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Development of Coriolis mass flowmeter with digital drive and signal processing technology

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ABSTRACT

Coriolis mass flowmeter (CMF) often suffers from two-phase flowrate which may cause flowtube stalling. To solve this problem, a digital drive method and a digital signal processing method of CMF is studied and implemented in this paper. A positive–negative step signal is used to initiate the flowtube oscillation without knowing the natural frequency of the flowtube. A digital zero-crossing detection method based on Lagrange interpolation is adopted to calculate the frequency and phase difference of the sensor output signals in order to synthesize the digital drive signal. The digital drive approach is implemented by a multiplying digital to analog converter (MDAC) and a direct digital synthesizer (DDS). A digital Coriolis mass flow transmitter is developed with a digital signal processor (DSP) to control the digital drive, and realize the signal processing. Water flow calibrations and gas–liquid two-phase flowrate experiments are conducted to examine the performance of the transmitter. The experimental results show that the transmitter shortens the start-up time and can maintain the oscillation of flowtube in two-phase flowrate condition.

1. Introduction

CMF occupies an important position in the field of flow measurement because it can measure the true mass flowrate directly and obtain the fluid density simultaneously. CMF consists of flowtubes and an electronic transmitter. The transmitter maintains the flowtubes oscillation and performs the signal processing of the sensors attached to the flowtubes. The proper oscillation of the flowtubes is a basis for the operation of CMF, therefore the drive method is an important technique for CMF. The most common drive method is based on the analog positive feedback technique. The sensor signal is amplified and fed back into an electromagnetic driver in the electronic transmitter. This approach can ensure the phase matching between the sensor signal and the drive signal because there is little delay in the analog feedback circuitry. But the analog drive method will result in a long start-up time of the flowtubes. Especially when measuring the gas–liquid two-phase flow, the analog drive system is prone to stalling. This is because the dynamics of gas–liquid two-phase flow causes high damping. At this time a high drive gain is required so as to maintain the flowtube operation. But the analog drive system is unable to provide sufficient drive gain rapidly, so the flowtubes stalls.

For solving this problem, digital drive methods have been studied and applied to CMF in recent years.

Maginnis [1] introduced an initialization algorithm for drive control of CMF. A MDAC is used to generate the drive signal. MDAC receives the analog sensor signal from one of the pick-offs and its gain is controlled by the processing unit. MDAC outputted an analog signal, and this signal is then amplified as the drive signal. This control method is easy to be realized, and there is only one parameter which is the gain of drive signal, needs to be controlled, as the frequency and phase of the drive signal match that of the sensor signal automatically. Barger [2] also utilized this drive method. However, since the drive signal is derived from the sensor signal, there will be no output of pick-offs before the flowtubes vibrate. This will result in a long start-up time of the flowtube.

Shimada [3] combined the analog drive method with the digital wave synthesis drive method based on phase-locked loop (PLL). Before the flowtubes vibrate, the analog drive method is used to perform drive activation processing. When the amplitude of the sensor signal is larger than a predetermined level, the analog drive mode is switched to the digital drive mode. However, using the analog drive method to start an initial oscillation will lead to a long start-up time.

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Henry et al. [4–9] studied many drive methods of CMF. An approach of driving the conduit is to use square wave pulses [7]. The fixed (positive and negative) direct current sources are switched on and off at timed intervals to provide the required energy. The switching is synchronized with the sensor voltage phase. But it is not told us how to determine the "timed interval" and the relationship between "switching" and "phase", i.e. how to perform switching according to the phase of the sensor signal in this reference. A random sequence mode, a positive feedback mode and a digital synthesis mode were proposed [8]. The random sequence mode is used in the start-up of flowtube, in which filtered, random frequencies are applied as a drive signal to a flowtube. Once the flowtube reaches a resonant mode of vibration, the digital flowmeter may transition to a positive feedback mode, in which the sensor signals are input through the input channels of coder–decoder (CODEC), sampled and buffered within the field-programmable gate array (FPGA), and then fed back through the output channels of the CODEC to the flowtube as the drive signal. Once an oscillation of the flowtube is achieved and analyzed, a digital synthesis mode of operation may be implemented, in which the analyzed sensor signals are used to synthesize the drive signal. The digital synthesis mode was used in [9], and the pure sine waves having phases and frequencies required were synthesized and outputted through CODEC to the drivers. Fan et al. [10,11] also utilized this drive method. However, it needs a large amount of computation to synthesize the sine waves, and a large memory to buffer the sine waves.

The digital drive method overcomes some limitations of the analog drive approaches. But there are two challenges in the implementation of digital drive method. The first one is that what kind of signal can be used to excite the flowtube vibration when the flowtube natural frequency is unknown. Before the flowtubes vibrate, there is no the sensor output signal. Thus the processor cannot obtain the flowtube natural frequency, and cannot determine the frequency of the drive signal. So the flowtubes cannot be excited to vibrate by the drive signal with an improper frequency, because only the drive signal frequency is very close to the flowtube natural frequency, the flowtubes can vibrate. After the flowtubes vibrate, the processor should calculate the amplitude, frequency and phase of the sensor signals in real time, and synthesize a drive waveform whose parameters must be satisfied excitation requirements to excite the flowtubes for obtaining the stable oscillation. Therefore the second one is how to obtain the parameters of the sensor signals rapidly and accurately. In other words, a digital signal processing method with both high processing accuracy and fast tracking speed is needed to track the variation of sensor signal for the drive control.

There are some digital signal processing methods for CMF, including the discrete Fourier transform (DFT), PLL, digital zero-crossing, adaptive line enhancer (ALE), sliding Goertzel, discrete-time Fourier transform (DTFT), etc.

DFT was used to process the sensor output signals of CMF [4,7,12]. Henry et al. [4] found that Fourier-based technique was very precise. This method has good resistance to higher harmonics. However, it needs to adopt additional technique for eliminating the effect of non-integer period sampling.

Freeman et al. [13] utilized the digital phase locked loop to process the signals of CMF, and Xu et al. [14] also studied on this method. This method is of high processing precision under no noise interference. But its anti-noise ability is poor.

Derby et al. [15,16] introduced ALE into the signal processing of CMF. The phase difference between the sensor signals is obtained using Fourier analysis or Goertzel Fourier transform. Xu and Ni et al. [17] improved the above algorithm. However, there is a long convergence stage in Goertzel algorithm.

Zhang and Tu [18] utilized discrete-time Fourier transform (DTFT) considering negative frequency contribution to solve this problem. During the calculation, the negative frequency is considered, so the convergence process is shortened greatly and the computation accuracy is improved effectively. The simulation results for steady signals show a better performance of DTFT than that of SGA [18]. This algorithm was realized in real time by us based on a Coriolis mass flow transmitter developed with TMS320F28335 chip, and the testing results showed its high accuracy and good repeatability. However, it is found that the whole algorithm has a large amount of computation and there may be little time left for drive control.

Aiming at above problems, the start-up method using the positive–negative step signal is studied and implemented for CMF in this paper. This approach can initiate the flowtube oscillation reliably when there is no knowledge of the flowtube natural frequency. This can overcome the problem of long start-up time when using analog drive method to initiate the flowtube oscillation. And this approach is more effective than that of using random sequence to excite the flowtube in [8]. Then the digital drive method based on MDAC and DDS chip is put forward. The MDAC chip can control the drive gain flexibly, and the DDS chip can synthesize the sine wave with required frequency and phase information automatically. So the large amount of computation to synthesize the sine waves and the large memory to buffer the sine waves in [8] can be saved. At the same time, a digital zero-crossing detection method based on Lagrange interpolation is used to calculate the frequency and phase difference of the sensor outputs because of its small amount of calculation and good tracking speed. During the implementation of zero-crossing method based on DSP chip, some effective measures are taken to improve the processing precision. Finally a digital transmitter is developed with TMS320F28335 DSP chip, and the drive ability tests, water flow calibrations and gas–liquid two-phase flowrate experiments are conducted to validate the digital drive and signal processing techniques, and the digital transmitter.

The organization of this paper is as follows: in Section 2, the start-up method using positive–negative method is presented. Section 3 is devoted to the theory and simulation results of zero-crossing detection method. The digital drive method based on DDS and MDAC chip is outlined in Section 4. The development of transmitter, including hardware and software is given in Section 5. In Section 6, experiments of transmitter are performed to examine the performance of the transmitter. The paper ends in Section 7 with the conclusions followed by the acknowledgments and references.

2. Start-up method using positive and negative step signals

In order to study the start-up of the flowtube, a model of the flowtube is built up by using the one-dimensional damped forced vibration system. Its transfer function is expressed as

$$G(s) = \frac{ks}{s^2 + 2\zeta\omega_n s + {\omega_n}^2} \quad (1)$$

where k is the stiffness; ω_n is the natural frequency; ζ is the damping factor, and its value is very small, e.g., 0.001.

When the frequency of drive signal equals to the flowtube natural frequency, the flowtubes will vibrate easily with the lowest power cost. In the beginning, the transmitter generates a particular waveform to excite the flowtubes for the start-up of the flowtubes. After the flowtubes vibrate, when the signal amplitude of the sensor attached to the flowtubes is larger than a predetermined value A_s, the transmitter stops exciting the flowtubes, and enters into the zero-drive mode. During this stage the transmitter