智慧型渦流流量計之技術發展

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Development of a Vortex Flowmeter with Intelligent Capabilities(3/3)

Abstract-An algorithm is developed to compute vortex shedding frequency from a vortex flowmeter in real-time manner. The algorithm is implemented in a digital signal processor of TI TMS320 C6711. It mainly comprises a fast Fourier transform and a software phase locked loop. By the fast Fourier transform, a reference vortex shedding frequency is determined from a smoothed frequency spectrum. According to the reference vortex shedding frequency, parameters in the software phase locked loop including the center frequency and gains are tuned dynamically in order to trace the vortex shedding signal. Outputs of the software phase locked loop are then utilized to compute vortex shedding frequency for output. The algorithm is examined with a 2” vortex flowmeter in a flow calibration system. The accuracy of the vortex flowmeter is about 0.59% to 0.35% in a flow rate range from 50 to 509 m³/hr. Keywords: vortex frequency, SPLL, FFT, DSP

1. Introduction

Vortex flowmeters are favorably used in many occasions of industrial flow measurements, owing to its wide range of applicability in liquid, gas and steam flows in hostile environments. It works based on the measurement principle that the frequency of Karman vortex shedding generated by flow over a vortex shedder is linearly proportional to the flow velocity. Therefore, the measurement of volumetric flow rate by a vortex flowmeter reduces to an issue of estimating a reliable vortex shedding frequency.

With piezoelectric elements detecting vortex shedding, the signals obtained in piping flow measurement are inevitably contaminated by noises from piping vibration, pulsation flow, and even by flow turbulence [1-3]. On the other hand, it has been realized that the amplitude of a vortex signal measured by piezoelectric elements is about proportional to the fluid density and the square of flow velocity. Hence, for a flowmeter with a turn down ratio of 10, i.e., ratio of maximum flow rate to minimum flow rate, the amplitude of the signal output can vary in a much wider range, say two orders of ten. In such situations, it is almost impossible to obtain accurate pulse outputs of vortex shedding through a simple circuit design such as Schmitt trigger. Usually lots of efforts have to be paid on filtering the vortex shedding signal and a proper, even actively tuned, triggering level has to be carefully chosen. However, excessive or missed pulses still can not be completely avoided.

Several methods have been proposed in literature to estimate vortex shedding frequency. Among them, the most popular and simplest one is to measure the time length between zero-crossing, but this method fails as SNR, signal-to-noise ratio,
gets poor. To improve the performance of zero-crossing on estimating vortex shedding frequency, a prefilter employed at low signal-to-noise ratio (SNR) and a band-pass filter with an adjustable center frequency and bandwidth are required prior to the zero-crossing unit [3]. Phase-locked loop is also proposed for obtaining the vortex shedding frequency, which is commonly used in communication field. In the study of Clark [4], a design of dual PLL algorithm was applied to locate the vortex shedding frequency, which improved the drawback of using only a single PLL that could not cope with a wide range of frequency measurement. However, tuning the parameters of PLL to obtain good accuracy and high tracking ability of vortex shedding frequency is usually difficult. Also a well-designed prefilter is necessary.

Concerning frequency analysis on stationary signals, fast Fourier transform has been the most widely used mathematical tool. However, to obtain higher resolution of frequency spectrum, the time length and data size for fast Fourier transform should be large, and then requires huge computation time. For real-time application, this might become a serious problem. Therefore, designers have to make a compromise between computation time and frequency resolution. In addition, square wave or pulse outputs of a vortex flowmeter are usually required for several reasons in industrial application, which can not be achieved only with fast Fourier transform.

In this paper, an algorithm is designed as the combination of fast Fourier transform (FFT) and software phase locked loop (SPLL) for providing both real-time vortex shedding frequency and reliable square wave outputs of vortex shedding. The algorithm is applied to a 2” vortex flowmeter, which is then tested in a flow calibration system.

2. Experimental Facility

The algorithm presented in this paper is evaluated by applying it to a T-shaped vortex flowmeter whose diameter is 50 mm [5]. The T-shaped vortex shedder has a piezoelectric element to sense vortex shedding. Since the piezoelectric sensor detects vortex shedding through stress variation of the vortex shedder, it is inevitable to sense piping vibrations which are regarded as a noise component to vortex shedding signal. In addition, noises from EMI and RFI are usually embedded in the output signal of a piezoelectric sensor.

An air flow calibration system is employed for testing the performance of the vortex flowmeter. The mass flow rate in the pipeline was controlled by a set of choked sonic nozzles and pressure regulators upstream the vortex meter. The flow range for the calibration system is ranging from 10 to 2.4 \(10^4\) m\(^3\)/hr at ambient pressure condition, whose extended uncertainty of flow rate measurement is 0.31% certified by CNLA (Chinese National Laboratory Accreditation). In this study, the vortex flowmeter was tested in a velocity range from \(U = 3.5\) m/s to 72.6 m/s, equivalent to a volumetric flow rate of 25 m\(^3\)/hr to 513 m\(^3\)/hr.

Real-time computation of the algorithm is implemented by a 32-bit digital signal processor of TI TMS320 C6711. The processor has a clock cycle time of 10ns.

3. Computation algorithm

Figure 1 shows the procedures of signal processing, which are indicated by the blocks of a signal source, an analog band-pass filter and a digital signal processing unit (DSP). Details of each block are given below.

The electric charge generated by a piezoelectric element due to vortex shedding is converted into AC voltage by a charge converter. As mentioned above, the output voltage of a vortex signal is about proportional to the square of flow velocity, which increases the difficulty for data processing when the turndown ratio is larger than 20. To reduce the difference between output voltages obtained at minimum and maximum flow rates, a passively analog band-pass filter (ABPF) whose higher and lower frequency cut-offs are both set as 30 Hz. The 30Hz high-pass filter is somewhat like an integrator functioned to reduce the amplitude level of vortex signal obtained at higher flow rate, and it also damps high frequency noise components. In Figure 2, we demonstrate vortex shedding signal obtained at \(U = 3.5, 16.8, 72\) m/s, respectively. The root mean squares of the vortex shedding signals obtained at different velocities are plotted in Figure 3. Within the flow velocity range from \(U = 3.5\) to 72 m/s, the ratio of the maximum root-mean-square value to the minimum is about 165.6, while it is noted that the turndown ratio for the flow velocity is about 20.5.

The analog vortex shedding signal is digitized by a 16-bit A/D converter, whose sampling frequency is set as 8000Hz. Then, the digital
vortex shedding signal enters the DSP unit, which is utilized by both FFT and SPLL units.

In FFT unit, the original sampling frequency of the input data is divided by 4. Hence, in Fourier transform computation the sampling frequency is 2000Hz, instead of 8000Hz. The input data is stored in a data buffer of 1024 points in size. Immediately after the buffer filled up, the 1024-point data record are transfer to the other buffer for Fourier transform computation. On the other hand, the original data buffer keeps receiving data from the A/D converter. Since the sampling rate is 2000Hz, the full length of each data record is 0.512s. Hence, the frequency spectrum computed has a frequency resolution of 1/0.512 Hz. The raw frequency spectrum is further smoothed by a standard moving average of 11 items [6]. Specifically, for each frequency of the raw spectrum, \( f(i) \), the corresponding amplitude \( A(i) \) is summed with the other 10 points symmetric to itself. Equation (1) gives the formula description, where \( A_m(i) \) denotes averaged result.

\[
A_m(i) = \left[ \sum_{k=-5}^{k=5} A(i+k) \right] / 11
\]  

The smoothed frequency spectrum helps to reduce random error from locating the peak frequency in the spectrum. As an illustration, Figure 4a shows the raw frequency spectrum corresponding to the signal trace at \( U = 3.5 \text{m/s} \). The signal-to-noise ratio, SNR, is about –10dB [7]. The vortex shedding frequency is indicated as \( f_r \). As seen, there are several peaks comparable and even larger than the peak of vortex shedding frequency. Hence, it is difficult to identify the vortex shedding frequency in a straightforward manner. However, after smoothing, see Figure 4b, the peaks corresponding to noises components were reduced significantly. This is because the noise components are of quite narrow band of frequency. Therefore, the vortex shedding frequency can be easily picked up at the smoothed spectrum. However, for some reasons, the vortex shedding frequency determined by fast Fourier transform serves as only a reference frequency, instead of serving as the final output frequency. The reference frequency is provided to tune the center frequency of a phase locked loop.

In parallel to the FFT computation, the sampled data is also utilized for SPLL computation [7]. The data coming from the A/D converter at a frequency of 8000Hz are all used in the SPLL computation. Although, according to the sampling theorem, the algorithm of SPLL only has to be executed two or four times in each cycle of the vortex shedding signal, our real-time test on the vortex flowmeter shows that at least eight times computation per vortex shedding cycle can guarantee a complete square wave output. The maximum vortex shedding frequency for the vortex flowmeter employed in this study is near 1000Hz.

It is realized that for a good noise-rejection phase locked loop the frequency lock-on range would be quite narrow, e.g. 10% of the center frequency. However, for a vortex flowmeter, the flow rate often varies in a wide range with time, and so is the vortex shedding frequency. For general commercial product of vortex flowmeter, the turndown ratio of 10 is quite normal. Therefore, the center frequency of the phase locked loop has to be tuned dynamically and automatically according to the input signal. In the present study, the SPLL receives the reference vortex shedding frequency, \( f_r \), from the FFT unit every 0.512s to tune the center frequency of voltage control oscillator. Furthermore, instead of keeping a constant level, the amplitude of the input signal varies with frequency, referring to Figure 3. Therefore, gains for phase detector and voltage control oscillator should be adjusted according to the reference frequency to maintain reasonable lock-on range and noise rejection ability. In our algorithm, the lock-on range is designed to be about \( 0.9 f_r \) to \( 1.1 f_r \).

The output of the SPLL unit is of binary, i.e., either 1 or 0. A timer and counter are designed for calculating the vortex shedding frequency. For \( f_r \) less than 100Hz, the timer is set as 2 seconds. Hence, the numbers of binary switch within the time period are accumulated, and then the vortex shedding frequency is obtained through dividing the switching numbers by the time length selected. The vortex shedding frequency is denoted as \( f_s \). For \( f_r \) larger than 100Hz, the timer is set as 1 second. In order to reduce the dynamic variation of \( f_s \), it is averaged with the previous nine values to have \( \overline{f_s} \). \( \overline{f_s} \) is then displayed on a LCD unit. On the other hand, the binary output of SPLL is simultaneously delivered to a D/A converter to provide an analog square wave to the outside world.
Figure 5.

4. Algorithm verification

The performance of the algorithm is evaluated in real pipe flow measurement by applying it to a 2” vortex flowmeter made in laboratory. An air flow calibration system is employed for the test. The straight pipe length upstream the vortex flowmeter is 6.8 m, while 3.15 m downstream. The vortex flowmeter was tested at eight different flow rates ranging from \( Q = 25 \text{m}^3/\text{hr} \) to 513m\(^3/\text{hr} \), equivalent to \( U = 3.5 \text{m/s} \) to 72.6m/s. A total of 18 sets of calibration data for each flow rate were collected in two months. During experiment, 30 records of the LCD display, i.e., \( F_n \), were recorded as a set of calibration data. The average value of the 30 records is denoted as \( \overline{F} \). The vortex shedding frequency of interest is frequently expressed as flow coefficient, usually called \( K \)-factor. \( K \) is defined as \( \overline{F} / Q \), where \( Q \) denotes the mean flow rate during the 30 records of \( F_n \). Hence, there are 18 values of \( K \) for each flow rate. Data of \( K \) with respect to \( Q \) are plotted in Figure 5.

In Figure 5, the \( K \) factor varies drastically when \( Q \) is less than 50 m\(^3/\text{hr} \). This is explained as the region of onset of vortex shedding. While \( Q \) becomes larger than 50 m\(^3/\text{hr} \), the \( K \) factor distributes more flat. In other words, the vortex shedding frequency is approximately linear to flow rate. The solid line shown in the figure presents as the calibration curve. The uncertainty level of the curve in reference to the experimental data can be evaluated as follows.

\[
U_k^2 = U_1^2 + U_2^2 + U_3^2
\]  

(2)

where \( U_k \) denotes total uncertainty of \( K \) factor for each flow rate, \( U_1 \) is the system uncertainty of 0.31\%, \( U_2 \) presents the repeatability of \( K \), and \( U_3 \) refers to the maximum deviation of the experimental data from the calibration curve. In specific, \( U_2 \) is derived from the standard deviation of the 30 records of \( F_n \) divided by \( \sqrt{30} \) [8]. In the present case \( U_2 \) was chosen as the maximum among the 18 sets of calibration data. Note that \( U_k \) and \( U_1-U_3 \) denote the expanded uncertainties [8], each of which is referred to the 95% confidence interval.

By (2), the uncertainty level for each flow rate can be evaluated. Table 1 shows the results. For the flow rate in the onset region of vortex shedding, i.e., \( Q \) is less than 50 m\(^3/\text{hr} \), the uncertainty level is as high as 3\%. On the other hand, the uncertainty level is about 0.59\% to 0.35\% from \( Q = 50 \) to 509 m\(^3/\text{hr} \). It is noteworthy that the present algorithm do improve the measurement accuracy of vortex flowmeter. As a comparison, the accuracy for the dual-PLL algorithm is about 3.0\% to 0.5\% within a flow range from 0.25 to 3 l/s; while for the lower flow rate down to 0.1 l/s, the accuracy is 6.5\% [4].

Several cases for the real-time output of square waves are demonstrated in Figures 6 to 8. The vortex shedding signal in Figure 6 is obtained at \( U = 3.5 \text{m/s} \), i.e., the lower measurement limit of the vortex flowmeter. The vortex undulation level of the signal is about 5mV. Other high and low frequency noise components are also discernible. However, the SPLL can still trace the vortex shedding well, seeing the square wave signal in the figure. Noted is that the square wave is between 1.2V to 3V. Figure 7 is obtained at \( U = 16.8 \text{m/s} \). The vortex shedding signal looks better than that in Figure 6, but amplitude modulation is still strong. During some period, the vortex undulation almost disappears. Even so, the square wave output does not lose any shed vortices. The signal level is about 0.1V for this case. Figure 8 is the case obtained near the upper measurement limit of the vortex meter. Although the signal level is larger, the vortex shedding signal starts to be distorted by low-frequency undulation and high frequency noises. Again, the SPLL trace the main undulation caused by vortex shedding well.

5. Conclusions

An algorithm developed for DSP signal processor on vortex flowmeter measurement is proposed in this study. It primarily comprises two parts. One is the fast Fourier transform (FFT), and the other is software phase locked loop (SPLL). The FFT unit delivers a referenced vortex shedding frequency to SPLL unit obtained from a smoothed frequency spectrum. According to the reference vortex shedding frequency, parameters in the SPLL unit including the center frequency of voltage control oscillator and gains for phase detector and voltage control oscillator are tuned dynamically in order to trace the vortex shedding signal well. Outputs of the SPLL are then utilized to compute vortex shedding frequency. The algorithm is examined with a 2” vortex flowmeter in a flow calibration system. The tracing ability to vortex...
shading signal are evaluated in a flow range from \( Q = 25 \text{m}^3/\text{hr} \) to \( 513 \text{m}^3/\text{hr} \). The accuracy of the vortex flowmeter is about 0.59\% to 0.35\% from \( Q = 50 \) to \( 509 \text{m}^3/\text{hr} \). For the flow rate in the onset region of vortex shedding, i.e., \( Q \) is less than \( 50 \text{m}^3/\text{hr} \), the uncertainty level is about 3\%. As compared with the data in literature [4], the present algorithm do enhance the measurement accuracy of vortex flowmeter.

**Reference**


![Figure 1 Block diagram of operation](image1)

Figure 1 Block diagram of operation

![Figure 2 Vortex shedding signal](image2)

Figure 2 Vortex shedding signal. (a) \( U = 3.5 \text{ m/s} \), (b) \( U = 16.8 \text{ m/s} \), (c) \( U = 72 \text{ m/s} \)

![Figure 3 Root-mean-square value of vortex shedding signal](image3)

Figure 3 Root-mean-square value of vortex shedding signal.
Figure 4 Frequency spectrum at $U = 3.5$ m/s, (a) without smoothing, (b) smoothed.

Figure 5 $K$ factor versus $Q$.

Figure 6 Vortex shedding signal and square wave output for $U = 3.5$ m/s.

Figure 7 Vortex shedding signal and square wave output for $U = 16.8$ m/s.

Figure 8 Vortex shedding signal and square wave output for $U = 72$ m/s.

Table 1 Calibration Data

<table>
<thead>
<tr>
<th>Flow Rate (m$^3$/hr)</th>
<th>K Factor (pulse/m$^3$)</th>
<th>Total uncertainty (%)</th>
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