Development of Dynamic Response Characteristics Calibration Device for Liquid Flowmeter

Yongsheng Zhang[1], Yanjun Liu[2]

[1, 2]Changcheng Institute of Metrology & Measurement , Beijing, China
E-mail: zhangyongsheng304@163.com

Abstract

In order to study the dynamic response characteristics of liquid flowmeter, a dynamic flow device based on superposition principle is established. The device generates the main flow through the screw pump; The positive step or negative step flow component is generated by opening or closing the high-speed solenoid valve; and the Sinusoidal pulsating flow component is formed by the sinusoidal mechanism. The real step flow or pulsating flow can be formed by superimposing the step flow component or pulsating flow component on the main flow. The system is equipped with a weighing system to measure the average flow. The test shows that the step flow component can change from 4L/min to 20 L/min, and the uncertainty of step amplitude is 5% (*k*=2); The frequency of pulsating flow can change from 5Hz to 50Hz, the amplitude can change from 5L/min to 20L/min, and the uncertainty of instantaneous flow is 0.5% (*k*=2). The device can be used to calibrate and evaluate the time constant, frequency response characteristics and mean flow error of flowmeter, and is expected to improve the accuracy of unsteady flow measurement.

1. Introduction

Unsteady flow is everywhere within the process industries, such as valve action, oil pump operation, motor operation and pipeline structure in the system, which may lead to instantaneous changes or periodic fluctuations in the process of fluid flow[1]. The true steady flow exists only in the low Reynolds number range in the laboratory. Traditional flow calibration is based on stable flow, so it is impossible to calibrate or evaluate the dynamic response characteristics of flowmeter.

When the flow rate changes constantly, the measurement performance of the flowmeter will be greatly affected, such as turbine flowmeter[2-6], When subjected to a time-dependent flow, the inertia of the rotor can cause the rotor speed to lag behind the steady state condition in an accelerating flow and to exceed it in a decelerating flow. The influence of a decelerating flow is greater than that of an accelerating one ， so that the mean speed can be greater than that corresponding to the mean flowrate. Another example is the differential pressure flowmeter[7,8], under dynamic flow, on the one hand, it will produce square-root error, on the other hand, due to the omission of inertia term, it will cause great error and can not work normally under some working conditions.

Under the steady-state flow condition, the flow calibration device and calibration method are relatively complete. Weighing method, volumetric method and pipe prover can be used for liquid flow calibration. However, for dynamic flow, both calibration device and method are very inadequate.

In the research, a dynamic flow device based on superposition principle is established. The device can be used to calibrate and evaluate the time constant, frequency response characteristics and average error of flowmeter, and it’s possible to improve the accuracy of unsteady flow measurement.

2. Description of the device

2.1 Overall scheme of the device

Figure 1 is the schematic diagram of flowmeter dynamic characteristic calibration device. The device includes the main flow system, step flow generator, pulsating flow generator and measurement system. The standard device uses white oil as the working medium, and the fluid in the oil tank is transported by the screw pump to form the main flow; The device is equipped with step flow branch and pulsating flow branch, and two branches are respectively used to superimpose the step flow component and pulsating flow component generated by the step flow generator and pulsating flow generator on the main flow, and then the standard step flow and standard pulsating flow are formed finally. The device is equipped with a weighing system for the periodic calibration of the reference flowmeter in the calibration device and the calculation of the average flow of pulsating flow.

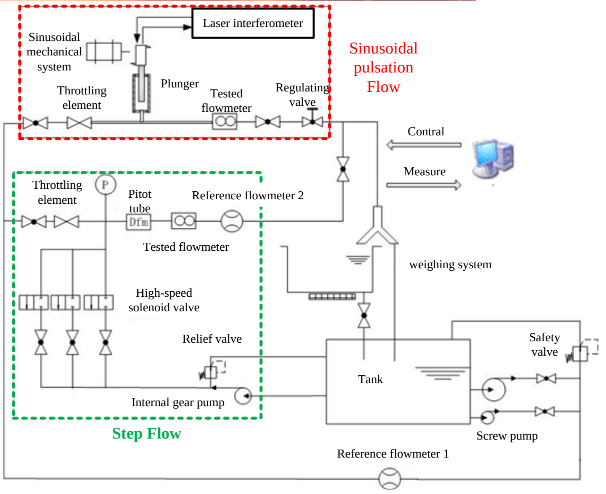


Figure 1: Schematic representation of the dynamic flow device.

2.2 Subsystem composition

2.2.1 Main flow system

In the main flow system, two screw pumps cooperate with the diverter valve to transport the fluid medium to form the flow; Two Coriolis mass flowmeters are used as the reference flowmeter to measure the main flow. The reference flowmeter 1 is used to measure the main flow under the pulsating flow condition, and the reference flowmeter 2 is used to measure the steady flow before and after the step flow; The main flow system is equipped with a weighing system to calibrate the reference flowmeter and to measure the average flow under pulsating flow; The throttling device is installed at the upstream of the confluence location of flow component and main flow to ensure that the pressure difference between the upstream and downstream of the confluence location is greater than 2MPa; A filtering system and a temperature control system are installed in the bypass of the system to ensure that the oil in the system is clean and that the oil temperature is stable during operation. The temperature transmitter and pressure transmitter are installed in the system to measure and monitor the system fluid temperature and pressure.

The flow range of the main flow system is 10L/min ~ 200L/min, and the pump pressure is greater than 3MPa. The expanded uncertainty of the weighing method system is 0.1% (k=2), and the measurement uncertainty of the reference flowmeter is 0.2% (k=2).

2.2.2 Step flow generator

The step flow component is formed by the internal gear pump in the step flow generator. When the high-speed solenoid valve is suddenly opened, the step flow component will be quickly superimposed on the main flow. The instantaneous change of velocity in the pipeline is measured by pitot tube; and the reference flowmeter 2 in the main flow system is used to measure the steady flow before and after superposition.

The opening time of the high-speed solenoid valve is less than 4.5ms, and the closing time is less than 6ms. The flowrate is about 6L/min under the pressure of 3MPa, and four solenoid valves are installed in the system.

The rise time of step flow is monitored through the pitot tube. Two dynamic pressure sensors are installed in the pitot tube to measure the total pressure and static pressure of the fluid in the pitot tube, and then the dynamic pressure and the flowrate can be calculated. The response frequency of the two dynamic pressure sensors is greater than 20kHz and the response time is less than 0.05ms.

2.2.3 Pulsating flow generator

The servo motor is used as the power source in the pulsating flow generator, and the rotation of the motor is converted into the sinusoidal reciprocating motion of the plunger through the sinusoidal mechanism, and then periodically discharges and inhales the fluid to produce a flow pulsation by the plunger. The running speed of the plunger is measured by a laser interferometer, and the instantaneous pulsating flow component is calculated by the plunger cross-sectional area and plunger speed. The working principle is shown in Figure 2. The instantaneous displacement of the plunger and pulsating flow component can be calculated by equations (1) and (2). The pulsating flow component is related to the eccentricity of the sinusoidal mechanism and the speed of the servo motor. The eccentricity of the sinusoidal mechanism can be continuously adjusted.

$$l = R\cos(\omega t)\,. \tag{1}$$

$$q_p = AR\omega\sin(\omega t) \tag{2}$$

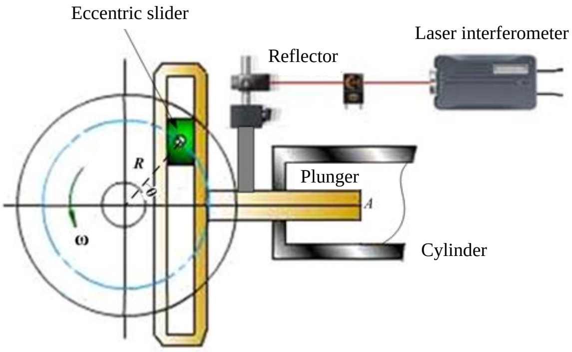


Figure 2: Schematic diagram of pulsating flow generator.

The rated speed of the servo motor in the pulsation generator is 3000rmp, and the maximum speed can reach 6000rmp, and the minimum stable speed can reach 1rmp. Thus, the pulsation frequency can be continuously adjustable within the range of 5Hz ~ 50Hz. The XL-80 laser interferometer of Renishaw company is selected to measure the displacement of plunger, and the accuracy is better than ± 0.005%, and the continuous pulse trigger mode is used to measure the plunger displacement, and data recording shall be completed within ± 0.5μs of the falling edge of the pulse; The standard pulse is generated by the signal source, and the uncertainty of the standard pulse period is better than 0.01%; The plunger velocity can be calculated by the instantaneous displacement of the plunger and the period of the standard pulse, and the uncertainty of the instantaneous velocity is less than 0.1%.

2.2.4 Measurement system

The signals of dynamic pressure sensor, trigger pulse, reference flowmeters and measured flowmeter are collected through PXI system of NI company, and the sampling frequency can reach 2MS/s.

3. Device test verification

3.1 Step flow

The rise time[9] t_{95} of the step flow is the time from the response of the total pressure sensor to the dynamic pressure reaching 95% of the step amplitude. Figure 3 is the schematic diagram of step flow rise time calculation. The average value of the front platform total pressure is p_{t0}, and the average value of the dynamic pressure is p_{d0}, and the average value of the rear platform dynamic pressure is p_{d1}, and then the dynamic pressure change reaching 95% amplitude can be expressed as p_{95}. t_0 is the step start time when the sudden change of the total pressure occurs, and the corresponding time of p_{95} is t_1, and then the rise time Δt can be calculated by subtracting t_0 from t_1.

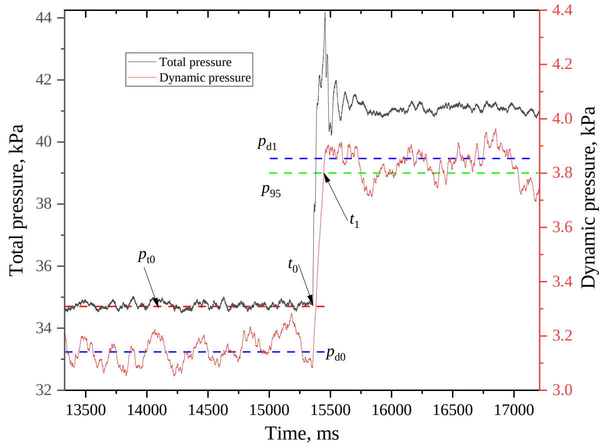


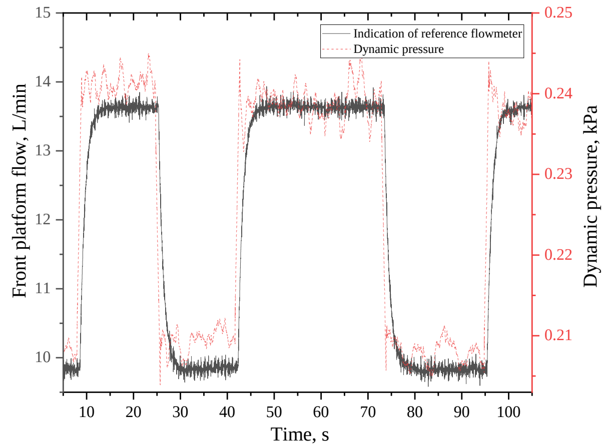
Figure 3: Schematic diagram of step flow rise time calculation.

The steady flow before the step change is the front platform flow, expressed as q_0, and the steady flow after the step change is the rear platform flow, expressed as q_1, the step flow amplitude is expressed as Δq, and it can be calculated by equations (3). The uncertainty of step flow amplitude can be estimated by equation (4), Where U_{rf} is the measurement uncertainty of reference flowmeter 2, and U_{rf} =0.2%（*k*=2）.

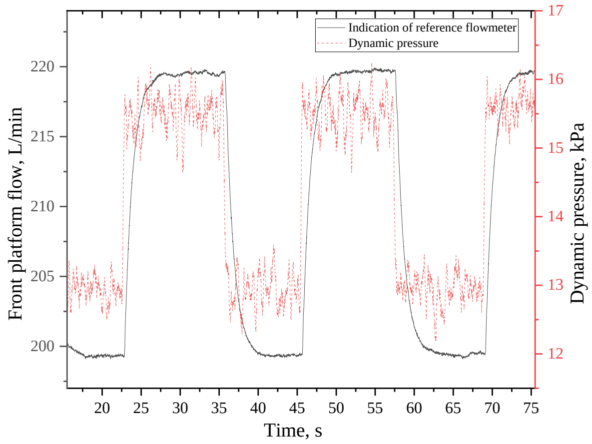
$$\Delta q = | q_1 - q_0 | \quad (3)$$

$$U_{rel}(\Delta q) = \frac{U_{rf}(q_1 - q_0)}{q_1 - q_0} \le U_{rf}(q_0 + q_1) / \Delta q \quad (4)$$

Table 1 shows the Verification results of step flow test. It is verified that the front platform flow of the test device covers 10 L/min ~200 L/min, the step flow range is 4L/min~20L/min, and the maximum rise time of step flow is 8.8ms, and the maximum step amplitude uncertainty is 4.6%(*k*=2). Figure 4 shows the flow meter indication and dynamic pressure curve during step process.



(a) Front platform flow is 10L/min, Step amplitude is 4L/min



(b) Front platform flow is 200L/min, Step amplitude is 20L/min

Figure 4: Flow meter indication and dynamic pressure curve during step process.

Table 1: Verification results of step flow test.

Front platform flow (L/min)	Rear platform flow (L/min)	Step amplitude (L/min)	Rise Time (ms)	Amplitude uncertainty (%)，*k*=2
9.84	13.63	3.79	6.3	1.2
24.88	28.78	3.90	6.7	2.7
40.27	44.00	3.73	7.5	4.6
25.73	35.56	9.83	7.2	1.2
60.50	70.28	9.77	7.2	2.7
98.74	110.00	11.27	8.8	3.7
49.57	69.06	19.50	6.7	1.2
100.38	116.83	16.43	8.7	2.6
199.33	219.53	20.20	5.3	4.1

3.2 Pulsating flow

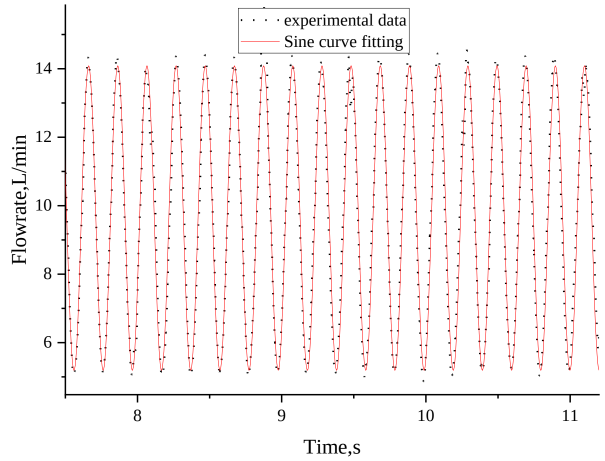
The instantaneous pulsating flow is calculated by equation (5)， q is the instantaneous flow, q_0 is the instantaneous value of reference flowmeter 1, q_p is the instantaneous pulsating flow component, A is the plunger cross-sectional area, and V is the instantaneous plunger speed.

$$q = q_0 + q_p = q_0 + AV \ . \tag{5}$$

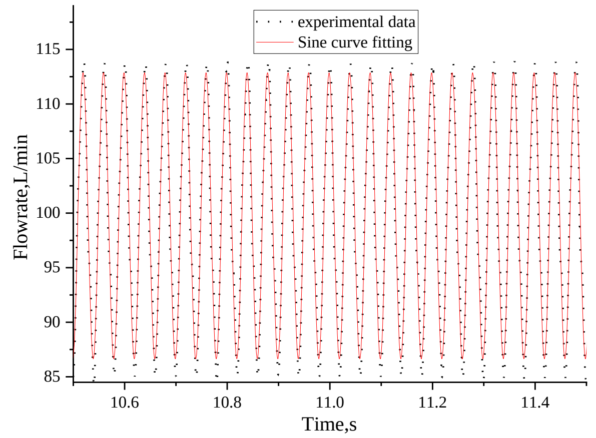
The test data are fitted with sine function, which is expressed by equation (6). Where A_q is the amplitude of pulsating flow; f is the frequency of pulsating flow, θ is the initial phase of pulsating flow, and q_0 is the mean flow, that is, platform flow.

$$q(t) = A_q \sin(2\pi ft - \theta) + q_0 \ . \tag{6}$$

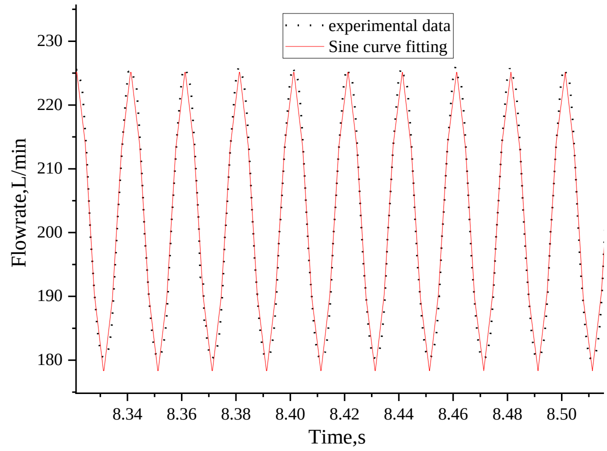
Figure 5 shows the standard pulsating flow curve under various working conditions. The main flow is 9.6L/min, 100L/min and 202L/min respectively, and the pulsation frequency is 5Hz, 25Hz and 50Hz respectively, and the pulsation amplitude is 4.6L/min, 13L/min and 23L/min respectively.



(a) The main flow is 9.6L/min, and the pulsation amplitude is 4.6L/min, and the pulsation frequency is 5Hz



(b) The main flow is 100L/min, and the pulsation amplitude is 13L/min, and the pulsation frequency is 25Hz



(c) The main flow is 202L/min, and the pulsation amplitude is 23L/min, and the pulsation frequency is 50Hz

Figure 5: Standard pulsating flow curve.

When the pulsating flow is at the trough of wave, the relative uncertainty of the instantaneous flow is the largest, which can be expressed as formula (7)[10], where $u(q)_{\max}$, $u_{rel}(q_0)$ and $u_{rel}(q_p)$ are the uncertainty of the instantaneous flow at the trough, the measurement uncertainty of the reference flowmeter 1 and the uncertainty of the pulsating flow component respectively. The uncertainty of pulsating flow component can be expressed as equation (8). $u_{rel}(A)$ is the uncertainty of the plunger cross-section, which mainly includes the uncertainty of the outer diameter measuring instrument and the repeatability of multiple measurements. The combined uncertainty of the plunger cross-section is about 0.023%. $u_{rel}(V)$ is the uncertainty of plunger velocity, which mainly includes the uncertainty of displacement measurement of laser interferometer and the uncertainty of standard signal source. The combined uncertainty of plunger velocity is less than 0.1%.

$$u(q)_{\max} = \frac{\sqrt{[u_{rel}(q_0)q_0]^2 + [u_{rel}(q_p)q_p]^2}}{(q_0 - q_p)} \qquad (7)$$

$$u_{rel}(q_p) = \sqrt{u_{rel}^2(A) + u_{rel}^2(V)}\ . \qquad (8)$$

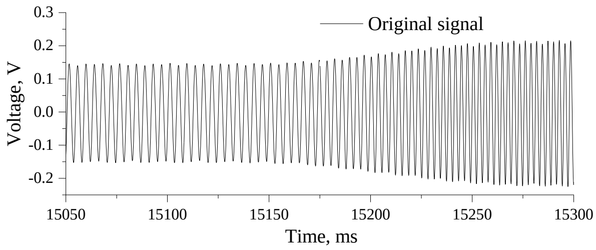
It is verified that the main flow of the test device covers 10L/min~200L/min, and the amplitude of pulsating flow covers 5L/min~20L/min, and the pulsating frequency is 5Hz~50Hz, and the maximum uncertainty of instantaneous flow is 0.43% (*k*=2). Table 2 shows the Verification results of pulsation flow test.

Table 2: Verification results of pulsation flow test.

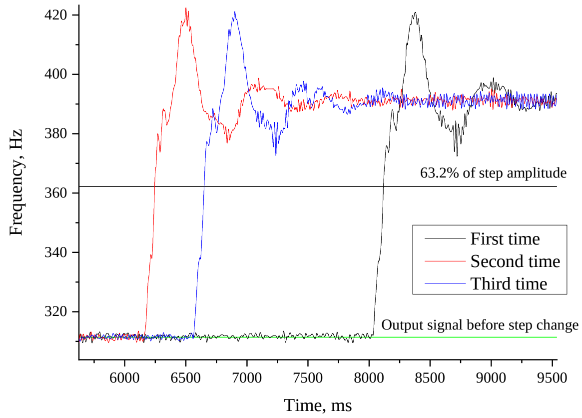
Set working condition			Sine fitting result			uncertainty (%)，k=2
main flow (L/min)	Pulsation amplitude (L/min)	Pulsating frequency (Hz)	main flow (L/min)	Pulsation amplitude (L/min)	Pulsating frequency (Hz)	
10	5	5	9.67	4.58	5.0	0.43
10	5	50	10.08	4.19	49.2	0.38
50	5	5	49.08	4.73	5.0	0.22
50	5	50	49.83	7.78	50.1	0.24
50	20	5	49.78	18.6	5.0	0.35
50	20	50	49.61	23.65	50	0.43
100	10	5	99.74	9.40	5.0	0.22
100	20	50	97.49	23.53	50	0.27
200	20	5	198.9	18.98	5.0	0.22
200	20	50	202.2	23.32	50	0.24

4. Preliminary calibration test of flowmeter

After the calibration device was completed, a preliminary calibration test was carried out for the turbine flowmeter. Figure 6 is the calibration curve of the turbine flowmeter under the step flow condition. Figure 6 (a) shows the original signal output. Under the condition of steady flow, the frequency and amplitude of the original signal are relatively consistent. When the step flow is generated, the amplitude of the original signal increases, and the original signal becomes more compact, and the frequency increases, and then the original signal becomes stable gradually. Figure 6 (b) shows that the original signal of the turbine flowmeter is converted into the frequency signal. The time when the output signal starts to change and the time when the signal output reaches 63.2% step amplitude can be obtained from the curve, and then, the time constant of the turbine flowmeter can be calculated.



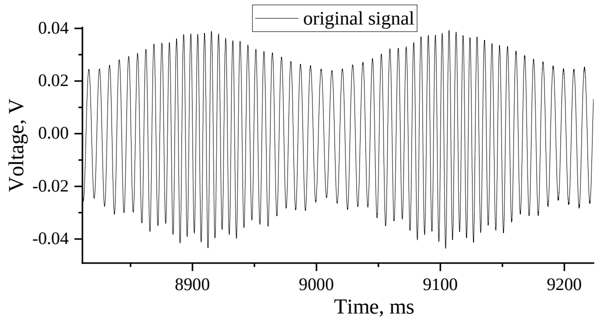
(a) Original signal of turbine flowmeter.



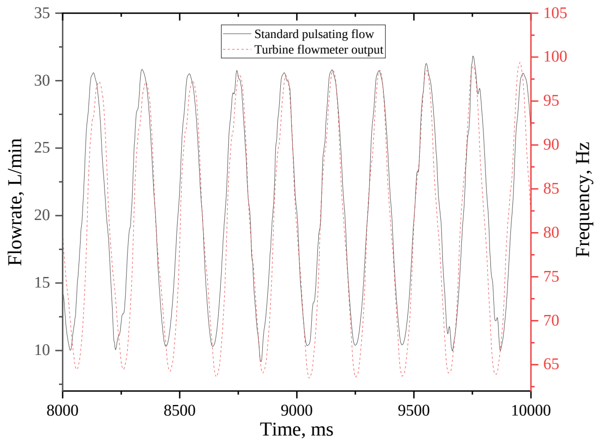
(b) Turbine flowmeter output frequency signal.

Figure 6: Calibration curve under step flow.

Figure 7 is the calibration curve of the turbine flowmeter under the pulsating flow condition. Figure 7 (a) shows the original signal output of the turbine flowmeter. With the increase of flowrate, the amplitude of the original signal increases and the waveform becomes more compact; As the flowrate decreases, the original signal amplitude decreases and the waveform becomes loose; The amplitude and frequency of the original signal change periodically. Figure 7 (b) shows that the original signal of the turbine flowmeter is converted into the frequency signal.



(a) Original signal of turbine flowmeter.



b) Turbine flowmeter output frequency signal.

Figure 7: Calibration curve under pulsating flow.

Sinusoidal curve fitting can be carried out for standard pulsating flow and turbine flowmeter output respectively, and the mean flow, pulsating amplitude, pulsating frequency and initial phase of standard pulsating flow and flowmeter output can be obtained respectively, and then the dynamic response characteristics such as mean flow error, amplitude frequency characteristics and phase frequency characteristics can be calculated.

5. Conclusion

A calibration device for the dynamic response characteristics of liquid flowmeter is established in the study. The calibration device can generate standard step flow and pulsating flow, and it can carry out calibration tests for the dynamic characteristic parameters of flowmeter, such as time constant, amplitude frequency characteristic, phase frequency characteristic and mean flow error. With the increasing demand for the accuracy of unsteady flow measurement in process control, more and more attention is paid to the dynamic characteristics of flowmeter. The device is helpful to evaluate the dynamic response characteristics of the flowmeter. It can guide the correction of unsteady flow measurement and improve the accuracy of dynamic flow measurement.

References

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