO/TR 3313: *Measurement of fluid flow in closed conduits -- Guidelines on the effects of flow pulsations on flow-measurement instruments*, 2018.

[3] Engel, Rainer, and H. J. Baade. “Quantifying impacts on the measurement uncertainty in flow calibration arising from dynamic flow effects,” *Flow Measurement & Instrumentation*, 44, 51-60, 2015.

[4] Y. Zhu. “Study on the measurement error of differential pressure flowmeter in pulsating flow,” *Chinese Journal of Scientific Instrument*, 27, 894-897, 2006.

[5] J. Berrebi, , et al., “Ultrasonic flowmetering errors due to pulsating flow,” *Flow Measurement & Instrumentation*, 15, 179-185, 2004.

[6] T. Dinh, H. P. Phan, T. K. Nguyen, et al., “Solvent-free fabrication of biodegradable hot-film flow sensor for noninvasive respiratory monitoring,” *Journal of physics d-applied physics*, 50, 215401, 2017.

[7] E. Meng, P. Y. Li, Y. C. Tai, “A. biocompatible Parylene thermal flow sensing array,” *Sensors & Actuators A Physical*, 144, 18-28, 2008.

[8] T. Meng, S. C. Fan, C. Wang et al., “A Flow Stability Evaluation Method Based on Flow-Pressure Correlation,” *Flow measurementand instrumentation*, 64, 155-163, 2018.

[9] T. Meng, S. C. Fan, C. Wang et al., “Analysis of Fluctuation Parameters in Flow Stability Based on Uncertainty Method,” *Review of Scientific Instrument*, 89, 055005, 2018.

[10] J. Berrebi, J. V. Deventer, J. Delsing, “Reducing the flow measurement error caused by pulsations in flows,” *Flow Measurement and Instrumentation*,15, 311-315, 2004.

[11] H. Kasban, H. Arafa, S. M. Elaraby, “Principle component analysis for radiotracer signal separation,” *Applied Radiation and Isotopes*, 112, 20-26, 2016.

[12] N. E. Huang, Z. Shen, S. R. Long, et al., “The empirical mode decomposition and the Hilbert spectrum for nonlinear and non-stationary time series analysis,” *Proceedings Mathematical Physical & Engineering Sciences*, 454, 903-995, 1998.

[13] C. Amo, L. D. Santiago, R. Barea, et al., “Analysis of Gamma-Band Activity from

Human EEG Using Empirical Mode Decomposition,” *Sensors*, 17, 989, 2017.

[14] Pletcher, H. Richard, “Computational fluid mechanics and heat transfer,” *Hemisphere Pub. Corp*, 154-196, 1997.

[15] R. Deng, Y. Cheng, C. H. Wang, “Experiments and simulation on a pulse dampener system for stabilizing liquid flow,” *Chemical Engineering Journal*, 210, 136-142, 2012.

[16] T. Eichler, T. Lederer, “Flow development behind a swirl generator in a hot-water standard measuring facility for large volume rates,” *Flow Measurement & Instrumentation*, 42, 89-97, 2015.