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Application of Interferometry in Ultrasonic System for Vibration

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Abstract. Vibration signals are important state parameters for mechanical equipments' status monitoring and fault diagnosis. In this paper, in order to overcome the limitations of the traditional vibration measurement methods and instrument, a new non-contacting vibration method based on ultrasonic for vibration detection in special environment was presented. The mainly researched in this paper were the circuit for ultrasonic transmitting, receiving, algorithm and the module based on LabVIEW for signal analysis and processing. New algorithm was adopted in the system design. The measurement for vibration signals, which may have higher accuracy, was based on ultrasonic wave of different frequency. Experiments were carried on for proving the theory and the result was expected, verifying the reliability and feasibility of the system.

Keywords: Vibration Signal, Ultrasonic, Signal Processing, Fault Diagnosis.

1. Introduction

Vibration signals are important state parameters for mechanical equipments status monitoring and fault diagnosis. The method of vibration signals measurement is very limited. Such as displacement sensor, speed sensor and acceleration sensor, they are limited of itself. Most of the sensors are mounted to measure the objects. Testing vibration on Eddy current sensor is a noncontact system, but the distance is very limited. The traditional vibration measurement methods and instrument can not achieve effective measurement in HTHP industrial environment. A new non-contacting vibration method based on ultrasonic for vibration detection is completed high precision, long-distance measuring in special environment.^[1]

To overcome the limitations of the traditional vibration instruments, a non-contacting vibration method based on ultrasonic for vibration detection in HTHP environment was presented in this paper. The noncontact system of vibration measurement is based on optical interferometry. Ultrasonic has advantages such as high frequency, shorter wave-length, steady direction of propagation, and easily obtainment of directional and focused ultrasound beam. The principle of the vibration measurement system is based on Doppler. A continuous wave ultrasonic beam is transmitted toward the vibrating surface, and the ultrasound signal reflected by this

moving surface is sensed by a second transducer. The received ultrasound signal is phase modulated. Therefore, features can be extracted from the vibration signal by analyzing the factors that affect the variations of traffic load.

2. Method

The method of the vibration measurement system is based on the phase. The schematic diagram of the ultrasonic system for vibration measurements is given in the **Fig.1.**, $y(t)$ and $y(r)$ are respectively the transmit signal and the receive signal. In operation, the ultrasonic transmitter transmits $y(t)$ continuously and the ultrasonic receiver will simultaneously receives $y(r)$ reflected by the object. Besides, the w is the angular frequency of ultrasonic wave, the C is speed of ultrasonic wave, and the $L(t)$ is distance between the ultrasonic transducers and the measured object.^[1] The transmitted and the received wave forms are given by

$$y(r) = \sin(\omega t + \phi) \quad (1)$$

$$y(t) = \sin \omega t \quad (2)$$

The distance that the signal spreads from transmitting transducer to receiving transducer is $2L(t)$. The $L(t)$ depends on effective vibration length $d(t)$. The change of phase $\Phi(t)$ is determined by the formula,

$$\phi(t) = \frac{2L(t)}{\lambda} * 2\pi \quad (3)$$

The effective vibration length is determined by the formula,

$$d(t) = \Delta L(t) = \frac{\Delta\phi(t)}{2\pi} \frac{\lambda}{2} \quad (4)$$

The λ is the wavelength of the ultrasonic wave used in this system; the $\Phi(t)$ is the change of phase and it is changed among 0 to 2π ; the $\Phi(t)$ depends on the effective vibration length $d(t)$. The peak amplitude d_{max} is peak amplitude of the ultrasonic wave. The θ has some repeated and the $d(t)$ is not judged when the $d(t)$ exceeds the length of $\lambda/2$. So the $d(t)$ is bounded by $\lambda/2$ and the $D(t)$ that it the $d(t)$ is bounded by $\lambda/2$ that is defect. To overcome this limitation, an effective algorithm was selected and low frequency wave and high frequency wave was adopted in this paper. The low frequency wave has large wavelength, so that the measurement range was increased. The high frequency wave has high frequency, so that the measurement precision is improved. The total displacement $D(t)$ is determined by the formula,

$$D(t)=2 d(t) = \Delta L(t) = \frac{\Delta\phi(t)}{2\pi} * \lambda = n * \lambda + \frac{\theta}{2\pi} * \lambda \quad (5)$$

The θ_1 is the phase shift and its value usually cycles between zero to 2π . As shown in the **Fig.2.**, the D is the total displacement, the θ_1 is the phase, the λ_1 is the

wavelength and the f_1 is frequency of the low frequency wave. The total displacement $D(t)$ is determined by the formula,

$$D(t) = D_1(t) = \frac{\theta_1}{2\pi} * \lambda_1 \quad (6)$$

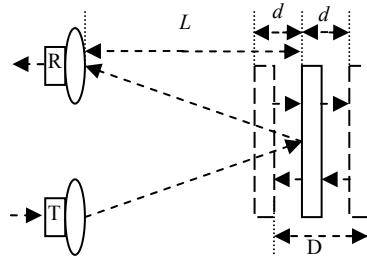


Fig.1. Schematic diagram of ultrasonic system for vibration measurements.

The θ_2 is the phase, the λ_2 is the wavelength and the f_2 is frequency of the low frequency wave. The θ_2 is a greater phase shift than phase frequency of the f_1 because the f_2 is greater than the f_1 . The integer number N_2 of wavelength of frequency f_2 signal can be calculated from $N_2 = \text{Int}[D_1/\lambda_2]$. The total displacement $D(t)$ is determined by the formula,

$$D(t) = D_2(t) = N_2 * \lambda_2 + \frac{\theta_2}{2\pi} * \lambda_2 \quad (7)$$

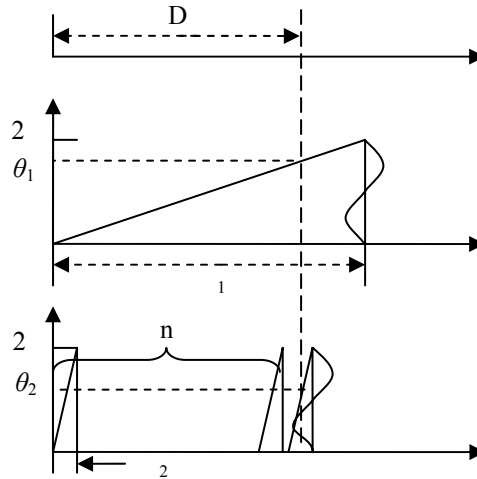


Fig. 2. Schematic diagram of the method.

The final equation concluded from the above equations is shown as follows,

$$\begin{aligned}
D(t) &= \text{Int}[D_1/\lambda_2] * \lambda_2 + \frac{\theta_2}{2\pi} * \lambda_2 = \text{Int}[\frac{\theta_1}{2\pi} * \lambda_1 * \frac{1}{\lambda_2}] * \lambda_2 + \frac{\theta_2}{2\pi} * \lambda_2 \\
&= \text{Int}[\frac{\theta_1}{2\pi} * \frac{f_2}{f_1}] * \frac{c}{f_2} + \frac{\theta_2}{2\pi} * \frac{c}{f_2}
\end{aligned} \tag{8}$$

where c is the speed of sound. The frequencies of 10 kHz and 40kHz are chosen in the experiment. So, the maximum distance is 1.70 cm.^{[1],[2],[3],[4]}

3. The Hardware System Architecture

The hardware of the vibration measurement system consists of two ultrasonic transducers, for transmitting and receiving the signals, and the circuit for ultrasonic transmitting and receiving signal processing. The part completes signal acquisition and processing function automatically.

3.1 Design of Transmission Circuit

The design of the circuit for ultrasonic transmitting adopted NE555 time-based circuit and also the peripheral circuits and the more harmonic oscillator circuit. The circuit of NE555 time-based worked for the setting and reset alternately repeatedly on without the steady-state operation mode. The 3 pin of output terminal is outputting utalternate with low level and high level, the output waveform approximated rectangular wave. There are many kinds of ultra harmonics of rectangular, therefore, the circuit without the steady-state operation mode can be called multi vibrator as self-excitation.^{[4],[5]}

As shown in the **Fig.3.**, the circuit for ultrasonic transmitting consists of the circuit of NE555 time-based and the correlative circuit. The output of capacitor C₁ is unchanged. The 2 pin of NE555 outputs low level, the 3 pin of NE555 outputs high level and inward transistors are in off condition. The 7 pin is impending and the capacitor C₁ is charged by V_{DD}. Then, the voltage of C₁ is building up. The V_{C1} reaches the threshold level 2V_{DD}/3 after a time of T₁. So, now the circuit of NE555 time-based has overturned and reseted. Then the 3 pin outputs low level, and the inward transistors are in conducting state. The 7 pin outputs low level, the capacitor C₁ is discharging. When the V_{C1} is dropping to V_{DD}/3 after T₂, the circuit of NE555 time-based has overed and reseted, and the 3 pin outputs high level and the 7 pin is impending again, circulate down so. So the 3 pin can output a rectangular wave. The T₁ of high-level outputs charging time is determined by the formula,

$$\begin{aligned}
t_1 &= -(R_1 + R_2)C_1 \ln[(V_{DD} - 2V_{DD}/3)/(V_{DD} - V_{DD}/3)] \\
&= (R_1 + R_2)C_1 \ln 2 = 0.693(R_1 + R_2)C_1
\end{aligned} \tag{9}$$

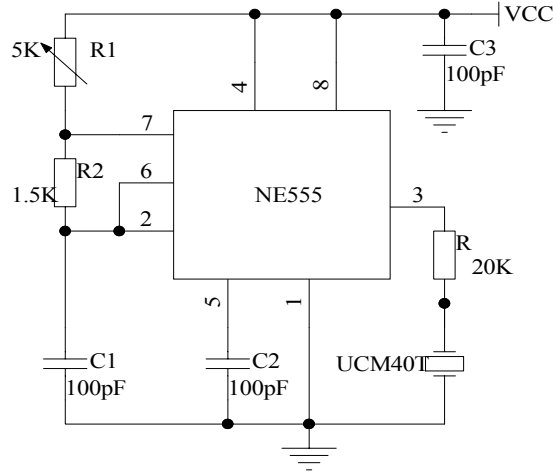


Fig. 3. the circuit for ultrasonic transmitting.

The T_2 of low-level outputs charging time is determined by the formula,

$$t_2 = 0.693R_2C_1 \quad (10)$$

The cycle time of rectangular wave is determined by the formula,

$$T = t_1 + t_2 = 0.693(R_1 + 2R_2)C_1 \quad (11)$$

The oscillation frequency f ,

$$f = 1/T \approx 1.44/(R_1 + 2R_2)C_1 \quad (12)$$

The duty factor D of output pulse is determined by the formula,

$$D = (R_1 + R_2)/(R_1 + 2R_2) \quad (13)$$

The output is a square wave signals when the R_2 is much greater than the R_1 and the duty factor D equals to 50%.

The oscillation frequency f is up to R_1 and R_2 to determine. Center-frequencies of the ultrasonic transmitter are respectively 40 kHz, 10 kHz. When the center-frequency is 40kHz, the C_1 is $0.1 \mu F$, and the resistances of R_1 and R_2 are respectively $0.6k \Omega$ and $1.5k \Omega$. When the center-frequency is 10kHz, the C_1 is $0.1 \mu F$, Resistances of R_1 and R_2 are respectively $1k \Omega$ and $72k \Omega$.

3.2 Design of Receiving Circuit

As show in the **Fig.4.**, the circuit for ultrasonic receiving, that in which signal amplification, filtering, DC signal eliminating are included, has function of signal processing, avoiding the shortcomings of feeble signal and noise. The 2 stage signal

amplification system was adopted in this experiment. The signal that is processed is deduced to PC computer. The signal can be shown by the software system.

The circuit for ultrasonic receiving can be used in combination with the circuit for ultrasonic transmitting. The circuit is composed of four parts: the amplifying circuits A_1 and A_2 , the rectifying circuit R_3 , the filter circuit RC , and the comparator circuit A_4 .

The filter circuit has frequency selectivity that it amplifies 40 kHz signal and the yield value equals to 5. Multistage filter circuit was adopted. The half-wave rectifying circuit consists of operational amplifiers. The cut-off frequency of the filter circuit is 40 kHz. The comparator circuit also consists of operational amplifiers.

4. Testing

The system for experiment was composed of three parts: the hardware of the system, the interface circuit and the software of the system.

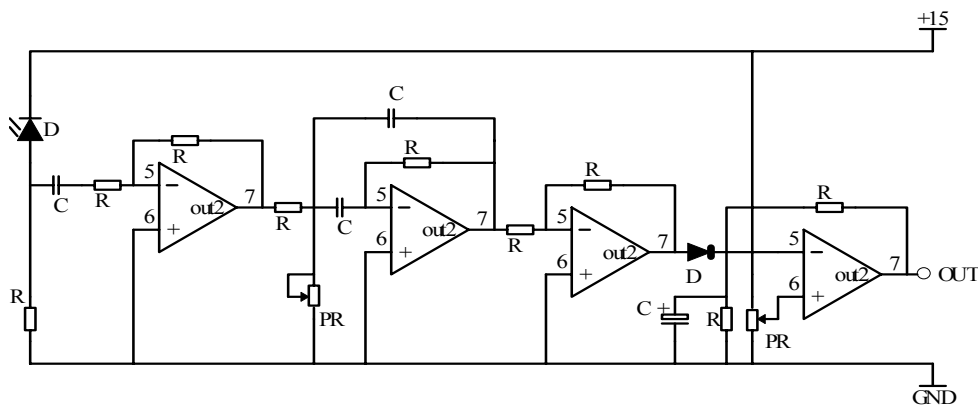


Fig.4. the circuit for ultrasonic receiving.

The experimental facility included a flexible manipulator, a vibration exciter, two ultrasonic transducers, various circuits and a data acquisition card. The vibration source consists of the flexible manipulator that was driven by vibration exciter. The vibration exciter was adjusted among 20 to 20 kHz. The data was gathered by the multifunction data acquisition card which is made in the NI Company.

The system of software can realize the real-time signal ongoing acquisition and storage. The change of phase is transformed into the visualization function graphic of $D(t)$. The software extracted effectively characteristic value of the vibration signal.^{4,5} The frequency of the excitation signal in the experiment was selected at 71.2Hz. The irregular original signal was provided in **Fig.5**. In addition, **Fig.6** gives the changing law of phase-shifts. After the collection and analysis of the phase-shifts change, completed vibration signal will be obtained, as well as the characteristic value. However, when the amplitude of the flexible manipulator is too large, the changing signal of phase shift signals confusion and cannot be measured then, as show in **Fig.7**.

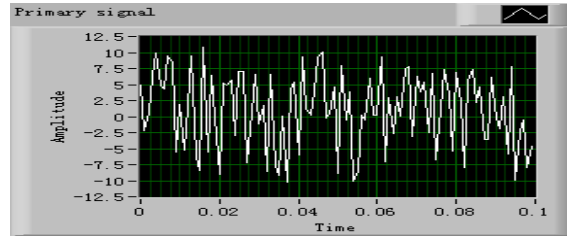


Fig.5. Original signal oscillogram.

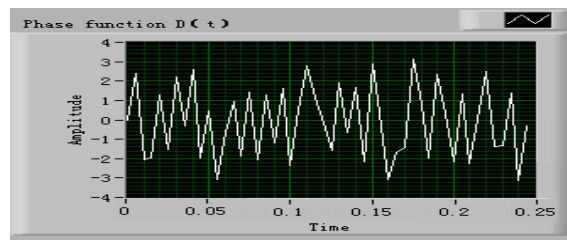


Fig.6. Phase-shifts $D(t)$ oscillogram.

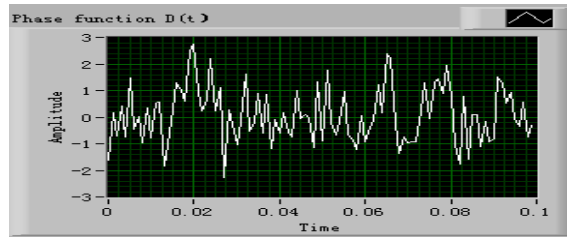


Fig.7. phase-shifts $D(t)$ oscillogram when the amplitude is too large.

5. Conclusion

With the new system, which is based on vibration detection with ultrasonic wave, designed in this paper, remote objects can be detected on the vibration, overcoming the limitations that contact measurement has, such as piezoelectric sensors etc. The new system can also be applied to low frequency vibration measurements, with a much wider measurement range than the eddy current sensor. Here, no accessory is needed to be mounted on the vibrating object, avoiding the influence of vibration objects. The measurement technique based on the ultrasonic wave is a supplement for non-contact vibration measurements. It has many advantages such as low cost, convenient operation, high test speed, and so on. So that this measurement technique has much potential applicative value for condition monitoring of some industrial machinery equipments, especially for application in vibration measurement of fine structure or in some special working environment, such as high temperature, high

pressure, dust, strong corruption, non-Contact and so on. Certainly, there are some shortcomings of this measurement technique. Great restrictions are still existed for the amplitude of vibration, not being solved completely. Continue study and further improvement are still needed in the future.

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