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EXPERIMENTAL STUDY ON DYNAMIC PERFORMANCE OF CORIOLIS MASS FLOW METER AND COMPENSATION TECHNOLOGY

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Abstract – The Coriolis mass flow meter, for its features of directly measuring mass flow and high precision, is widely utilized in the flow measuring fields like batch filling and commercial trade. However, the unsatisfactory dynamic performance is one major constraint to Coriolis mass flow meter from being even more widely used in batch filling industry. To solve the problem, an experimental system which generates refined flow step stimulus signals for Coriolis mass flow meter was designed and based on which experimental and theoretical study on dynamic performances of typical Coriolis mass flow meter was carried out. On top of this, a time-domain recursive digital filter was designed to provide dynamic compensation and the experiments showed this filter can reduce the step response time of Coriolis mass flow meter by about 50%.

1. INTRODUCTION

Coriolis mass flow meter (CMF) possesses the advantages of high precision, good stability, and multi-parameter measurement [1]. With the increasing requirements for flow dynamic measurement accuracy in a number of industrial batch filling applications, the dynamic performance of CMF which becomes more and more important further restrict widespread use of such flow sensors.

At present, the study on dynamic response of CMF abroad is focused on theoretical analysis, finite element simulation and experimental research. The flow research group of Brunel University in Britain derived the differential equations with numerical methods when the measuring tube was stimulated by pulsating flow and step flow, and analyzed the dynamic response performance. In addition, they also did research on the dynamic response of the vibration tube and the dynamic response performance after the secondary instrument resolving [2–4]. The domestic research on the dynamic performance of CMF is at the initial stage and is focused on the finite element simulation.

The main experimental hardware of dynamic performance is built up and the software scheme for dynamic flow measurement is designed. Then, the anticipative flow dynamic step signal is achieved to meet the dynamic measurement requirements in more practical engineering fields. Based on numerous experiments, a large amount of experimental data is analyzed and processed. And the compensation model was adopted to improve the dynamic response performance of CMF.

2. EXPERIMENTAL RESEARCH

2.1. Dynamic calibration excitation

The flow signal has many properties such as large damping and hysteresis, so it is more difficult to generate ideal excitation signal. Up to now, the flow stimulus applied in experimental study is low-frequency pulse and step flow. Step response can be used as the most stringent incentives to indicate the dynamic performance of sensor systems. In the industrial applications, flow control valves' suddenly open or close in batch process, large damping caused by a sudden flow of gas in multiphase flow measurement, and the loading and unloading ways of the flow meter are very similar to the step incentives [5]. Besides, with a view of the simple data processing and the possibility of dynamic calibration, the step flow is an ideal dynamic calibration source. So a fast solenoid valve is used to generate the step flow excitation signal in this paper.

2.2. Dynamic calibration device

It is necessary to establish a specialized unit to study the dynamic performance, to provide a reliable traceability basis for dynamic measurement, also to provide the foundation to improve the dynamic performance of flow meters. A complete experimental system is built, shown as Fig. 1. The system can be used to do experiments on static calibration and dynamic step response.

The experimental system includes two parts: pipes and the flow source system, signal collection and electronic control system. The pipes and the flow source system consists of piping holder, the main pipeline, by-pass, pump (WILO Mhike-205A), CMF(Taiyuan Aero-Instruments Co. Ltd.LZLG-2-70JD20/1020),

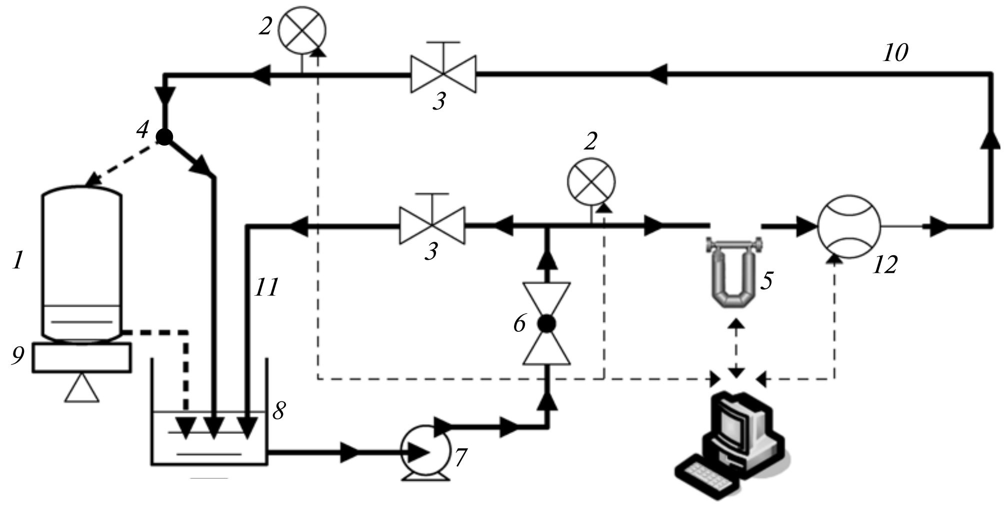

Fig. 1. Diagram of flow step calibration facility: (*1*) weight tank, (*2*) pressure gauge, (*3*) solenoid valve, (*4*) commutator, (*5*) CMF, (*6*) ball valve, (*7*) pump, (*8*) sump, (*9*) electronic scales, (*10*) main pipeline, (*11*) by-pass, (*12*) turbine flow meter.

turbine flow meter(Kaifeng Instruments Factory LW-ZY-015612621103), ball valve, solenoid valve (Burkert 0290-type), the export (import) pressure gauge, commutator, weight tank, sump, and electronic scales.

Signal acquisition and electronic control systems is composed by computers, data acquisition card (National Instruments 6251), LabVIEW and solenoid valve controller. LabVIEW as the development platform, together with the data acquisition card, constitute the dynamic signal data acquisition system to monitor, display and store various parameters in real-time. Besides, it is able to trigger the switch solenoid valve, and measure the output signal of reference meter and CMF at the same time.

2.3. Dynamic calibration

A complete dynamic calibration process is as follows.

(1) Accomplish preparatory work including experimental line connection, Labview port settings, and various related inspection.

(2) Ensure that the initial state of solenoid valves is valve 1 (on main pipeline) open and valve 2 (on by-pass) off. Then open the pump to provide steady traffic. Adjust flow to the set value by regulating the variable aperture of the ball valve manually.

(3) Run Labview program when the flow is stable, then change the state of solenoid valves (valve 1 off, valve 2 open) with the controller, after a certain time (about 10 s) stop the Labview program. Thus, the data has been collected for a negative step, and then close the Labview program trigger.

(4) Run Labview program when the flow is stable, then change the state of solenoid valves (valve 1 open, valve 2 off) with the controller, after a certain time (about 10 s) stop the Labview program. Thus, the data has been collected for a positive step, and then close the Labview program trigger. Back to the initial state, a process is completed.

2.4. Dynamic calibration results

The output of CMF is pulse frequency signal, of which changeable frequency represents the instantaneous flow, collected after the treatment of the transmitter. Zero-crossing detection method is used to measure each pulse cycle to get the frequency, which is converted to flow with scale factor. As the impact of acquisition environmental, there is noise mixed in the signal, filtering is necessary. MATLAB is used to analyze and process the step response data acquired from the experiments. The max flow is 54 kg/min in the experiment. Select ten flow points of 10 to 100% of full scale at equal intervals, repeat five times for each flow point test, and record the data. Taking positive step as an example, step response curves under different amplitudes are shown in Fig. 2.

It is obvious that CMF step response curve is similar to the first-order system or second-order overdamped system, the shape of the curve is characterized by a stationary no overshoot, no oscillations of non-periodic form. Therefore, it can assume a first order system or second-order system to calculate and analyze the dynamic performance index [6].

3. DYNAMIC MODELING AND COMPENSATION

3.1. Dynamic modeling

It is very important to get accurate mathematical model to improve the dynamic performance of CMF. According to the obtained input/output experimental data, this paper adopts simultaneous identification of

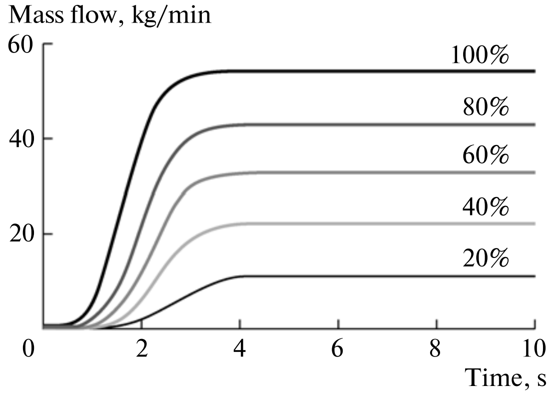

Fig. 2. CMF step response curves between different amplitudes.

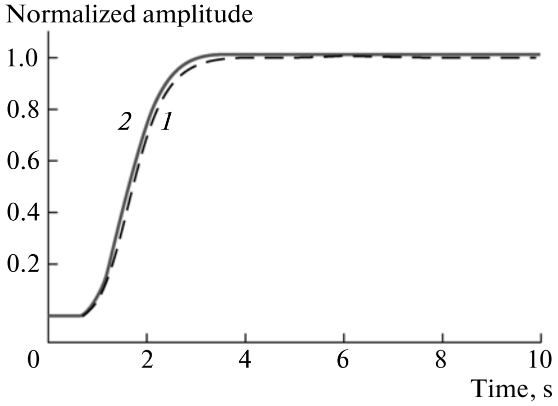

Fig. 3. Comparison of CMF practical output (*1*) and dynamic mathematical model output (*2*).

model order and parameters based on the principle of the least squares for CMF dynamic modeling. Single input-single output differential model is applied in modeling, which can be expressed as the following equation:

$$\begin{aligned} &y(k) + a_1y(k-1) + \cdots + a_ny(k-n) = \\ &= b_0u(k) + b_1u(k-1) + \cdots + b_nu(k-n). \end{aligned} \tag{1}$$

Where $u(k)$ and $y(k)$ referring to the practice input and output of the system, and n is the model order. According to the given observed sequences $\{u(k), y(k), k = 1, 2, ..., N_0\}$, the model order n is determined and parameters a_i, b_i $(i = 0, 1, ..., \hat{n})$ are estimated. The basic procedure is as follows [7]:

(1) Use the known system observing input and output sequences $\{u(k), y(k), k = 1, 2, ..., N_0\}$ to construct a specific matrix D;

(2) D is transformed to R by Householder;

(3) The least squares estimation error J_n $(n = 1, 2, ..., V)$ can be calculated by the diagonal element of R, then use appropriate criteria to determine $\hat{n}$;

(4) Use the elements of R to derive the iterative initial value of model parameters. Then, set the corresponding iterative number and iterative accuracy according to the required accuracy, system model will be obtained after iteration process.

Outputs of step response of turbine flow meter and CMF are separately input data $u(k)$ and output data $y(k)$ of the model. Taking step flow 32 kg/min as an example, programming can identify model order and parameters through MATLAB. The model order is second order. Identification of the differential equation model is:

$$\begin{aligned} &y(k) = 1.9998y(k-1) - 0.9998y(k-2) + \\ &+ 8.1836 \cdot 10^{-3}u(k) - 1.6365 \cdot 10^{-2}u(k-1) + \\ &+ 8.1818 \cdot 10^{-3}u(k-2). \end{aligned} \tag{2}$$

The transfer function is:

$$\begin{aligned} &G(z) = \frac{Y(z)}{U(z)} = \\ &= \frac{0.8184 - 1.6365z^{-1} + 0.8182z^{-2}}{1 - 1.9998z^{-1} + 0.9998z^{-2}} \cdot 10^{-2}. \end{aligned} \tag{3}$$

Use the experimental step input data in identification model, the result is shown in Fig. 3. It can be seen that the output of model and the step response measured during the experiments are consistent, indicating that the identification model is accurate.

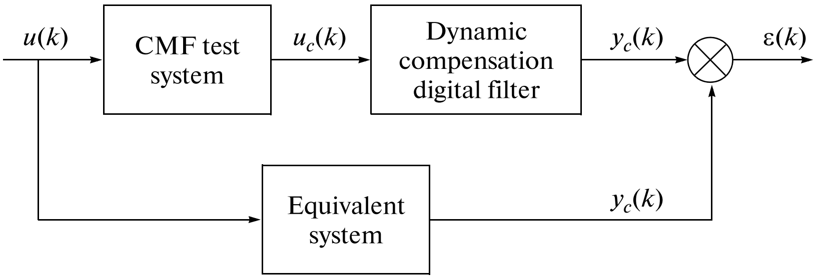

Fig. 4. Dynamic compensation system diagram.

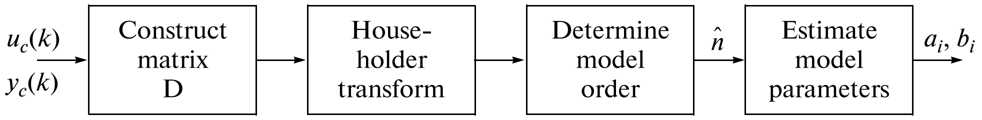

Fig. 5. The method of time-domain recursive digital filter.

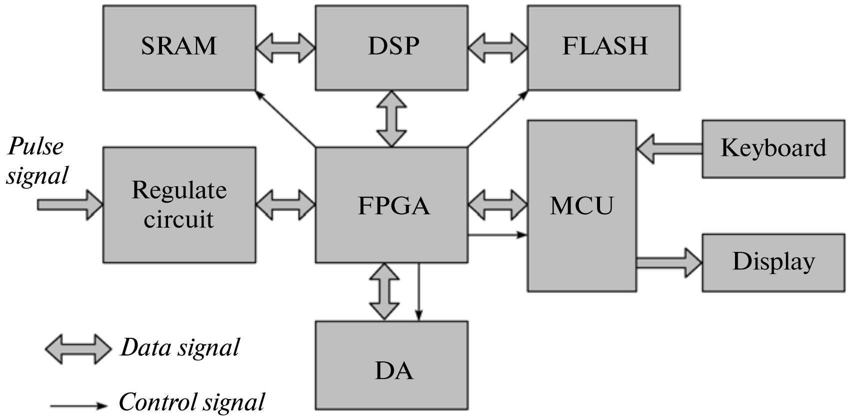

Fig. 6. Hardware diagram of dynamic compensation system.

3.2. Dynamic compensation

3.2.1. Design of dynamic compensator. Dynamic compensation is a powerful tool for improving the dynamic performance of sensors, of which the effectiveness has been proved by the successful apply on some different kinds of sensors [8, 9]. This paper uses a dynamic compensation filter in series CMF to improve its dynamic performance. The design block diagram is shown in Fig. 4.

The design of dynamic compensator is as follows [10]. For one thing, determine the desired equivalent system which is assumed as a second-order system. According to the improvement proportion of time constants, the continuous transfer function is determined. It becomes into the discrete transfer function after the bilinear transformation. For another, with the excitation signal of experiment as the input, find discrete output sequence of the equivalent system as the output sequence $y_c(k)$ of the compensation filter, discrete sequence of step response of excitation signal as the input sequence $u_c(k)$ of compensation filter. Finally, the dynamic compensation digital filter is directly designed by using time-domain recursive digital filter to identify the order and parameters. The digital filter is shown as Fig. 5. The simultaneous identification of model order and parameters is used to get the compensator's order $\hat{n}$ and parameters $\hat{\theta}$.

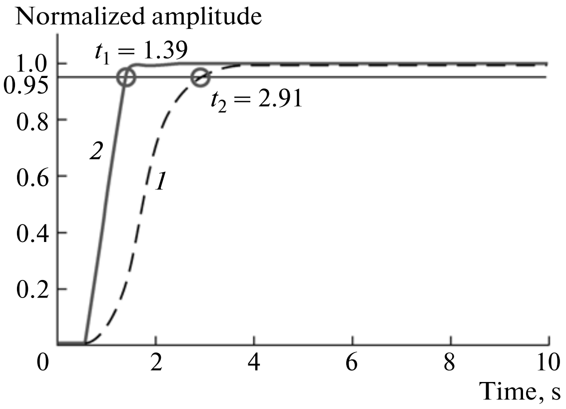

Fig. 7. Comparison of CMF step response curves before (*1*) and after (*2*) dynamic compensation.

The model of the digital filter is obtained, and the transfer function is:

$$G_c(z) = \frac{Y_c(z)}{U_c(z)} = \\ = \frac{1 + 0.9999z^{-1} - 0.9997z^{-2} - 1.0013z^{-3}}{1 - 0.9971z^{-1} - 0.9998z^{-2} - 0.99972z^{-3}} \cdot 1.8644. \qquad (4)$$

3.2.2. Dynamic compensator achieving. The hardware of the system completes step response signal acquisition and conditioning, dynamic modeling and compensation algorithms. The sensor off-line compensation is achieved by algorithm transplantation, and follow-up can be applied for online compensation development. Considering the system of computation and the development of real-time scalability, DSP and FPGA are used, the former completes the system operator, while latter is responsible for timing control and data storage.

The hardware circuit consists of input signal conditioning, analog-digital conversion circuitry, FPGA

Response time before and after dynamic compensation

Mass flow, kg/min	Response time before compensation, s	Response time after compensation, s
43.2	2.74	1.25
38.4	2.89	1.33
32.0	2.91	1.39
27.9	3.05	1.52
21.8	3.10	1.59
16.2	3.18	1.72

control module, DSP core computing module, digital to analog conversion circuits and power management circuits, as shown in Fig. 6 [11].

Pulse frequency signal is transferred to FPGA directly after pretreatment, measured by the software and stored in internal FIFO. The acquired frequency data is sent from FPGA into DSP for compensation by interrupt procedure. Then the calculated data is sent to D/A, with displaying the waveform comparing the output curve of pre-compensation and after-compensation in real-time by oscilloscope.

The curves of CMF step response before and after compensation are shown in Fig. 7. Table shows response time with compensation system. The experimental results show that the dynamic response time of the compensated decreases by 50%. The effect of compensation is obvious, and it proves the effectiveness of the dynamic compensation algorithm.

4. CONCLUSION

This paper designed the experimental facility and program for research on CMF dynamic performance, and then obtained fine step stimulus signals. The precise dynamic mathematical model of CMF was established based on experiment data via massive data analysis and system identification. A digital filter was designed based on the model. After the compensation, the step response time was reduced by around 50%, which indicates that the dynamic performance of CMF has been significantly improved. Thus, theoretical and experimental foundation was laid for further study on dynamic performance. With these efforts the application areas of CMF can be extended.

ACKNOWLEDGMENTS

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