Development of DSP-Based Dynamic Signal Processing Module for Turbine Flowmeter

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Abstract: Traditional signal processing methods for turbine flowmeter are unable to solve the contradiction between the real-time performance and the accuracy during the aeroengine bench test or hardware in the loop (HIL) simulation of aeroengine control system. A dynamic flow measurement method based on cycle number of the flowmeter is proposed. And a DSP-based multi-functional dynamic signal processing module for turbine flowmeter is built to validate the method. The developed system can provide three types of output modes including PWM, frequency and D/A. At the same time, the results can be displayed instantly with the module of serial communication interface to obtain dynamic flow signal with good precision. Experimental results show that the stability of flow measurement is greatly improved with precision guaranteed and the real-time response reaches the maximum limit of turbine flowmeter.

Key words: turbine flowmeter; DSP; cycle-number filter; dynamic flow measurement

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0 Introduction

Dynamic measurement of fuel flow plays an important role in the control of aeroengines. Measurement of fuel flow is vital to engine in operation, and also is essential for early steps of control design, such as hardware in the loop (HIL) simulation or bench test. With the advantages of simple structure, high sensitivity, low pressure loss, fine repeatability and stability, turbine flowmeter has been widely used in the measurement of fuel flow[1]. In turbine flowmeter, the fluid velocity is approximately proportional to the rotation speed of turbine. Thus, the volumetric flow through the rotor can be achieved by measuring the frequency of the pulse signal output generated by turbine flowmeter. For a good turbine flowmeter, the frequency of its output pulse signal can quickly follow the change of flow. When turbine flowmeter is chosen, its characteristics are decided, too. Therefore, the processing method of the pulse signal will decide the final accuracy and real-time performance. However, traditional signal processing methods, such as frequency measurement, cycle measurement, F/V conversion and frequency multiplication, cannot ensure dynamic performance and measurement accuracy at the same time. In the paper, a dynamic flow measurement based on cycle number is presented and experimentally validated using a DSP-based multi-functional dynamic signal processing module.

1 Traditional Signal Processing Methods

One conventional processing method is to figure out the signal frequency by counting the number of pulses during a period, which is called "frequency measurement"[2]. The signal frequency generated by turbine flowmeter is usually just several hundred Hertz, which leads to the prob-

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lem of real-time. Therefore, a longer testing time is needed to ensure the accuracy. If taking cycle measurement to ensure real-time, unsteadiness of the signal and uncertainty of the measurements will occur because of the manufacturing tolerances in turbine blades[3]. F/V conversion method seems to be able to solve the real-time problem, which indirectly tests the frequency by voltage signal. The frequency multiplication method based on the phase locked loop (PLL) technique is also used to improve the performance of real-time. However, the dynamic performance of the method is not ideal.

The dynamic performance and measuring accuracy of these three methods will be tested in the next part.

1.1 Cycle measurement method analysis

The high frequency cycle counter working for frequency signal acquisition program is 32 bit with the clock source of 24 MHz. In a relatively stable flow, 11 count values at rising edge of continuous signals from the turbine flowmeter are obtained. The corresponding 10 pulse frequencies are as follows:

18.291 Hz 19.106 Hz 18.238 Hz 19.899 Hz 17.928 Hz 19.616 Hz 18.154 Hz 18.924 Hz 18.085 Hz 19.718 Hz

Thus, the conclusion can be drawn that the cycle measurement has a large fluctuation (1.971 Hz).

1.2 F/V conversion method

Fig. 1 shows the response curve of F/V conversion circuits working at 1 kHz stably when suddenly given a positive step change of 1 kHz. It takes about 300 ms for the output voltage back to equilibrium, as is shown in the response curve.

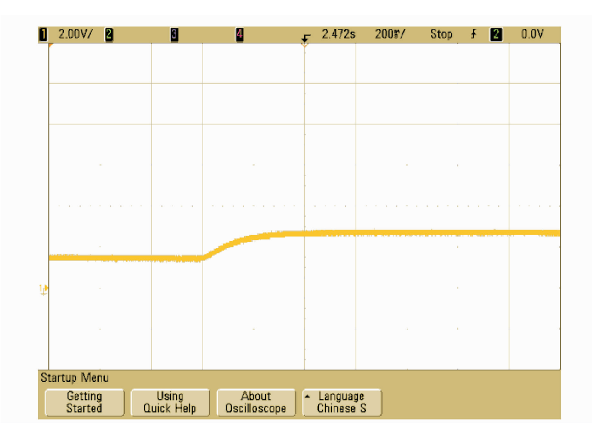

Fig. 1 Response curve of F/V conversion circuit (Input frequency changing into 1 kHz from 2 kHz)

Fig. 2 depicts the response curve of F/V conversion circuit working at 2 kHz stably when a negative step change of 1 kHz is suddenly given. And it costs the output voltage signal 1 s back to equilibrium.

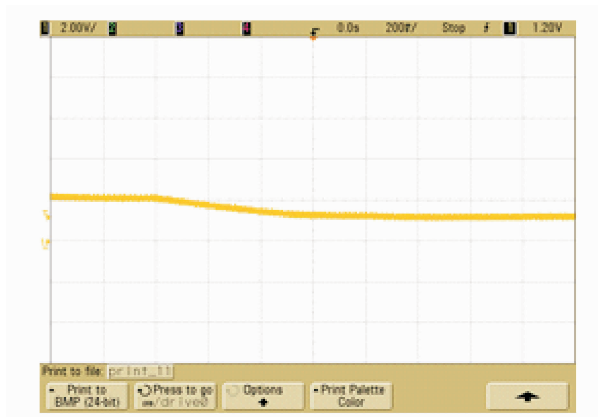

Fig. 2 Response curve of F/V conversion circuit (Input frequency changing into 2 kHz from 1 kHz)

Consequently, the quick change of the frequency will result in lag of output voltage, up to hundreds of milliseconds, which means bad real-time performance. As the conversion time varies a lot when the frequency increases or decreases, the dynamic frequency is not easy to measure leading to unsatisfactory dynamic performance. Thus, F/V conversion which indirectly tests frequency by voltage is not ideal in practical application.

1.3 Frequency multiplication method

Fig. 3 shows the response curve of PLL doubling circuit working at 1 kHz stably when a step change of 1 kHz is suddenly given. In the figure, high level represents that the loop is locked and low level represents that the loop is lost. It takes approximately 0.9 ms for the input frequency until PLL is locked.

As mentioned, PLL needs about 1 s to be locked when a negative step change is given. Besides, the manufacturing tolerances of turbine blades will cause unsteadiness of the signal cycle,

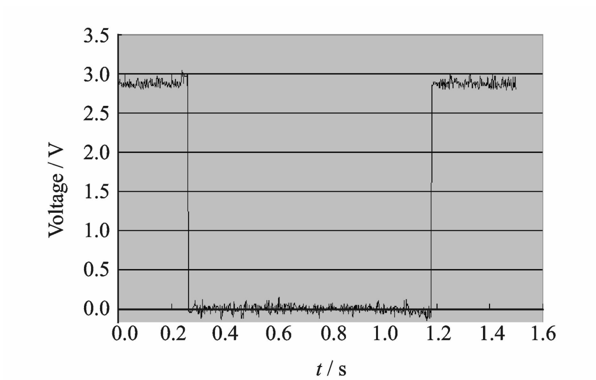

Fig. 3 Response curve of PLL circuit (input frequency changing into 1 kHz from 2 kHz)

which results in unsteadiness of PLL. Therefore, frequency multiplication based on the PLL circuit cannot improve the real-time performance and the measurement accuracy.

2 Module System Design

2.1 Hardware structure

The hardware components of the dynamic signal processing module for turbine flowmeter include a DSP main controller, a power supply module, a pulse signal acquisition module, a PWM (Pulse width modulator) output module, a frequency output module, a D/A output module and a serial communication module. Fig. 4 is the block diagram of hardware modules.

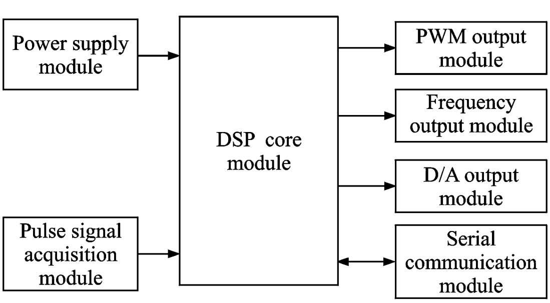

Fig. 4 Hardware chart

TMS320F2808 made by U. S. TI company is selected, which includes 64 kB×16 Flash, 18 kB ×16 SARAM (Single access RAM), three 32-Bit CPU timers, a watchdog, 4 capture inputs, 16 PWM outputs, 2 way SCI (Serial communication interface), 4 way SPI (Serial peripheral interface) and 6 external clocks. DSP can be easily debugged and downloaded through JTAG online[4,5].

2.2 Software structure

Modular development is used in the design of the software structure, which is convenient for debugging, linking, modifying and transplantation of programs. The software components of the dynamic signal processing module in turbine flowmeter include ECAP (Enhanced capture) module, EPWM (Enhanced pulse width modulator) module, SCI module, SPI module as well as other modules. The modular structure of the software is presented in Fig. 5.

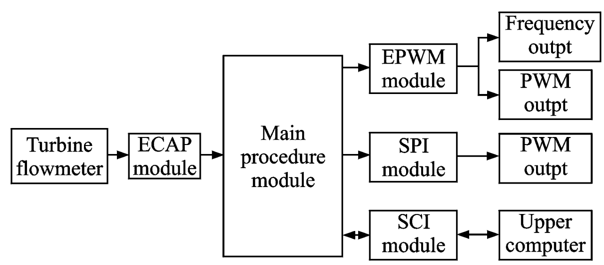

Fig. 5 Software structure chart

The front and back end mechanism is adopted to meet the demand of real-time characteristic and multi-task management. The main procedure runs in the background and the interrupt service program runs in the foreground. The main procedure is an infinite loop that calls different modules to complete their corresponding tasks. In addition, DSP calls the interrupt service program to realize specific functions through interrupt response.

The main procedure consists of system initialization, signal capture and processing, PWM output, frequency output, analog signal output and data generation through the serial interface. Interrupt sources in module include timer interrupt, CAP (Capture) interrupt, serial communication and receiver interrupts. Interrupt methods improve the response speed, so that the program is faster and more reliable. Timer interrupt determines the period of main procedure which is set to 10 ms. Fig. 6 shows the main program flow chart.

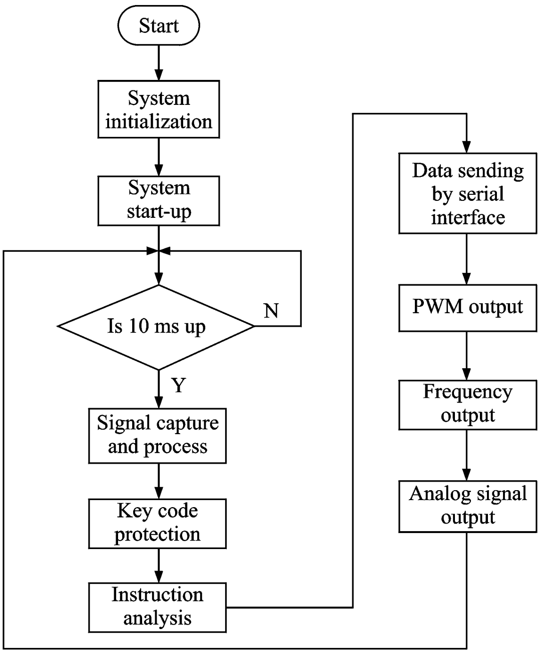

Fig. 6 Main program flow chart

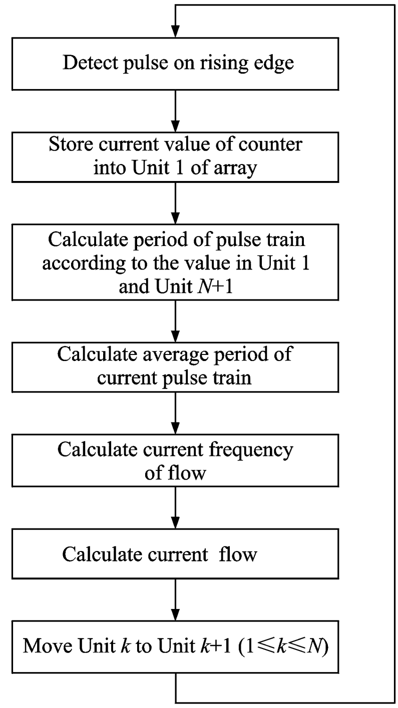

Fig. 7 Signal capture and process dynamically flow chart

3 Data Processing Principle and Method

3.1 Dynamic flow measurement based on cycle number

Due to manufacturing tolerance of turbine flowmeter blades, the pulse signal output is likely to be unstable. In order to reduce this impact, a dynamic flow measurement based on cycle number is proposed. Its fundamental principle is that DSP collects several cycles of pulse signal (The cycle number is equal to the number of blades), and then the average period of pulse train is calculated as soon as a new pulse signal is captured. Thereupon, the current flow is obtained according to the current frequency converted by period[6].

The detailed process is shown in Fig. 7. Firstly, we set an array with $N+1$ integers to store the value of the counter (N is the cycle number). The current value of cycle counter will be recorded in Unit 1 of the array at the rising edge of the pulse signal, and the past values are stored into the array sequentially, starting with Unit 2 until Unit $N+1$. Then we obtain the period of pulse train by the value of Unit 1 and Unit $N+1$: If the number of Unit 1 VALUE[1] is greater than that of Unit $N+1$ VALUE[$N+1$], the period of pulse train T can be calculated (The period of standard pulse of counter is t)

$$T = (\mathrm{VALUE}[1] - \mathrm{VALUE}[N+1]) \times t \quad (1)$$

Otherwise,

$$T = (\mathrm{VALUE}[1] - \mathrm{VALUE}[N+1] + M) \times t \quad (2)$$

where M is the maximum of cycle counter.

Thus, the current frequency and flow can be drawn by T. The specific process of rolling acquisition is that the values ranging from Unit 1 to Unit N move to the right until the value of Unit N takes place of that of Unit $N+1$.

3.2 Software implementation

According to the principle above, the part of data processing is shown in Fig. 8. Num represents the number of periods captured in 10 ms.

4 Experimental Verification

In order to verify the accuracy and improve the results of the module based on the method above, an experimental verification is carried out with a flow simulating the real working conditions of an aeroengine. In this experiment, a turbine flowmeter FT4-8 made by U. S. Flow Tech-

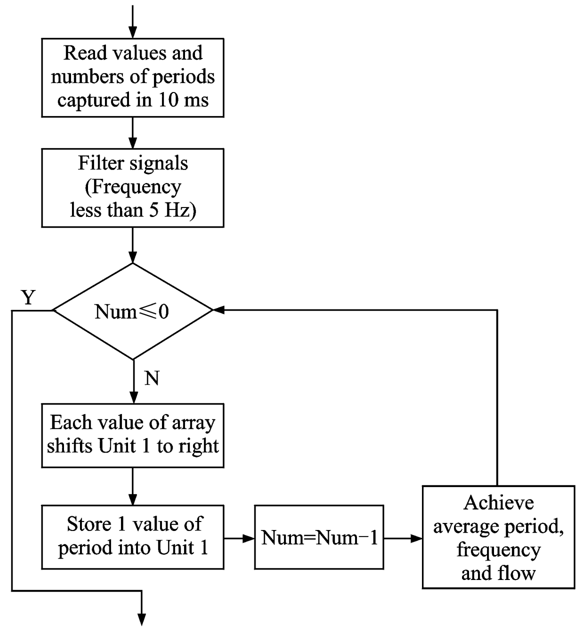

Fig. 8 Data processing flow chart

nology company is used, whose flow range is between 0. 11 and 11. 0 L/min and the maximum output frequency is about 2 kHz. Theoretically, the output signal of the turbine flowmeter with six blades should cycle every six pulses. As shown in Fig. 9, the cycle number can be estimated using a piece of data chosen from the frequency of flow plateau. Periodic trends can be seen in the figure and the cycle number is 6, which is the same as that of blades. Besides, the maximum fluctuation of signal frequency reaches 5. 3 Hz during the measuring section, corresponding to 25. 81 mL/min in flow fluctuation. Obviously, it is conflicted with practice situation. Therefore, for signal acquisition of turbine flowmeter, frequency fluctuation caused by manufacturing tolerance of blades should be considered.

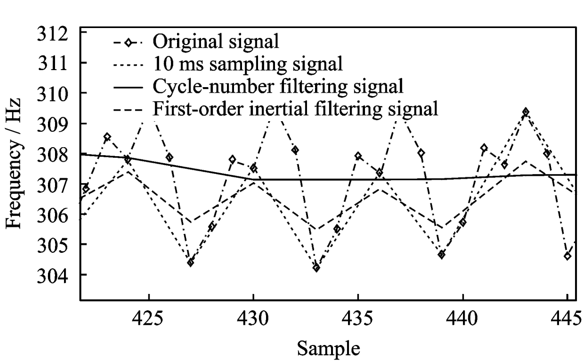

Fig. 9 Frequency of flow plateau

Currently, there are primarily two methods in processing signals of turbine flowmeter at home and abroad, fixed-step direct sampling and first-order inertial filtering. Fig. 9 shows comparison of the result of cycle-number filtering with these two methods. The sampling period is 10 ms and the time constant of first-order inertial filtering is 0. 01 s. As Fig. 9 shows, when the flow is basically stable, the frequency fluctuation of direct sampling is up to 5. 2 Hz, corresponding to 25. 32 mL/min in flow fluctuation. The original data of first-order inertial filtering is obtained by direct sampling. Thus, affected by the position of original sample data, the frequency fluctuation is about 2. 2 Hz, corresponding to 10. 7 mL/min in flow fluctuation, which is bigger than that of cycle-period filtering method. Taking cycle-period filtering method, the frequency fluctuation is the smallest. It is only 0. 8 Hz and corresponds to 3. 89 mL/min in flow fluctuation which is consistent with actual flow fluctuation. Therefore, the stability of flow measurement is greatly improved with precision guaranteed.

As Fig. 10 shows, compared with the first-order inertial filtering method, the real signal can be tracked more quickly by using the cycle-number filtering method. Improved and optimized from cycle measurement, the method proposed in the paper can obtain the current flow within 2. 5 ms (That is a period of a pulse signal), which reaches the highest level under this frequency. What's more, the data fluctuation of samples obtained by cycle-period method is smaller than that by direct sampling and more precise than that by first-order inertial filtering.

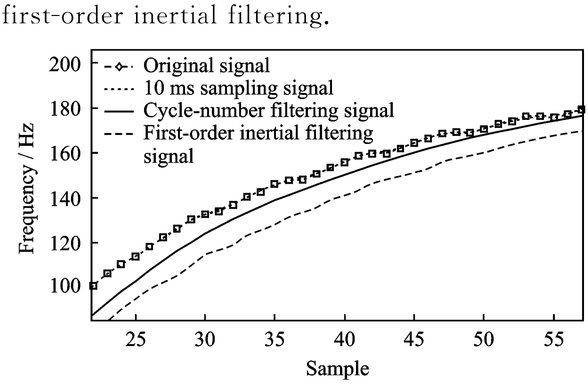

Fig. 10 Frequency of rising section

5 Conclusions

Aiming at real time and precision problems in flow measurement during bench test or semi-physical simulation, a dynamic flow measurement method based on cycle number is proposed. And a dynamic signal processing module of multi-functional turbine flowmeter which is based on DSP is also presented. It solves the problem of periodic fluctuation in output frequency, caused by blades manufacturing tolerance. The research result shows that the module has both good real-time performance and precision. It can quickly and accurately obtain measurement results in every frequency band. What's more, compared with other methods, the proposed method greatly improves signal stability of turbine flowmeter and measurement precision.

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