Determination of Real-time Vortex Shedding Frequency by a DSP

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ABSTRACT

An algorithm is designed for a digital signal processor to perform computations of fast Fourier transform and auto-correlation to determine real-time vortex shedding frequency of a 6” vortex flowmeter. In the algorithm, a digital band-pass filter which is able to tune its center frequency according to the input signal is arranged at the first step to remove noise components from a vortex shedding signal. After filtering, the vortex shedding signal is utilized to compute vortex shedding frequency, which is done by the technique of auto-correlation as the vortex shedding frequency estimated is less than 200 Hz or by the technique of fast Fourier transform as the frequency estimated is larger than 200 Hz. The test result shows that the maximum error of vortex shedding frequency computed is less than 0.3% when the vortex flowmeter measures at moderate to higher flow rates. For the case in lowest flow rate, the signal-to-noise ratio for the vortex shedding signal is about 1/12. Even so, the vortex shedding frequency determined is about 1.1% deviated from the true value. Furthermore, the vortex shedding frequency determined by the algorithm has a time lag of 0.512 second from the true vortex shedding frequency as the flow rate is slewing.

INTRODUCTION

Vortex flowmeters has been applied in many cases. The measurement principle that the Karman vortex shedding frequency 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 a problem of obtaining a reliable vortex shedding frequency. There are several methods to detect shedding vortices from a vortex shedder. Among them, piezoelectric material is favorably used due to its simplicity and low cost. However, its drawback is that vortex shedding signals are susceptible to be contaminated by noises due to piping vibration, pulsation flow, and even by flow turbulence (Ogawa & Matsubara, 1985; Takahashi & Itoh, 1993; Miau et al., 2000; Ghaoud & Clark, 2002). When a vortex flowmeter measures at moderate flow rates, the signal-to-noise ratio, denoted as SNR, of the vortex shedding signal is usually high, and the vortex shedding frequency can be identified with less difficulty. However, as the vortex flowmeter is used at lower flow rates, the SNR gets poorer, which poses a challenge to obtain an accurate vortex shedding frequency.

Several methods have been proposed in literature to calculate vortex shedding frequency. Among them, the most popular and simplest one is to measure the time length between consecutive zero-crossings of a vortex shedding signal, but this method fails as the SNR value becomes poor (Ghaoud & Clark, 2002). Phase-locked loop, denoted as PLL, is also proposed for tracing vortex shedding signal. In the study of Clark & Ghaoud (2003), a design of dual-PLL circuit is applied to a vortex flowmeter. With the parameters of the dual-PLL circuit having been carefully determined, the dual-PLL is able to trace vortex shedding signal well. A prefilter have to be arranged prior to the dual-PLL unit to remove noise components from vortex shedding signal. If the prefilter doesn’t function properly, an erroneous center frequency might be obtained for the phase-locked loop and then a fake vortex shedding component would be traced.

In addition, correlators have been applied to vortex flowmeters. In the study of Menz (1997), two sets of ultrasonic sensors separated by an axial distance L are
used to determine the vortex shedding signals. A time-lag cross-correlation function between the two sensors’ signals is reduced by a correlator in order to find the transit time of the vortices, and hence the vortex shedding frequency. It is noteworthy that the vortex shedding frequency estimated from transit time has a resolution uncertainty of $\Delta \tau / T_r$ if the correlation result is calculated from digital data. Herein, $\Delta \tau$ is the sampling interval of the digital data and $T_r$ is the transit time of vortices estimated, i.e., vortex shedding period. As a result, the uncertainty of vortex shedding frequency estimated by this method would increase with the flow rate.

Concerning the analysis of stationary signals, fast Fourier transform, denoted as FFT, has been known as the most widely used mathematical tool. However, performing fast Fourier transform requires a large amount of computations. Due to this cause and lack of high-performance microprocessors in the past, it was difficult to perform fast Fourier transform for vortex flowmeters in real-time flow measurement. Fortunately, by the rapid advance in integrated-circuit technology, high speed digital signal processors are now easily obtained. As compared to traditional microprocessors, digital signal processors show much better performance in real-time signal processing and intensive numerical calculations. Hence, performing fast Fourier transform in real time with the aid of a digital signal processor becomes possible.

In this study, an algorithm is designed to perform auto-correlation and fast Fourier transform to locate vortex shedding frequency of a 6” vortex flowmeter. To implement the algorithm in real time, a digital signal processor, denoted as a DSP, is employed.

**EXPERIMENTAL FACILITY**

The algorithm presented in this paper is evaluated by applying it to a T-shaped vortex flowmeter (Miau et al., 1996) whose diameter is 6 inch, seen in Fig. 1. Vortex shedding signals are detected by a piezoelectric element rigidly embedded in the shedder, seen also in Fig. 1. The vortex flowmeter was installed onto an air flow calibration system for test. The mass flow rate of the calibration system is regulated by a set of choked sonic nozzles and pressure regulators upstream of the vortex flowmeter. The flow rate for the calibration system is able to be controlled ranging from 10 to $2.4 \times 10^4$ m$^3$/hr at ambient pressure condition. The extended uncertainty for the calibration system is 0.31 % certified by National Laboratory Accreditation of Taiwan. In this study, the vortex flowmeter was tested at different flow velocities ranging from $U_0 = 5.44$ m/s to 84.88 m/s.

A 32-bit digital signal processor, TMS320 C6711, made by Texas Instrument is employed to execute the algorithm designed in this study. The processor has a clock rate of 100 MHz.

**COMPUTATION ALGORITHM**

The procedure of signal processing proposed in this study is schematically shown in Fig. 2. From left to right, it is composed of three main components, i.e., a signal source from PZT, an analog band-pass filter and a DSP processing unit. Details of each block are given below.

**Signal processing prior to DSP**

The electric charges generated by the piezoelectric element due to vortex shedding are converted into AC voltage by a charge converter. Figure 3a shows the raw signal obtained from the 6” vortex flowmeter at the
incoming flow velocity of $U_0 = 5.44$ m/s, about the lower limit of the present flow rate measurement. The corresponding frequency spectrum is shown in Fig. 4a. The vortex shedding frequency is noted about 23.48 Hz. As seen, the vortex shedding component is completely buried in noises. The SNR value for this case is about 1/12. The SNR is defined as $P_f / P_n$ (Best, 1997), where $P_f$ denotes the energy residing in the vortex shedding component in a power spectrum, and $P_n$ denotes the energy of residual components.

The raw signal is then filtered by an analog band-pass filter, denoted as ABPF in Fig. 2, to avoid aliasing of data sampling before entering the DSP processor. Since the vortex shedding frequency under consideration would be in the range between 20 Hz to 400 Hz, the sampling rate of a 16-bit A/D converter for the DSP is chosen to be 1000 Hz, i.e., the Nyquist frequency is 500 Hz. Consequently, the band-pass for the ABPF is set between 20 Hz and 500 Hz. As an illustration, the raw signal trace originally shown in Fig. 3a is now processed by the ABPF and the result is shown in Fig. 3b. Figure 4b gives the corresponding frequency spectrum. The SNR value is about 1/7 for the trace shown in Fig. 3b. After ABPF, the analog vortex shedding signal is then digitized by the 16-bit A/D converter for further DSP processing.

**Algorithm in DSP**

Active Band-Pass Filter

Before introducing the algorithm in the DSP, it is noteworthy that the frequency spectra in both Figs. 4a and 4b show that several noise components are comparable and even larger than the vortex shedding component. Hence, it is difficult to identify the vortex shedding frequency in a straightforward manner. On the other hand, Fig. 5 shows the auto-correlation results of the signal traces in Fig. 3. In Fig. 5, the auto-correlation function, $R_{vv}(\tau)$, with respect to the time lag, $\tau$, for $\tau = 0$ to 0.1 second, is deduced from a raw signal of a time length of 0.512 second. In Fig. 5a, the high frequency undulation embedded in the auto-correlation trace is noted due to noise components in Fig. 3a, which makes it impossible to reduce the vortex shedding frequency by identifying the local maxima in the auto-correlation curve. In Fig. 5b, the situation of the ABPF-filtered signal trace seems better than that in Fig. 5a, but the undulation of the auto-correlation curve is still featured with other frequency components which produce undesirable local maxima.

In order to facilitate identifying the vortex shedding frequency from either auto-correlation or fast Fourier transform results, an additional band-pass filter with an adjustable center frequency prior to the auto-correlation or fast Fourier transform computation is deemed necessary. Along this concern, the digital vortex shedding signal in the DSP processor is then arranged to be filtered by a finite impulse response band-pass filter, denoted as DBPF in Fig. 2, with an order of 81. The DBPF has a band-pass whose low-frequency cut-off is $0.7f_c$ and high-frequency cut-off is $1.3f_c$. $f_c$ is the center frequency of the DBPF, which is determined by an amplitude detector described below. Figure 3c shows the DBPF-filtered result from
the trace in Fig. 3b, for $f_c$ being set as 30 Hz. As seen, the vortex shedding component in the signal trace is clearly discernable. Further, Figs. 4c and 5c are the corresponding frequency spectrum and auto-correlation trace. The SNR value at this stage is improved to a level of 2.4. Therefore, the vortex shedding frequency can be accurately determined from both frequency spectrum and auto-correlation results, which are 23.44 Hz and 23.53 Hz, respectively.

After DBPF, the signal is routed to a D/A converter, and then to a Schmitt trigger for pulse output. Meanwhile, the signal is stored in a data buffer of 512 points in size. Immediately after the buffer filled up, the 512-point data record is transfer to another buffer for auto-correlation or fast Fourier transform computations. On the other hand, the original data buffer keeps receiving data from the output of DBPF. Since the sampling rate is 1000 Hz, the full length of each data record is 0.512 second. Hence the computation result can be updated every 0.512 second.

Amplitude Detector

In order to determine the center frequency of the DBPF, an amplitude detector is arranged in the algorithm as shown in Fig. 2. Since the strength of vortex shedding is known proportional to the density of fluid and square of flow velocity, it is possible to make a rough estimation of the vortex shedding frequency from the strength of a vortex shedding signal (Takahashi & Itoh, 1993; Ghaoud & Clark, 2002), which can be measured by an amplitude detector. An amplitude detector usually comprises an absolute function, peak-detector, and a low-pass filter (Ghaoud & Clark, 2002). In this study, referring to Fig. 6, the design of amplitude detector is simplified to reduce the computation efforts in the DSP, which contains only an absolute function and a low-pass filter, denoted as LPF.

The LPF in Fig. 6 actually is a finite impulse response low-pass filter with an order of 81. It should be noted that the setting of cut-off frequency for the low-pass filter deserves careful considerations. If the cut-off frequency is too high, the amplitude detector became too sensitive to the amplitude modulation of a vortex shedding signal, which might not be caused by the variation of flow velocity. Inversely, if the cut-off frequency is too low, the amplitude detector would not be able to follow the amplitude variation due to flow velocity slewing. In this study, the cut-off frequency is set as 10 Hz.
flowmeter was installed at the location where fully-developed pipe flow condition is reached (Corpron, G. P., 1987a,b). Following the result of Fig. 7, the average signal level at different flow rates can be obtained. Figure 8 shows the relation between vortex shedding frequency and averaged signal level for $U_0$ = 5.44 m/s to 84.88 m/s. As seen, the vortex shedding frequency shows a trend linearly proportional to the root of the signal amplitude detected, which can be described as $f_c = 466.09 \times A^{0.5} + 6.07$. $f_c$ denotes the vortex shedding frequency reduced from this relation and $A$ is the amplitude of vortex shedding signal in voltage. The maximum deviation between the linear curve fitted and the experimental data is occurred at the lower limit of the range, which amounts to 30%. At higher flow rates, the discrepancies are less than 10%. With this relation, once the signal level is obtained, the center frequency for the DPBF is determined accordingly.

Frequency Computation Unit

Conventionally, when reducing vortex shedding frequency by auto-correlation or cross-correlation techniques, only the first local maximum of correlation function is utilized to estimate the time delay or the transit time so-called (Menz, 1997). A drawback of this method is that the uncertainty of vortex shedding frequency estimated gets large as the vortex shedding period gets shorter. In this study, to minimize the uncertainty due to this concern of time resolution, the auto-correlation function, $R_{ii}(\tau)$, of the vortex shedding signal is computed for $\tau = 0$ to 0.1 second. After the completion of the computation, the numbers of local maxima in the correlation curve are counted, denoted as $N$, and the time delay corresponding to the last local maximum is identified as $\tau_f$. Subsequently, the vortex shedding frequency is deduced from $N/\tau_f$.

See Fig. 5c for an illustration, where $N = 2$ and $\tau_f = 0.085$ second. Hence, the uncertainty of vortex shedding frequency due to time resolution is reduced to a level of $\Delta t/\tau_f$, i.e., 0.001/0.1 for this study, and it keep almost a constant value as the vortex shedding period gets shorter.

The computation of fast Fourier transform in this study has a frequency resolution of 1.95 Hz, i.e., (1/0.512) Hz. If the vortex shedding frequency is greater than 200 Hz, the uncertainty of frequency resolution by fast Fourier transform becomes lower than that by autocorrelation function.

PERFORMANCE VERIFICATION

The algorithm is verified with some artificial signals. The artificial signals are made up from true vortex shedding signals, but the component of vortex shedding frequency is replaced artificially. This is made for the sake that one could refer to a known frequency, therefore evaluate the tracing ability of the vortex shedding frequency. In the paper of Ghaoud & Clark (2002), a model was built for simulating the real vortex shedding signals. The simulated shedding signal primarily comprised a sinusoidal component at a given vortex shedding frequency and an additive band-limited noise. In this study, instead of employing the simulated model by Ghaoud & Clark (2002), a simple and more direct procedure is adopted. The raw signal acquired from the real pipe flow measurement is processed by a band-stop filter to remove the vortex shedding component, but the noise components, $n(t)$, is kept. Subsequently, a sinusoidal component with its amplitude and frequency comparable to the removed vortex shedding component is added to $n(t)$. Hence, the simulated signal with a known vortex shedding frequency and real noise components is obtained. Figures 9a and 9b present two simulated vortex shedding signals whose shedding frequencies are given as 23Hz and 315Hz, respectively. The signals are then employed for examining the frequency tracing ability of the algorithm. It is noted that the signal trace in Fig. 9a has a noise level comparable to that in Fig. 3b. Figures 10a and 10b show the test results correspondingly.

In Fig. 10, the dashed line indicates the reference vortex shedding frequency, and the triangular and the circular symbols denote the frequencies obtained by auto-correlation function and fast Fourier transform with respect to time, respectively. In Fig. 10a, the deviations of the triangular and circular symbols from the dashed line are about 1.1%, and 1.9%, respectively. The result shows that vortex shedding frequency estimated by auto-correlation has a smaller error then that by fast Fourier transform in the low frequency range. It is noted that the time interval between two neighboring symbols is 0.512 second. On the other hand, in Fig. 10b the deviations of triangular and circular symbols from the dashed line are about 0.5% and -0.17%, respectively, inferring that at high frequency the results reduced by fast Fourier transform are more accurate than those reduced by auto-correlation.

As a result, a combined strategy of auto-correlation and fast Fourier transform is proposed, i.e., auto-correlation is employed for $f_c$ less than 200 Hz, while fast Fourier transform is for $f_c$ larger than 200 Hz.
This strategy is further verified by examining its dynamic response. Figure 11 shows the result obtained. It is seen that the flow starts with a constant vortex shedding frequency of 177 Hz and then accelerates to a higher flow rate for $f_s = 224$ Hz. The slew rate of this case, expressed in terms of the rate of change of frequency, is 18.3 Hz/s. Figure 12 shows the artificial signal corresponding to the time period of $t = 5$ to 7 second in Fig. 11. As the flow rate reached $f_s = 271$ Hz, the flow is slowed down with a rate of -30.1 Hz/s and finally reached a flow rate of $f_s = 40$ Hz. As seen, the vortex shedding frequency estimated by the algorithm, denoted by the triangular symbols, shows highly consistent with the reference frequency, indicated by the dashed line, during the periods of constant flow rate. Specifically, the maximum deviation is less than 0.3%. However, during the slewing periods, the estimated frequency has a lag of 0.512 second referring to the reference frequency, which is due to that the data record is processed every 0.512 second. For reference, the time lag of the conventional algorithms, reported by Ghaoud & Clark (2002), is about 1 to 3 second.

**DISCUSSION**

By comparing the present algorithm with conventional methods for computing the vortex shedding frequency, several comments can be made as below.

1. In this study, both fast Fourier transform and auto-correlation are employed to determine the vortex shedding frequency. Since the length of a data record for computation is 0.512 second, the time length could be more than ten or even hundreds of vortex shedding periods, depending on the flow rate. Consequently, it is supposed to be more reliable than the zero-crossing technique, which employs only one wave period of the signal for computation. For reference, the accuracy of a zero-crossing technique found in the study of Clark & Ghaoud (2003) is between 0.5 to 2.9% within a flow range from 3 to 0.25 l/s.

2. In the study of Menz (1997), only the first local maximum of the correlation curve was used to estimate the vortex shedding frequency. The accuracy by this approach is about 1% to 2% (Menz, 1997). One of the drawbacks concerning this approach is that the frequency resolution became poorer as vortex shedding frequency gets higher. In this study, all the local maxima on the auto-correlation curve are collected for estimating the vortex shedding frequency, and hence improves...
the problems mentioned.

3. PLL provides an alternative way to lock vortex shedding frequency. Clark & Ghaoud (2003) designed a dual-PLL circuit with an active prefilter to trace vortex shedding signal. However, tuning the parameters of PLL is usually troublesome. According to the study of Clark & Ghaoud (2003), the accuracy for the dual-PLL circuit is about 0.5 to 3.0% within a flow range from 3 to 0.25 l/s, while for the lower flow rate down to 0.1 l/s, the accuracy is 6.5%.

4. Regardless of zero-crossing, PLL, correlation function and the present algorithm, the accuracy of vortex shedding frequency estimation is strongly dependent upon the performance of prefilters. Usually a smart filter with its center frequency as a variable is desirable. If the center frequency reduced by the amplitude detector are too far from the true vortex shedding frequency, an erroneous frequency might have been locked or computed by zero-crossing, PLL, correlation function or the present algorithm. This situation could be happened as the piezoelectric sensor decays with time or the gain for signal amplification is changed inadvertently. In this case, the frequency-amplitude relation might break down. Hence, a more reliable pre-filter with more intelligent capability seems necessary.

CONCLUSIONS

In this study, an algorithm is designed to estimate real-time vortex shedding frequency of a vortex flowmeter. The algorithm mainly comprises two parts, one of which is the active band-pass filter with an adjustable center frequency determined by an amplitude detector, and the other is the computation subroutine for determining vortex shedding frequency, which is composed of auto-correlation and fast Fourier transform. Due to the concern of the frequency resolution, the auto-correlation technique is implemented if the vortex shedding frequency is less than 200 Hz, whereas the fast Fourier transform is for the vortex shedding frequency larger than 200 Hz. The test results of the algorithm demonstrate a tracing ability characterized by a time lag of 0.512 second on vortex shedding frequency for the flow rate varying with time. For constant flow rate at moderate and higher vortex shedding frequencies, the estimated error on vortex shedding frequency is less than 0.3%. For the lowest flow rate for which the SNR value is about 1/12, the vortex shedding frequency estimated is about 1.1% deviated from the true value. In summary, the combination of auto-correlation and fast Fourier transform computation in the present algorithm can provide reliable vortex frequency estimation.

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智慧型渦流流量計之滯放頻率即時運算

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摘 要
本本文主要在發展一渦流滯放信號處理演算法，以求得即時之渦流滯放頻率，該演算法由一數位信號處理器(TI TMS320 C6711)負桿付運算，為智慧型渦流流量計之滯放信號處理器。

該演算法主要包含一數位濾波單元及頻率計算單元，該數位濾波單元之中心頻率可隨著載入之渦流滯放信號的強度作即時的調整，以達到最佳的濾波效果，於實驗中，一組原本信號雜訊比(SNR)為4/12的渦流滯放信號，經過數位濾波單元處理後，可將信號雜訊比提高至2.4。在經過數位濾波後，該信號即被傳入頻率計算單元，該頻率計算單元由快速傅立葉轉換及自相關演算法所組成，為降低運算過程中頻率解析度所造成之誤差，該計算單元在渦流滯放頻率小於200Hz時，利用自相關演算法求得渦流滯放頻率，而當渦流滯放頻率大於200Hz時，則利用快速傅立葉轉換。

該信號處理演算法經實測後顯示，在中高流速的情況下，所求得之即時滯放頻率的誤差僅為0.3%，而在低流速且信號雜訊比為1/12的情況下，滯放頻率的誤差為1.1%。此外，當流速隨時間改變時，該演算法對渦流滯放頻率的追蹤能力有0.512秒的時間延遲。