Development and implementation on torsional vibration measurement of rotational machinery's shaft

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Abstract. The measurement and analysis on torsional vibration is an important aspect to research the performance state of rotating machinery’s shaft. This paper introduces the basic procedure of torsional vibration measurement, deduces the manifestation of torsional vibration signal, focuses on the hardware design and software implementation of torsional vibration measurement system, and applies the measurement system to a certain type of ship and steam turbine generator shaft in actual testing. The measurement results verify the practicability and accuracy of the system.

1. Introduction
Torsional vibration, as the main way to affect the reliability and safety of the dynamic system of rotating machinery, has always been concerned. Taking the ship as an example, the discontinuous fuel injection and combustion of the diesel engine, the error in the process of gear operation, the poor alignment of the shaft, the influence of the uneven flow field on the propeller, and the uneven force on each blade, will all cause the torsional vibration. The fatigue of shaft caused by torsional vibration stress is accumulating continuously, after reaching a certain extent, cracks and notches will be formed on the shaft, which may lead to shaft fracture [1]. Therefore, it is necessary to measure and analyze the natural frequency of torsional vibration of rotating mechanical shaft, so as to avoid the rotation shaft working at the natural frequency speed in the actual operation process.

In the research of rotor dynamics, the measurement and analysis of shaft vibration plays an important role. The purpose of torsional vibration measurement and analysis is to accurately measure the torsional vibration waveform and speed signal of shaft at various working speeds, and analyze the waveform to obtain the maximum amplitude and corresponding vibration frequency, vibration harmonic and critical speed, measure or check the additional torsional stress of shaft [2-3], and check the fatigue strength of shaft, judge the vibration impact on other related parts, and take targeted vibration reduction and avoidance measures as needed.

2. The measurement procedure
When measuring the torsional vibration of the shaft, a gearwheel disk is set at the measured position. When the gearwheel disk rotates with the shaft, the eddy current sensor generates a series of pulse signals. When the shaft rotates smoothly, the timing position of the pulse reflects the arrangement of the gears along the circumference. When the shaft torsional vibration occurs, the timing position of each pulse will change, and the sampling value of torsional vibration can be obtained by extracting
this change [4]. Generally speaking, the relative time of each pulse is recorded by high frequency counting.

A mark (usually a tooth or a groove) is determined on the rotating shaft as the reference point of the starting time of the rotation cycle [5], and then the arrival time of each pulse signal of the measured position is measured by encoder, which carries the information of the shaft rotation movement, as shown in Figure 1. The torsional vibration information of the shaft can be obtained by the corresponding digital signal processing for several sets of counting values [6-7].

![Figure 1. Waveform of encoder.](image)

Assume the number of teeth of the gear is $Z$, when the average speed of the shaft is $n$ rpm, the pulse repetition frequency induced by the eddy current sensor is [8-9]:

$$f = \frac{Z \times n}{60}$$  

(1)

Assume that the angular displacement of torsional vibration is:

$$\varphi(t) = A \sin(\omega t + \theta)$$  

(2)

Then it is angular velocity is:

$$v(t) = \frac{d\varphi(t)}{dt} = \omega A \cos(\omega t + \theta)$$  

(3)

Thus, the angular displacement of shaft caused by torsional vibration is:

$$\Delta n = \frac{v(t)}{2\pi} = \frac{\omega A}{2\pi} \cos(\omega t + \theta)$$  

(4)

It can be seen that when there is a torsional vibration in the shaft, the pulse repetition frequency output by the eddy current sensor is:

$$f = \frac{Z(n + \Delta n)}{60} = \frac{Zn}{60} + \frac{Z\Delta n}{60} = f_1 + f_2$$  

(5)

where: $f_1$ is the constant frequency component of the shaft under steady rotation, $f_2$ is the component of frequency variation caused by torsional vibration.

The signal picked up by the eddy current sensor drives the monostable circuit to work and outputs rectangular pulses with constant amplitude and width. The repetition frequency of these pulses is also $f$.

After low-pass filtering, the average voltage is obtained as follows:
\[ U(t) = \frac{t_0}{T} M_0 \tag{6} \]

where: \( t_0 \) is the duration of rectangular pulse, \( T \) is the period of rectangular pulse, \( M_0 \) is the peak value of rectangular pulse.

Substituting Equation (5) into Equation (6):
\[ U(t) = f t_0 M_0 = (f_1 + f_2) t_0 M_0 = \frac{2n t_0 M_0}{60} + \frac{Z t_0 M_0}{60} \left[ \frac{\omega A}{2\pi} \cos(\omega t + \theta) \right] \tag{7} \]

After filtering, the torsional vibration voltage signal can be obtained:
\[ U'(t) = \frac{Z t_0 M_0}{60} \left[ \frac{\omega A}{2\pi} \cos(\omega t + \theta) \right] \tag{8} \]

Finally, the output voltage signal \( U(t) \) is obtained through the integral amplification (the amplification factor is \( K \))
\[ u(t) = K \int U'(t) = \frac{Z t_0 M_0}{120\pi} \varphi(t) \tag{9} \]

It can be seen that the voltage output signal and the angular displacement of torsional vibration of the shaft have exactly the same variation form. After normalization, the output signal can be used to describe the angular displacement of torsional vibration at the measuring point of the shaft, and thus the natural frequency of the torsional vibration can be estimated by Fourier transform or power spectrum.

3. Hardware design

The block diagram of data acquisition system is shown in Figure 2.

**Figure 2.** Block diagram of data acquisition system.

3.1. Eddy current displacement sensor
SK-3000 eddy current displacement sensor is used to pick up the torsional vibration signal [10]. The sensor has good reliability, high sensitivity, strong anti-interference ability, non-contact measurement, fast response speed, and is not affected by oil, water and other media. It is very suitable for the torsional vibration signal measurement of rotating machinery.

3.2. Filter shaping circuit
SK-3000 eddy current displacement sensor is equipped with a pre-shaping circuit. Due to various reasons, the output rectangular waveform of the sensor will sometimes be distorted, which will bring error to each rectangular pulse signal. The MAX292 chip is used as a low-pass filter to reshape the signal entering CPLD to reduce the measurement error.
3.3. **TFT-LCD display circuit**
A TFT-LCD display screen is set in the system to display the working status of the current system in real time.

3.4. **CPLD XC95288XL**
CPLD adopts XILINX company’s XC95288XL high density and large-scale programmable logic chip. The circuits of counting, amplifying, data selecting, latch, switch control and display control are written into the chip after programmable design, with high integration, stable and reliable operation.

3.5. **MCU STM32F103C8T6**
MCU chooses STM32F103C8T6 chip [11-13], which is responsible for coordinating CPLD to read count value, buffering data, controlling serial port chip to complete data transmission with computer, and processing status information reading, writing and display.

The torsional vibration data acquisition program is solidified in 64K Flash of STM32F103C8T6 chip, which can quickly and reliably manage the test functions and data communication.

3.6. **Serial communication**
The serial communication uses MAX232 chip to convert TTL signal into RS232 signal, and then communicate with the host computer.

![Figure 3. The serial communication interrupt service flow.](image)

4. **Software design**

4.1. **MCU software design**
The MCU program uses RealView MDK 5.15 development environment and C language. Before writing the data acquisition system, keil.STM32F1xx_DFP.2.3.0. pack software development package must be downloaded. The serial communication interrupt service flow is shown in Figure 3.
4.2. Host computer software design

The host computer software uses Java program GUI graphical user interface [14-15], AWT and SWING, uses layout manager Layout and controls JPanel, JButton and so on to design specific menus and buttons, and uses event monitor to set action program. The main interface is divided into three parts: “menu”, “status display” and “data curve display”. There are “file selection”, “analysis”, “measurement”, “print curve”, “parameter setting” and “exit” in the “menu”. When the program is running, it will continuously receive data from the serial port. When the data needs to save, the program will automatically save the data to disk. When the stored data needs to display, use “file select” menu to open the file. It can select "analysis" menu to analyze the results of data through different algorithms, select "print curve" menu to print. In addition, it can also set the basic parameters of serial communication and measurement parameters. The most important parameters of serial communication are baud rate, data bit, stop bit and parity.

Java.comm class library controls the serial port events through Serial Port object, reads the serial port data through InStreaming() method, writes data to the serial port through CounterStream() method, and sets the communication protocol of serial port through Parameterizations() method. For real-time monitoring applications, the listener can be registered through Transcendental() method, set the events that the serial port needs to respond to through Elevenths() method. When the corresponding event or serial error event occurs, the system will activate the monitor program, and then carry out the corresponding operation.

The vibration signal of shaft torsional vibration is a time domain signal with the main engine speed as the period. The frequency (harmonic order) of the response in the spectrum is only related to the number of cylinders or shaft frequency of the main engine and the number of blades of the propeller. The speed range of shaft vibration measurement is large (minimum stable speed ~ 1.1 times of rated working speed), and the average speed of each required measurement condition fluctuates. In order to avoid the "aliasing" effect caused by improper sampling frequency selection of FFT and the "leakage" effect caused by using window function signal to intercept the measured signal, Yule-Walker algorithm based on AR model is used to analyze the sampled signal.

Two-dimensional data display mainly uses the drawing function in Java. When drawing the torsional vibration signal waveform and analyzing the power spectrum of torsional vibration signal, redrawing events will occur, which ensures the normal display.

5. System application and measurement

5.1. Application in a certain type of ship shaft

The maximum rotation speed of a ship’s shaft is 800r / min, the minimum speed is 500r / min, and the number of flywheel teeth is 291. The torsional vibration measurement system is used to measure the torsional vibration: starting from the lowest speed, 4 turns torsional vibration amplitude signal is collected each time, and then the torsional vibration amplitude signal is collected every 10 rounds, and so on to the highest speed. Several groups of measured time-domain signals are shown in Figure 4.

The period (its reciprocal is frequency, called fundamental frequency) of torque output by a single cylinder of diesel engine is the time of a working cycle. Such a periodic torque can be decomposed into several simple harmonic components with certain amplitude and phase, and the frequency is a positive integer multiple of the fundamental frequency. In order to connect the harmonic frequency with the speed of diesel engine, the number of simple harmonic torque in one revolution of crankshaft is called simple harmonic number. Because the amplitude of the harmonic component of torque decreases rapidly with the increase of the number of intermittences, only 12 ~16 times are considered in the calculation.

It can be seen from the time-domain waveform that the harmonics of torsional vibration recorded curve is 3 within one rotation of the crankshaft. Therefore, in the frequency-domain figure, the frequency-domain waveform of 3, 6, 9 and 12 harmonics torsional vibration wave is required for the
analysis of the torsional vibration of the shaft. Its third-harmonic frequency-domain curve is shown in Figure 5.

Figure 6 is the vibration spectrum waveform given in the calculation manual of this shaft torsional vibration.

As can be seen from Figure 5 and Figure 6, the actual measured first natural vibration frequency is 779 r/min, and the first natural vibration frequency of this shaft given in the calculation manual of torsional vibration of shaft system is 778r/min. The two results are consistent and meet the design requirements.
5.2. Application in a steam turbine generator shaft

The natural frequency of the first to sixth torsional vibration of a turbine generator set shaft are shown in Table 1.

| First natural frequency | Second natural frequency | Third natural frequency | Fourth natural frequency | Fifth natural frequency | Sixth natural frequency |
|-------------------------|--------------------------|------------------------|-------------------------|------------------------|------------------------|
| 12.9541                 | 19.4707                  | 26.6052                | 30.5738                 | 76.8036                | 80.7333                |

The first torsional vibration natural frequency of the shaft system obtained by theoretical calculation is 12.9541Hz, while the first torsional vibration natural frequency of the shaft system measured in the torsional vibration measuring system is about 13.5Hz, which is relatively close with only an error about 0.55Hz. The main sources of errors are the influence of bending vibration on torsional vibration, the influence of gear precision and the influence of low frequency interference signal in the measurement process.

6. Conclusions

On the basis of studying the working procedure of pulse counting torsional vibration measuring method, a practical high-precision torsional vibration measuring system is developed through the reasonable design of hardware, flow chart and host computer software. RS232 data transmission interface and large capacity buffer make the torsional vibration measurement system with high precision, high anti-interference performance and good fault tolerance performance, and meet the requirements of high speed, high precision, high real-time, etc. Through the actual verification analysis, the working performance of the system basically meets the requirements.

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