Effect of motor characteristics on uncertainty of electric flow diverter with large pipe diameter

Haiyang Li¹, Xuejing Li¹, Yuyang Chen¹ and Lijun Sun²,³

¹ Shanghai Institute of Measurement and Testing Technology, Shanghai, China; ² School of Electrical Engineering and Automation, Tianjin University, Tianjin, China
³ Email: sunlijun@tju.edu.cn

Abstract. Standard flow facility is a platform for performance test of flowmeters. Flow diverter is an essential component of liquid flow facility based on flying start-and-stop method, and is also a key equipment deciding the uncertainty of flow facility. In order to improve the accuracy of large flow facilities, the effects of acceleration performance and liquid shock force on the uncertainty of the flow diverter with large flow rate is analyzed. The actuation structure using servo motor and reducer to drive the flow diverter is put forward. The effect of step motor and servo motor on the uncertainty of the flow diverter is verified by real-flow test. The results of experiment indicate that servo motor driven flow diverter has faster transfer acceleration and more stable transfer process. The test results of transition time difference method show that the uncertainty of servo motor driven flow diverter is less than 0.003%.

1. Introduction

As a platform for performance test the flow facility is necessary for experimental research of flowmeters. The flow facility for flowmeter calibration is also an equipment for transferring the flow rate values and keeping them uniform in the world. Uncertainty is a key parameter reflecting the level of a flow facility since it directly affects the results of flowmeters test. The expanded uncertainty should be better than 0.017% (k=2) to calibrate the coriolis mass flowmeter with accuracy of 0.05%. The combined standard uncertainty of the whole facility should be better than 0.0085%.

Flow diverter is an essential component of liquid flow facility based on flying start-and-stop method. The flow diverter transfers the flow direction from bypass pipeline to weighing tank and starts the timer at the beginning of a test run. While the test is finished, the flow diverter changes the flow direction to bypass pipeline and stops the timer. The uncertainty of the flow diverter is a main factor contributed to the combined uncertainty of the flow facility. To optimize the structure of the flow diverter and reduce the uncertainty are very important for improving the flow facility.

National Metrology Institute of Japan developed a flow diverter with double-wing rotating in same direction at the beginning and the end of measurement, and reached an uncertainty of 0.0019% [1]. The nozzle of weighing system in flow facility at Physikalisch-Technische Bundesanstalt is able to keep the flow profile even under different flowrate conditions by adjusting the thickness of the nozzle cross-section. An encoder was also used for monitoring and controlling the rotating process of flow diverter. The relative standard uncertainty of this weighing system is better than 0.004% [2-4].

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But, most of these research aimed at small flow facilities. When the pipe diameter of flow facility exceeds 200mm and flow rate greater than 300m$^3$/h, it has been found that the measurement performance of flow diverter would be poorer for which the flow diverter is influenced by the liquid shock force and the large rotational inertia under the large flow rate condition. Then, this paper presents a research on electric flow diverter. The effect of acceleration performance and liquid shock force on the uncertainty of flow diverter with large pipe diameter is analyzed. The actuation structure using servo motor and reducer is put forward for improving the measurement performance of the flow diverter. It was shown by the results of test that the uncertainty of the servo motor driven flow diverter is better than 0.003%.

2. Flow diverter and sources of measurement error

2.1. Principle of flow diverter

The schematic of the flow facility based on flying start-and-stop method is shown in Figure 1. Where 1 is pump, 2 is flowmeter under test, 3 is flow diverter, 4 is weighing tank, 5 is liquid storage tank, 6 is bypass pipeline, 7 is electronic balance, 8~10 are switch valves, 11~12 are regulating valves. The process of flowmeter calibration is as below. Before the start of a test run, the liquid passes through the flow diverter and goes to the storage tank along the bypass pipeline. After the flowrate is stable at the required value for several minutes, the flow diverter changes the flow direction to weighing tank and triggers the timer. This is the beginning of a test run. As the liquid in the weighing tank reaches preset value, the flow diverter transfers the flow back to the bypass pipeline and stops the timer. This is the end of the test run. The average mass flow rate of the flow facility can be calculated through the mass of liquid in the weighing tank and the recorded time of liquid flowing into the weighing tank. The measurement performance of the flowmeter under test can be evaluated by compare its flowrate with the average flowrate measured by the flow facility.

![Figure 1](image1.png)  
**Figure 1.** The schematic diagram of the flow facility.

![Figure 2](image2.png)  
**Figure 2.** Transfer process of the flow diverter.

Figure 2 shows the transfer process of the flow diverter. Where 1 is feeding pipe, 2 is nozzle, 3 is flow distributor, 4 is cutting board, 5 is inclined plate. The flow velocity distribution of liquid at the outlet of the nozzle is basically symmetrical because the liquid from the feeding pipe is corrected by the nozzle. The cutting board of flow distributor can enable the liquid to flow into weighing tank or by-pass pipeline through different outlet by rotating the flow distributor. The curve from point 1 to point 0 shows the process of the flow distributor transfer out from the weighing tank to the by-pass pipeline and the curve from point 0 to point 1 is transfer in from the by-pass pipeline to the weighing tank. Points A and B are the positions which the top of the cutting board go through exactly right down the outside wall of the nozzle. The liquid flows into the bypass pipeline and weighing tank simultaneously as the cutting board is between these two points. Points A and B are called beginning and end points of effective transfer process.
Switch on the timer to record the beginning time at the moment of rotating the flow distributor and directing liquid to flow into the weighing tank. Turn off the timer and record the end time as flow diverter transfers automatically to make the liquid flow into the by-pass pipeline again once the preset value is reached. The curve in Figure 3 shows the variation of the flowrate $q_m$ that the liquid flowing into the weighing tank.

The $q_H$ means the real mass flowrate. $t_a \sim t_b$ is the process that the flow diverter transfer in the weighing tank and the flow rate increases gradually. $t_b \sim t_c$ means the relatively long and stable filling time. And, $t_c \sim t_d$ is the process that the flow diverter transfer out the weighing tank and the flowrate decreases gradually. The areas of A and C can be complementary if the motion performance of the transfer in and out process are similar. So in order to reduce the timing error in the process of transfer, $t_b$ and $t_d$ are recorded at the both sides of the nozzle using the double-optoelectronic timing method, that is, start timing at the end of the transfer-in and stop timing at the end of the transfer-out. $t_b$ refers to the time point that the cutting board turn to one of the nozzle edge(point B in Figure 2) and the liquid stop flowing into the by-pass pipeline. $t_d$ refers to the time point that the cutting board turn to the other edge of the nozzle(point A in Figure 2) and the liquid stop flowing into the weighing tank. In this way, the commissioning time taken by flow diverter installation and adjusting the position of beginning and ending timing can be reduced [5,6].

### 2.2. Analysis of measurement error

The average mass flow rate of liquid measured by the flow facility is $q_a$

$$q_a = \frac{m}{t_b - t_a}$$

Where, $m$ is the mass of liquid collected by the weighing tank and it is shown as equation (2)

$$m = \int_{t_a}^{t_b} q_1(t)dt + q_H (t_c - t_d) + \int_{t_c}^{t_d} q_2(t)dt$$

If the process that the flow diverter transfer in and out have equivalent motion performance, then it is assumed that

$$q_1(t) = q_H - q_2(t + t_c - t_a)$$

Combine equation (2) with equation (3), the equation (4) can be gotten.

$$m = q_H (t_d - t_b) + \int_{t_b}^{t_d} q_1(t)dt$$

$$\Delta t = (t_b - t_a) - (t_d - t_c)$$

Where, $\Delta t$ stands for the time difference between the process of transfer-in and transfer-out when the rotation process are not exactly equal. Then the equation (4) can be written as

$$m = q_H (t_d - t_b) + \int_{t_b}^{t_d} q_1(t)dt$$

Where, $q_1(t)$ comes from the process of the cutting board go through the nozzle and it can be gotten from Figure 2.
\[ q_i(t) = \frac{L \sin \phi(t)}{w} q_n \]  

(7)

Where, \( L \) is the length of the cutting board, \( \phi \) is the rotational angle of cutting board, \( w \) is the width of nozzle.

The \( \phi \) changes with time. If the effective transfer process of flow diverter keeps constant turn speed, then it will be predicted that

\[ \phi(t) = k t \]  

(8)

Finally the error between real mass flow rate and measured mass flow rate by using the flow diverter with the gravimetric method can be written as

\[ e = \frac{q_b - q_n}{q_n} = \frac{L}{k (t_1 - t_0)} (1 - \cos k \Delta t) \]  

(9)

It can be obtained from equation (9) that: first, the time difference \( \Delta t \) between the process of transfer in and out can result in the flow measurement error. Second, the repeatability of transition time will be bad, and the flow measurement error will be induced if the effective transfer process of flow diverter is not uniform motion, that is the parameter \( k \) is unsteady.

3. Influence factors of uncertainty

As mentioned above, the rotating performance of the flow diverter is the main source of flow measurement uncertainty if the flow velocity field at the outlet of the nozzle is uniform. Uniform motion is crucial to the process of effective transfer. So the performance of acceleration and shock resistance of the motor driving the flow diverter is the principal factors affecting measurement uncertainty. The influence factors of uncertainty are compared and analyzed as following for the actuation plans of servo motor with reducer and step motor with reducer.

3.1. Acceleration performance of flow diverter

A transfer process control strategy of “acceleration, uniform speed and deceleration” is applied in the electric flow diverter to avoid liquid splash and transfer time fluctuation caused by mechanical vibration in the transfer process. The motor driven flow diverter will steadily run at a preset speed after accelerated for a short distance from the beginning of transfer so the prospective process of effective transfer in and out are uniform.

The transition time is only several hundred milliseconds and the transfer speed of flow diverter is fast. Both of the servo motor and step motor plans are configured with reducer which can increase torque and decrease load inertia. But, the motor need to run at a higher speed. Very high acceleration performance of the motor is required to make sure the effective transfer process is uniform.

The motion equations of motor can be written as

\[ J \frac{d^2 \theta}{dt^2} + D \frac{d \theta}{dt} + T_L = T_M \]  

(10)

Where \( J \) is the sum of the rotational inertia converted to the end of the axle. \( T_L \) is load torque which is mainly composed of the friction torque of bearings. \( T_M \) is electromagnetic torque generated by the motor. \( D \) is the coefficient of proportional velocity. The value of the second item in this formula is very small so it can be ignored.

Then equation(10) can be written as

\[ J \beta = T_M - T_L \]  

(11)

The theoretical acceleration time \( t_{ac} \) can be gotten

\[ t_{ac} = \frac{J \times 2 \pi \times (n_0 - n_1)}{60 \times (T_M - T_L)} \]  

(12)

Where, \( n_0 \) and \( n_1 \) respectively refers to the initial and final rotation speed. The actuation plan of step motor adopts a three-phase hybrid step motor with torque about 60 N\( \cdot \)m and rotational inertia of the rotor 0.01 kg\( \cdot \)m\(^2\). A three phase alternating current permanent magnet synchronous motor is used in the
plan of servo motor. The nominal torque of the servo motor is 27 N·m, and rotational inertia is 0.01179 kg·m². Both of the step motor and servo motor use planetary reducers with reduction ratio 15:1.

The rotational inertia of the load, including that of the flow distributor and the liquid inside the flow distributor, can be calculated by equation (13) when converted to the end of the motor axle.

\[
J = J_M + \frac{J_1}{\chi^2 \cdot \eta} + J_2
\]  

(13)

Where \(J_M\) is the rotational inertia of the motor rotor, \(J_1\) is the rotational inertia of whole mechanical structure, \(J_2\) is the rotational inertia of the reducer, \(\chi\) is the reduction ratio of the reducer, \(\eta\) is the efficiency of the reducer. The effective transition time is about 150 ms, and the effective rotation angle of cutting board of flow diverter is 9°. Constant angular velocity of transfer is 10 rpm that corresponding to the motor speed of 150 rpm.

The servo motor with constant torque characteristics is able to output constant torque within the rated speed range. It has strong ability of overload so the maximum torque can reach 3 times of the rated value in a short period of acceleration and deceleration which can be used to overcome the inertial torque of the inertial load at the moment of start. So the torque output by the servo motor in acceleration process is 81 N·m for the scheme mentioned above. It was calculated that the theoretical acceleration time of servo motor is 70 ms.

The step motor start normally only the pulse frequency is limited below the self-starting frequency, otherwise, the phenomenon of out-of-step and locked-rotor will appear when the motor starts up. And step motor doesn’t have ability of overload and its torque output capacity is always weaker than servo motor. The electromagnetic torque output by the step motor is not stable and decreases gradually with the increase of motor speed. When start the step motor, the frequency of control pulse should be increased slowly to use high torque under low speed condition, so the motor can reach the preset high speed gradually. The step motor should not stop suddenly in a high speed-running state, otherwise, an overshoot usually happens because of inertia. To achieve fast and uniform transfers of flow diverter, an exponential control algorithm is proposed to control the speed of the step motor for the change of step motor speed follows a sort of exponential function. The acceleration time is designed as 150 ms in this paper.

3.2. Liquid shock resistance

The liquid shock torque appears as liquid shots into the atmosphere from the nozzle in a form of free jet flow, and hits the cutting board and the lower inclined plate of the flow distributor. The velocity of the jet has increased after it falls vertically downward. The velocity of the flow reaching the lower inclined plate is slightly different with that of the flow at the cutting board. The directions of the torques caused by liquid hitting the cutting board and the lower inclined plate are opposite so the torques cancel each other out in some degree. In the process of transfer, the liquid shock torque varies with the change of the rotary position of the flow distributor, that is, the torque changes according to the rotation of the flow distributor, which influences the constant velocity of the transfer.

The position control of step motor is determined by the total number of the pulse. The turn speed of the motor is proportional to the frequency of the command pulse. The control of the step motor is open loop which cannot acquire and adjust the current speed. The rotation of the step motor is influenced by external torque, so the speed fluctuation appears in the effective transfer process, which makes the coefficient \(k\) of equation 9 unstable and induces the measurement error.
Figure 4. Control system of servo motor.

The closed-loop control system of servo motor is composed of position control, velocity control and drive unit as indicated by Figure 4. The encoder feeds the information of the position and the velocity back to the driver, and the driver makes regulation based on the information. As the liquid shock torque changes the motor speed, the encoder measures the speed, and the velocity control unit will adjust the electromagnetic torque output by the drive unit, so speed perturbation can be corrected. The servo motor is stronger than the step motor in aspect of the performance resisting disturbance of external torque. When calibrate flowmeters under large flow rate conditions, the transfer velocity of servo motor controlled flow diverter will be much more stable, and the flow measurement error will be less.

4. Performance test of the flow diverter

Through the analyses above, it can be found that the velocity of effective transfer process is unstable due to the badness of acceleration performance and shock resistance property. It means that the coefficient $k$ fluctuates and the time difference $\Delta t$ appears, and then the measurement error occurs. In this section, the effect of the step motor plan and the servo motor plan on the uncertainty of the flow diverter is compared with each other by experimental test from the angle of acceleration and stability of the transfer process. The transition time difference method is applied in the uncertainty test of the motor-driven flow diverter.

The test process of the transition time difference method is as following. After the flow rate is stable at the required value for ten minutes, the flow distributor is controlled to transfer in and out for $n(n \geq 10)$ times and the transition times $t_{1i}$ for transfer in and $t_{2i}$ for out are recorded [7,8].

The mean times of $n$ times transfer in and out are $t_1$ and $t_2$, respectively.

$$t_1 = \frac{\sum_{i=1}^{n} t_{1i}}{n} \quad (14)$$

$$t_2 = \frac{\sum_{i=1}^{n} t_{2i}}{n} \quad (15)$$

Then the type A uncertainty $u_{A1}$, $u_{A2}$ and type B uncertainty $u_B$ can be written as

$$u_{A1} = \frac{1}{t_{\text{min}}} \sqrt{\frac{\sum_{i=1}^{n} (t_{1i} - t_1)^2}{(n-1)} \times 100\%} \quad (16)$$

$$u_{A2} = \frac{1}{t_{\text{min}}} \sqrt{\frac{\sum_{i=1}^{n} (t_{2i} - t_2)^2}{(n-1)} \times 100\%} \quad (17)$$

$$u_B = \frac{t_1 - t_2}{4t_{\text{min}}} \times 100\% \quad (18)$$

Where, $t_{\text{min}}$ is the minimum liquid filling time of the weighing tank under normal operating conditions. Finally the total uncertainty $u_{\text{total}}$ can be written as

$$u_{\text{total}} = \sqrt{u_{A1}^2 + u_{A2}^2 + u_B^2} \quad (19)$$
4.1. Acceleration performance test of transfer process

In order to test the effect of acceleration performance on uncertainty of motor-driven diverter, the experimental tests and analysis of comparison between servo motor driving and step motor driving are carried out. As shown in Figure 5, the motor driven flow diverter was fabricated. Where 1 is reducer, 2 is motor, 3 is nozzle, 4 is flow distributor, 5 is optoelectronic switch.

![Figure 5. The platform of diverter.](image)

The velocity-time curve of step motor driving is displayed in Figure 6. It is clear that the acceleration time of motor is 200ms which is longer than that of the preset control algorithm. The time span recorded by photoelectric sensors is 150ms, which represents the effective transfer process. The excess uniform rotating time reserved before and after the effective transfer process is 100ms in all, so the expected total uniform rotating time is 250ms. However, the actual uniform rotating time is about 200ms from the figure, so the flow diverter cannot keep uniform motion during the effective transfer process. The uncertain laws of speed-change can easily cause the time difference $\Delta t$ between the processes of transfer in and out, and generate the measurement error. The acceleration performance of step motor driven flow diverter is unsatisfied, which can lead to larger flow measurement uncertainty.

![Figure 6. Velocity-time curve of step motor driving.](image)

The test result of servo motor driving is shown in Figure 7. It can be seen from the curve that the acceleration time of servo motor is about 80ms which is consistent with theoretical calculation in section 3.1. The time of actual uniform motion which is about 250ms guarantees that the effective transfer process of flow diverter keeps a constant speed. The acceleration performance of servo motor driven flow diverter is acceptable and its measurement uncertainty is small. To avoid the disturbance of external factor, the transition time difference method is used to quantitatively evaluate the transfer

![Figure 7. Velocity-time curve of servo motor driving.](image)
acceleration performance of the flow diverter without liquid. Test results revealed that the total uncertainty $u_{\text{total}}$ of the flow diverter using step motor and servo motor is 0.0027\% and 0.0008\%, respectively. Therefore, when the flow facility with flying start-and-stop method is used to test the performance of flow instrumentation, the error of time measurement will be induced if the flow diverter cannot guarantee the uniform velocity in effective transfer process.

4.2. Stability test of transfer process
The liquid shock resistance properties of step motor and servo motor driven flow diverters are tested under same transfer conditions, respectively. Figure 8 shows the velocity-time curves of the step motor driving and the servo motor driving as the flow rate is 300 $m^3/h$, correspondingly. Comparing Figure 8 with Figure 6 and Figure 7, it’s apparent that these two velocity-time curves are both influenced by liquid shock. As faced with liquid shock force, the velocity fluctuation of servo motor driven flow diverter is much less than that of the step motor driven because of the feedback control of speed in servo motor.

According to the analysis above, fluctuation of velocity easily causes vibration of transfer time and then increases the measurement error. The effect of liquid shock resistance property on uncertainty of flow diverter is quantitatively tested by transition time difference method. The total uncertainty curves of these two actuation schemes are obtained by a series of experiments under different flowrate conditions. As shown in Figure 9, the total uncertainty of flow diverter driven by step motor increases quickly with flow rate growing. The uncertainty is 0.009\% as the flow rate is 350 $m^3/h$. That means the flow diverter of this scheme is easily influenced by liquid shock force and the measurement error is mainly introduced by the fluctuation of velocity in transfer process. The total uncertainty of servo motor driven flow diverter rises slowly with flow rate changes. The uncertainty is still less than 0.003\% as the flow rate reaches 350 $m^3/h$. The servo motor driven flow diverter is able to ensure the flow facility has low uncertainty in the process of performance test of the flow instrumentation with large flowrates.
5. Conclusion
Flow diverter is an important part of liquid flow facility based on flying start-and-stop method, and is also a key equipment contributed to the uncertainty of flow facility. The sources of flow measurement error and the influence factors of uncertainty about the motor-driven flow diverter with large pipe diameter are analyzed. The transfer acceleration performance and stability of the servo motor driving and the step motor driving schemes are tested in real flow experiments. It was found that the acceleration performance and liquid shock resistance property of driving mechanism are main factors influencing the uncertainty of the flow diverter with large pipe diameter. The results of experiment verified that servo motor driven flow diverter has faster transfer acceleration and more stable transfer process. The test results of transition time difference method show that the uncertainty of servo motor driven flow diverter is less than 0.003%. The servo motor driven flow diverter is able to provide satisfied service for the tests and research of flow instrumentation.

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