Experimental Analysis of Influencing Factors on Flow Stability of Water Flow Facilities

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Abstract

Because the flow fluctuation can cause the deviation of flow measurement, flow stabilizing methods are used in the most of the flow metering facilities. Two common flow stabilizing methods of water flow facilities are tested by a new flow stability measurement system which is consisted by a flowmeter and a pressure sensor. The amplitude of fluctuation can be measured by flowmeter, and the frequency of fluctuation can be obtained by FFT (Fast Fourier Transform) analysis of the pressure signal. The direction of fluctuation source can be distinguished by correlation analysis of pressure and flow signals. Based on this method, the characteristics of the fluctuation source can be obtained by experiments under different flow rate and pipe pressure.
An obvious fluctuation signal with a frequency of about 1.5Hz had been found in a test for a flow facility with a buffer tank. The amplitude of fluctuation increases with the decrease of flow rate. When the flow rate is less than 1/10 of the rated flow rate of the pump, the amplitude of fluctuation is about 1%. It is shown that the high frequency fluctuation produced by the pump can be effectively isolated by the buffer tank, but the low frequency fluctuation can be caused by the pump when it worked in a low efficiency range.
In another set of experiments, a flow facility with a constant head water tank and a buffer tank was tested, and two flow stabilizing methods were directly compared and analysed. The test results of the two methods are close under the similar working flow rate and pressure. And if it is under different operating conditions, the amplitude of fluctuation is closely related to the opening of the regulating valve which is installed downstream of the test bench. The fluctuation amplitude increases with the decrease of the valve opening. When the valve opening is less than 30%, the fluctuation amplitude is about 0.5%. Further, it is obtained that the cavitations is caused by the excessive local pressure loss of the regulating valve is the main reason of the fluctuation for the facility with constant head water tank.
In summary, the buffer tank and the constant head water tank are both effective methods for stabilizing flow, and the optimal stabilization effect can be obtained by setting a reasonable range of operation for the pump and the regulating valve.
Keyword: Flow Stability, Water Flow Facility, Buffer Tank, FFT, Correlation Analysis

1. Introduction

Flow stability is an important technical index of flow standard facilities. In recent years, with the decrease of uncertainty of flow facility, the influence of flow instability on the flow meter calibration process has been gaining increasing attention. For example, the study of Dr. Engel[1], J. Berrebi[2] and others have shown that the fluctuation of the flow not only affects the accuracy of water flow facility itself, but also may bring a large uncertainty to the calibration results. Due to the non-linearity or sampling error of various types of flowmeters, J. Berrebi *et al.*[3] pointed out in the study of ultrasonic flow meter that the effect has far exceeded its maximum permissible error.Therefore, it is of great significance to find out the causes of the fluctuation for improving the calibration capability and decreasing the uncertainty.

The buffer tank and the high constant water head tank are two kinds of methods for stabilizing flow widely used in the water flow facilities, the actual effect of them was studied by the experiments in this paper. In the previous study, Meng *et al*[4]. proposed a flow stability evaluation method based on flow-pressure correlation analysis, which was applied to measure the amplitude and frequency of flow fluctuation in this study. It was given that the main causes of the fluctuation and the improvement methods of the water flow facilities.

2. Measurement of flow stability

The flow stability measurement system is shown in Fig. 1, which is composed of a pressure sensor and a flow meter in series.

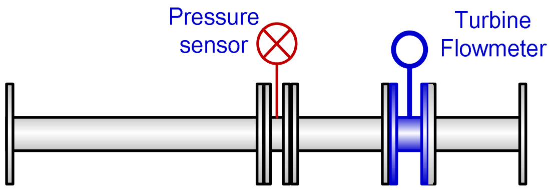


Figure 1: The flow stability test system

According to previous studies[4], the amplitude of flow fluctuation can be represented by the dispersion degree of the flow signal tested by the flow meter, as shown in formula (1).

$$D_q = \sqrt{\frac{\sum_{i=1}^{N}\left(q_i - \bar{q}\right)^2}{N}} \Big/ \bar{q} \qquad (1)$$

Where, q_i is the value given by flowmeter in a single flow measurement (i=1,2,... N), and $\bar{q}$ is the mean of q_i in one test.

By performing FFT (Fast Fourier Transform) analysis on the pressure signal, the frequency characteristic of the flow fluctuation can be obtained. The correlation between pressure signals and flow signals can be used to analyse the direction of fluctuations source, as shown in formula (2).

$$r_{qp} = \frac{\sum_{n=1}^{N} q(n)p(n+m)}{\sigma_q \sigma_p} \qquad (2)$$

where σ_q^2 and σ_p^2 are the variances of the flow and pressure measurements, respectively; *q*(n) is the nth measured value of the flow signal, *p*(n) is the nth measured value of the pressure signal, n = 1, 2, ... N. Because of the difference in the response speed between the flowmeter and pressure sensor, m is the delay between them.When the pressure signal and flow signal show obvious positive correlation（$0.3<r_{qp}<1$）, it indicates that the main wave source comes from the upstream of the measurement point; When there is a significant negative correlation between the two signals（$-1<r_{qp}<-0.3$）, it means that the main source of fluctuations comes from the downstream of the measurement point.

In the experiments of this paper, the turbine flow meter with good signal quality and high sampling frequency is selected in the measurement system[5], as well as the high-frequency response pressure sensor with sampling frequency up to 2kHz, which can detect the flow fluctuation signal in a wide range of frequency.

3. Experiment on buffer tank method

3.1 Experimental facility and scheme

The experiment was carried out on an hot and cold water flow facility (1# facility). That facility is mainly used to measure or calibrate the flow meter and heat meter in the diameter range of DN80 ~ DN400, and its relative uncertainty can reach 0.04% (*k*=2)[6], which is currently recognized as one of the most advanced water flow facilities in the world. A centrifugal buffer tank is installed between the pumps and the test pipeline to eliminate bubbles in the water and reduce flow fluctuation caused by the pumps. The process chart of the 1# facility is shown in Fig. 2.

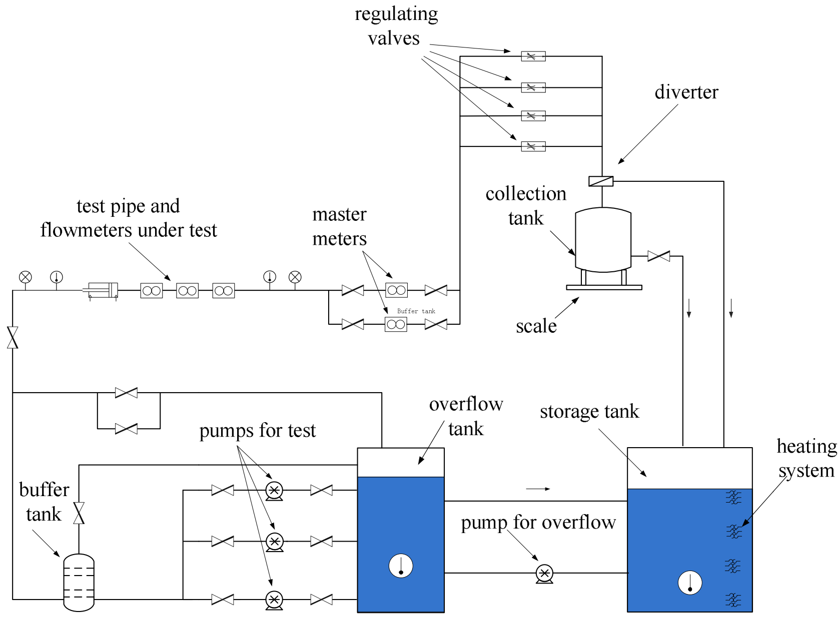
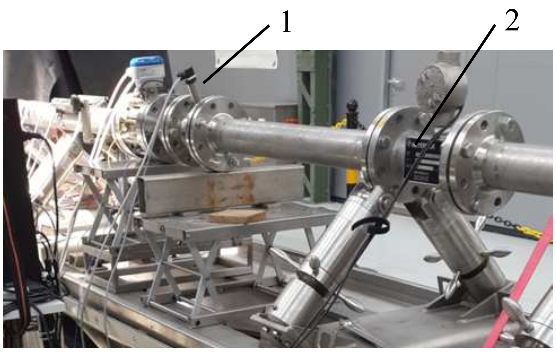


Figure 2: The schematic diagram of 1# facility

The experiment was done on the pipe diameter of DN80. According to the measuring range of the turbine flow meter, the experimental flow range was (15~120) m^3/h, and the outlet pressure of the test pipe was (0.1~0.2) MPa. The experiment began from 15m^3/h, and the flow increased by about 10m^3/h each time. The experimental results were summarized in Table 1.



1--Pressure Sensor; 2--Turbine Flowmeter

Figure 3: Experimental photos on 1# facility

Table 1: Summary of flow stability test results of 1# facility

Flow Rate (m3/h)	Flow Fluctuation Amplitude (%)	Flow Fluctuation Frequency (Hz)	Correlation Coefficient
15	1.36	1.45	0.70
20	0.95	1.48	0.77
30	0.34	1.61	0.77
40	0.18	1.73	0.68
50	0.13	1.91	0.61
61	0.10	--	0.49
71	0.09	--	0.56
80	0.09	--	0.39
90	0.09	--	0.38
100	0.08	--	0.33
109	0.09	--	0.23
120	0.08	--	0.25

3.2 Experimental results analysis of 1# facility

It can be seen from Table 1 that the main fluctuation frequency measured by the pressure sensor was low, and the sampling rate of the turbine flowmeter was high enough to measure fluctuation amplitude. The flow fluctuation amplitude showed a trend of rapid decrease with the increase of flowrate, as shown in Fig. 4.

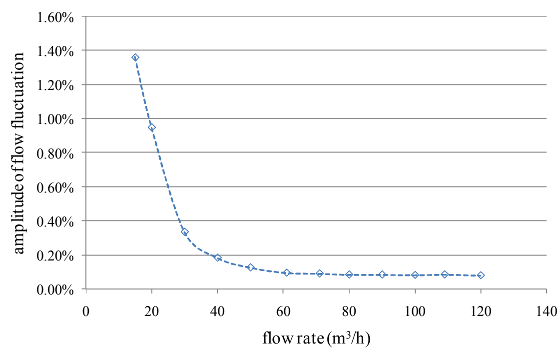
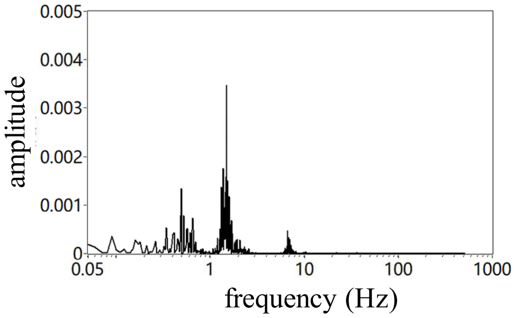


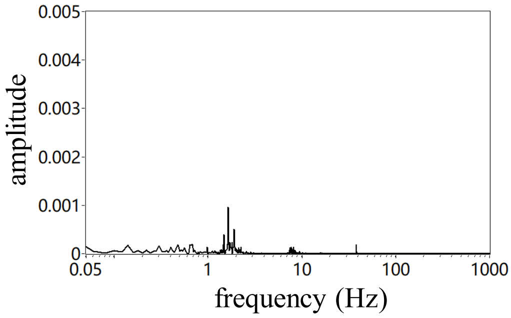
Figure 4: Variation curve of flow fluctuation amplitude with pipe flowrate in 1# facility

In the low flow rate area, the flow fluctuation of the facility was obvious. Within the flow range of (15~20) m^3/h, the flow fluctuation amplitude was about 1%. After the flow rate exceeded 40m^3/h, the fluctuation amplitude was less than 0.2%, which indicated that the facility entered a relatively stable working area. With the further increase of the flow rate, the corresponding fluctuation amplitude also continues to decrease. When the flow rate exceeded 50m^3/h, the relative fluctuation amplitude gradually reduced to 0.08%~0.10%.

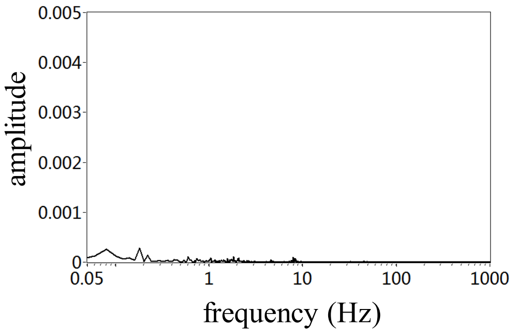
In terms of the characteristics of fluctuation frequency, the main fluctuation frequency was about 1.5Hz in the low-flow rate area, as shown in Fig. 5. However, when the flow rate is greater than 60m^3/h, there was no obvious characteristic frequency. In order to analyze and find out the causes of fluctuations, the research work was focused on the range of (15~50) m^3/h.



(a) flow rate, q=15m^3/h



(b) flow rate, q=40m^3/h



(c) flow rate, q=60m^3/h

Figure 5: FFT spectrum analysis results of pressure sensor in 1# facility

Within this flow range, it was an obvious positive correlation ($0.6<r_{pq}<0.8$) between flow and pressure, and it can be inferred that the fluctuation source mainly was at the upstream of the measurement system. In Fig. 6, the pump operating curve was overlaid with Fig. 4 for comparing the fluctuation amplitude with the performance of the pump.

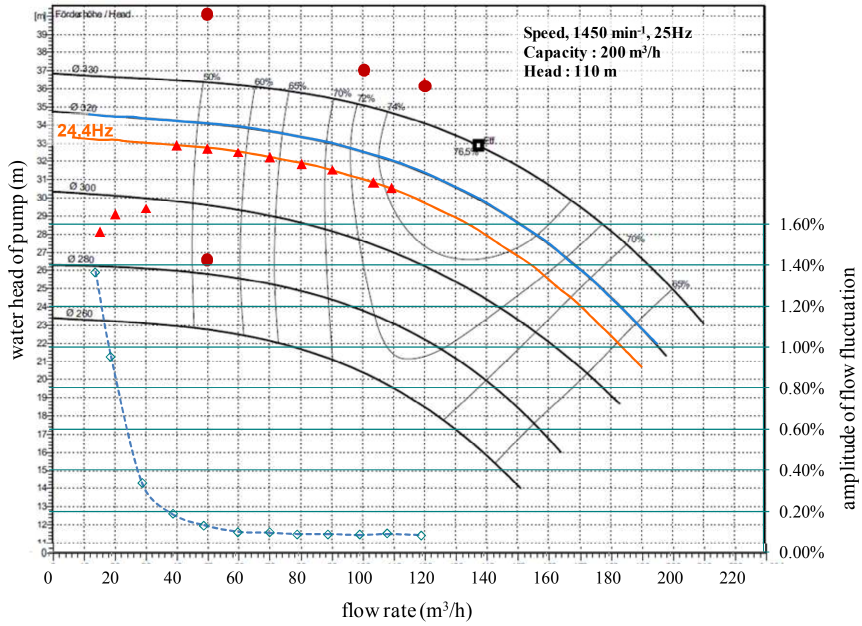


Figure 6: The comparison of pump operating curve with flow fluctuation amplitude

In Fig. 6, the orange curve was the operating curve of the pump at 24.4hz, the red triangle represented the experimental points, and most of the experimental flow rate in Table 1 were fixed at this frequency. In order to verify the correlation between pump frequency and flow stability, comparative experiments were carried out with different pump frequency at some flow rate which were marked with dark red dots. The dotted blue line was the curve of flow fluctuation amplitude with flow change in Fig. 4, and the experimental points were marked with hollow diamond. For instance, three experiments were done at the pump frequency of 21.2Hz, 24.4Hz and 27.7Hz at same flow rate of 50m^3/h. The results were shown in Table 2:

Table 2: The comparison of measurement results under 50m^3/h and different pump frequency

Water Pump Frequency (Hz)	Flow Fluctuation Amplitude (%)	Flow Fluctuation Frequency (Hz)
21.2	0.11	1.9
24.4	0.13	1.9
27.7	0.14	2.0

Seen from Table 2, the variation of amplitude and frequency between 3 experiments were very small, and they did not have obvious correlation. There were several efficiency curves of pump marked with thin dotted lines in Fig. 6, which was provided by the manufacturer, and the efficiency percentage was marked on the curve. For example, the best working point of this type of pump is flow rate of 130m^3/h at outlet water head of around 31m, and the efficiency value can reach 76.5% which gradually decreases along the working curve to both sides. Generally, the higher the working efficiency of the pump is, the more stable it is. It can be found in Fig. 6 that the flow stability got worse as the pump efficiency got lower, even the efficiency was lower than 50%. That pump was smallest one of this facility, but it was too big to being used at low flow rate range in these experiments. In order to improve the facility, the flow fluctuation amplitude can be reduced by adding a low flow rate pump or using a small constant head water tank.

Based on above experimental results, a good flow stability can be get by installing a well-designed buffer tank. There were no obvious high-frequency fluctuation that was detected, so it can be seen that the high-frequency pulsation generated by pumps can be effectively isolated by the buffer tank. But its effect on the low-frequency pulsation is limited. In addition, it was found that the unstable operation of the pump in the low efficiency area is the main factor causing the flow fluctuation.

4. Experiment on facility with high constant water head tank

4.1 Experimental facility and scheme

In order to further research the effect of different methods to stabilize flow in the water flow facilities, the experiments were carried out on a set of facility

(2# facility) with high constant water head tank. The process flow chart of the facility is shown in Fig. 7.

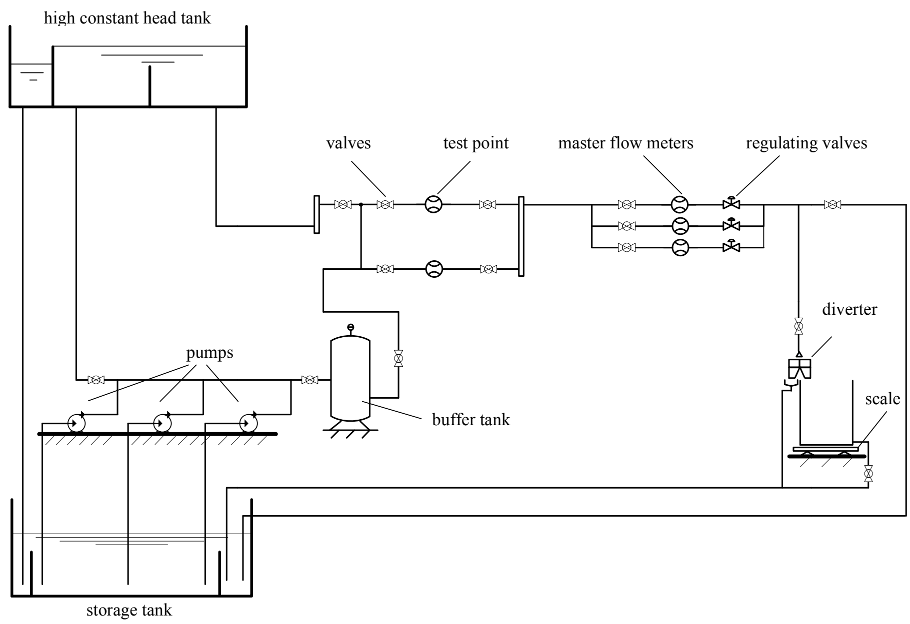


Figure 7: Schematic diagram of 2# facility

The flow range of 2# facility is (0.01~200)m^3/h, the best measurement uncertainty is 0.05% (k=2), and the maximum experimental pipe diameter is DN100. A characteristic of the facility is that it has two different methods for flow stabilization: (1) High constant water head tank. Because the pump flow is kept larger than the experimental flow, the pressure at the pipeline inlet is constant. This method is generally considered to be the most effective way to stabilize flow at present. However, since the inlet pressure cannot be adjusted, the flow adjustment can only be through the regulating valves installed at downstream of the test bench. (2) Buffer tank. This method is similar to 1# facility. Compared with the constant water head tank, this method can adjust the flow and pressure of the pipeline simultaneously by changing the frequency of the pump and the opening of valve. It is more flexible in use and the cost is much lower than that of the constant water head tank.

In this experiment, the diameter of the test pipeline was DN100. The regulating valve VT1 of this pipeline was a linear ball valve, and its flow adjustment range was (30~200) m^3/h. For easy to compare 2 kinds of flow stabilizing methods, the test flow range was (30~120)m^3/h. The experiments were divided into four groups, and the experimental conditions and purposes were as follows: The first group H-01~H-03, mainly tested the stability flow of high constant water head tank; The second group, H-04~H-06, used the buffer tank to stabilize the flow. For comparing with first group, the flow and pressure pipeline of two groups were similar; The third group of H-07~H-08 and the fourth group of H-09~H-10 experiments still used the buffer tank to stabilize the flow. By adjusting the opening of the valve VT1, the high-pressure experiment with the pipeline pressure of about 300kPa and the low-pressure experiment with the valve fully open were respectively carried out to observe the change of flow stability. The results of 4 groups were shown in Table 3.

Table 3: Comparison of the results of two pressure stabilizing methods

Experimental Group	**Experiment Number**	**Stabilizing Pressure Method and Working Condition**	**Flow Rate (m^3/h)**	**Fluctuation Amplitude (%)**	**Pipeline Pressure (kPa)**	**Valve Opening (%)**
Group 1	H-01	constant head tank	30	0.52	175	28
	H-02		50	0.36	171	40
	H-03		120	0.22	143	70
Group 2	H-04	buffer tank, mid-pressure	30	0.50	175	29
	H-05		50	0.38	172	40
	H-06		120	0.22	164	66
Group 3	H-07	buffer tank, high-pressure	50	0.47	299	31
	H-08		120	0.31	289	54
Group 4	H-09	buffer tank, low-pressure	50	0.20	39	100
	H-10		120	0.18	99	100

4.2 Experimental results analysis of 2# facility

According to the data in Table 3, the variation of flow fluctuation amplitude with flow rate was shown in Fig. 8.

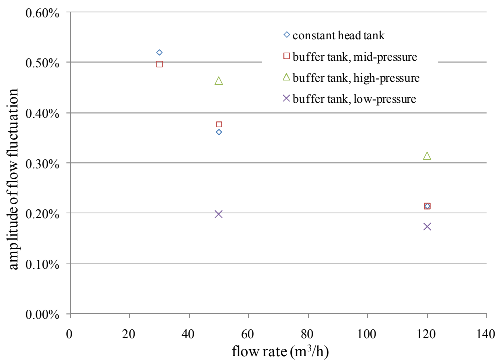
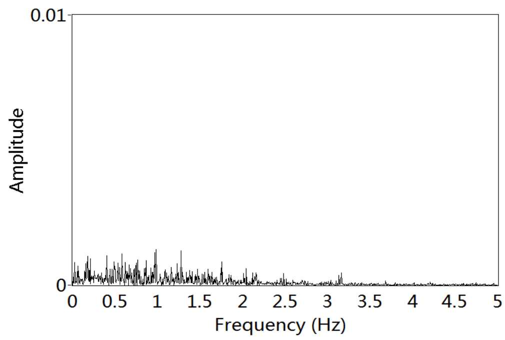
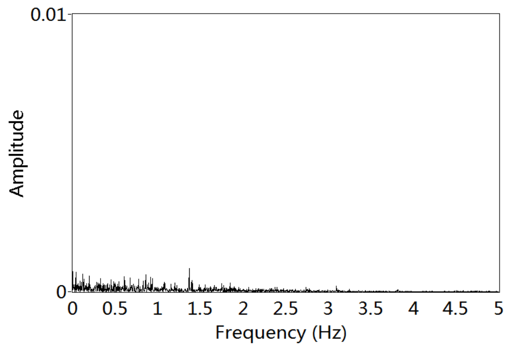


Figure 8: The relationship between flow fluctuation amplitude and flow rate of 2# facility

Compared with the result of group 1 and group 2, it can be found that the fluctuation amplitude of the two stabilizing flow methods were very close at different flow rate. In addition, at the low flow rate of 30m^3/h, the facility had the worst stability and the fluctuation amplitudes were more than 0.5%. However, in the FFT power spectrum of pressure signal (as shown in Fig. 9), no obvious characteristic frequency was found, and only some weak signals were found around 1Hz.



(a) experiment H-01 (water tower)



(b) experiment H-04 (buffer tank)

Figure 9: The spectrum analysis of experiment in 2# facility

In the correlation analysis of pressure and flow signals, it was found that there was a significant negative correlation between them, as shown in Fig. 10. It can be inferred that the fluctuation source mainly at downstream of the measuring point.

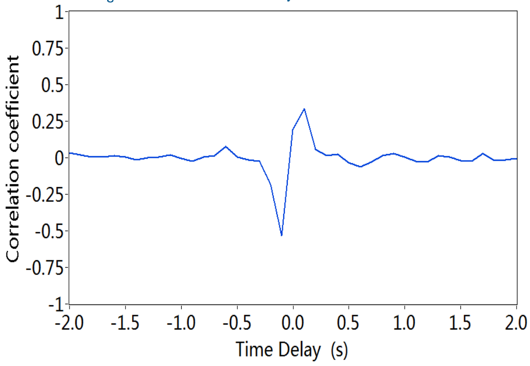


Figure 10: P2-TFM correlation curve of experimental H-07 in 2# facility

According to the downstream pipeline condition and the observation on field, when the VT1 valve had a small opening, for example less than 50%, the noise at VT1 valve increased evidently. Therefore, it can be judged that the excessive pressure loss leaded to cavitation at VT1 valve and flow fluctuation. Fig. 11 showed the variation of flow fluctuation amplitude with valve opening which also came from Table 3.

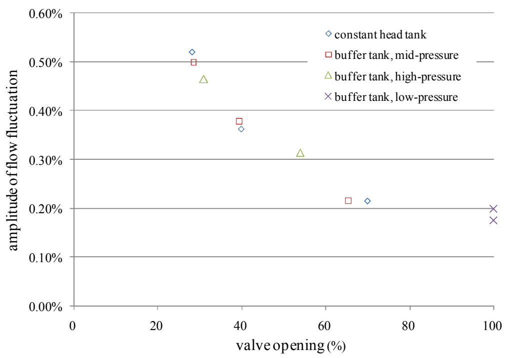


Figure 11: The relation between flow fluctuation amplitude and the opening of regulating valve in the 2# facility

In Fig. 11, the flow fluctuation amplitude decreased monotonically with the increase of valve opening, and the correlation coefficient of the two reached -0.92, showing a strong negative correlation. However, the experimental results of group 3 and group 4 at the same flow rate had a large dispersion in Fig. 8, which was obviously different from the distribution rule in Fig. 4, and the reasons were fully explained in Fig. 11.

The above experimental results showed that the well-designed buffer tank can achieve a stabilizing flow effect similar to that of the constant head water tank. When the regulating valve VT1 maintains a large opening, the flow fluctuation amplitude is always kept at a good level of 0.2%. The cavitation phenomenon caused by excessive pressure loss was the major cause of flow fluctuation. Therefore, in the design of the water flow facility, it is necessary to make a reasonable planning for the type selection of the regulating valve and its operating range, so as to avoid adjustment ratio too large.

5. Conclusion

The amplitude and frequency of flow fluctuation are not only the technical indicators to represent the flow stability of the facility, through the analysis of the direction of the fluctuation source and the change rule of flow stability at different working conditions (flowrate, pressure, pump operating parameters), the causes of the fluctuation can be effectively found.

Through the experimental study of two sets of facilities with different flow stabilization methods, it was found that they both had good isolation effect on the shaft frequency and blade frequency pulsation generated by the pump with relatively high frequency. However, for flow facilities with the buffer tank, working in low-efficiency areas of pumps should be avoided; and for facilities with the high constant water head tank, the reasonable regulating valve groups should be designed to avoid excessive local pressure loss, so as to obtain good flow stability.

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