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Magnetoelectric Speed Sensor to Detect Ultra-Low Frequency Vibrations

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Abstract

Ultra-low frequency vibrations are ordinary physical phenomena, and absolute vibrant sensors are usually used to detect them. The author presents a method that using magnetoelectric speed sensor to detect ultra-low frequency vibrations. With cascade correcting circuit, the lowest frequency that can be measured will be less than 0.5Hz while the best damping is maintained. The author has systematically analyzed the correcting circuit, transfer function, theory of operation, and the difference between output characteristics before and after correcting to the ultra-low frequency sensor.

Keywords: *sensor, ultra-low frequency, vibration, correcting circuit, transfer function*

1. Introduction

Ultra-low frequency vibrations are ordinary physical phenomena, such as the vibrations of well headframes, high-rise buildings, railway and highway bridges, dams and the earthquake waves. These vibrations have the characteristics of high amplitude (up to 10mm), low frequency, abundant of frequencies that lower than 1Hz and high destroy power. They seldom affect people's everyday lives under normal condition, but will lead to huge destroy once they exceed allowable limits. Therefore, the measure and research of ultra-low frequency vibrations is importance in engineering. There are two typical sensors in engineering test, magnetoelectric speed sensor and piezoelectric accelerometer. The piezoelectric accelerometers can not be used in ultra-low frequency vibration test because of their low sensitivity to ultra-low frequency signal, and piezoelectric crystal plate does not adapt to quasistate test. The magnetoelectric speed sensors have the advantages of anti interference and resistance to impact, but their low limit of test is all over 13Hz because of their high natural frequency, so their accuracy of ultra-low frequency test does not adapt to the needs of engineering [1]. The author systematically researched the methods that using correcting circuit to reduce the test frequency of magnetoelectric speed sensors.

2. Magnetoelectric Speed Sensor

Magnetoelectric speed sensors (speedometers) have the advantages of high output signal, simple subsequent circuit and good anti interference capability, and are extensively used in low frequency test. They belong to inertia sensors [2], and the mechanical model of inertia sensors is shown in Figure 1.

Speed sensors are single-degree-of-freedom systems, and their frequency domain has the characteristic of second order high-pass. The normalization transfer function between the output voltage and the input vibration velocity is shown as follows:

$$G_0(s) = \frac{s^2}{s^2 + 2\xi_0\omega_0 s + \omega_0^2} \tag{1}$$

where ξ_0 is damping ratio, and ω_0 is inherent angular frequency.

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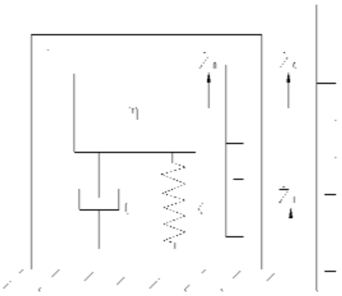


Figure 1. Mechanical model of inertia sensor

In general, the frequency that can be tested is higher than natural frequency of Speed sensors. At present, the natural frequencies of magnetoelectric speed sensors physical construction are generally not lower than 4Hz, and the frequencies that can be tested by them are usually higher than 13Hz, so they do not adapt to the ultra-low frequency test.

3. Design and analysis of sensor

3.1. Theory of Operation and Transfer Function.

In order to expand the frequency response of magnetoelectric speed sensors, correcting circuit is introduced. Correcting methods can be divided into two forms, feedback correcting and cascade correcting [3]. To second order high-pass segment, feedback correcting reduces the natural frequency while the damp is also cut down. In order to keep appropriate damp for corrected system output characteristic, the damp of original dynamic characteristic is often increased in advance [4]. For example a resistance is connected in parallel to magnetoelectric speed sensor, and the sensor damp can increased by the adjustment of magnetoelectric damp. But to a certain degree, this correcting is another decaying to frequency component that has already been attenuated as a result of sensor's frequency characteristic. So an amplification segment should be added in follow-up circuit, and this will affect signal-noise ratio. In addition, for the second order high pass segment, the phase of low frequency signal will distort, phase difference nearby zero-frequency is approximately 180º. This will lead to low frequency negative feedback turning into positive feedback, and be prone to chattering [5]. The author uses cascade correcting circuit for magnetoelectric speed sensor, and has designed a compensation segment C(s) which can be implemented in physics. Its transfer function is shown as follows:

$$C(s) = \frac{s^2 + 2\xi_0\omega_0 s + \omega_0^2}{s^2 + 2\xi_1\omega_1 s + \omega_1^2} \tag{2}$$

After the correcting by this compensation segment, the input still has the characteristic of second order high-pass, and the normalization transfer function is shown as follows:

$$G_1(s) = G_0(s)C(s) = \frac{s^2}{s^2 + 2\xi_1\omega_1 s + \omega_1^2} \tag{3}$$

The compensation segment C(s) make $\omega_1 < \omega_0$ and $\xi_1$the best damp. The natural frequency of system output characteristic that have been corrected is decreased. So the objective that expanding the lowest frequency that can be tested by sensors and correcting sensor's dynamic characteristics is achieved. Relatively higher mechanical natural frequency of original sensor maintains unchangeablely, physical construction is stable, and sensor has good performance on anti interference and resistance to impact. Natural frequency of system output characteristic that has been corrected completely depend on the correcting circuit connected in series. So the corrected sensor maintains the advantages of orginal senor as well as improves low frequency output characteristic.

The transfer function of the compensation segment expressed by Eq. (1) can be expanded as follows:

$$C(s) = 1 + \frac{K_1\omega_1^2}{s^2 + 2\xi_1\omega_1 s + \omega_1^2} + \frac{K_2\omega_1 s}{s^2 + 2\xi_1\omega_1 s + \omega_1^2} \tag{4}$$

where $K_1 = \frac{\omega_0^2}{\omega_1^2} - 1$, $K_2 = \frac{2(\xi_0\omega_0 - \xi_1\omega_1)}{\omega_1}$

when $\omega_1 < \omega_0$ and $\xi_1\omega_1 < \xi_0\omega_0$, K1 and K2 will all be greater than zero. So correcting segment can be realized by paralleling low pass segment, band pass segment and all pass segment. By adjusting proportional relation between three segments' gain, the zero point of correcting segment will counteract with the pole of original sensor, and system output characteristic will be the form of second order high-pass expressed by Eq. (3). The functional block diagram is shown in Figure 2.

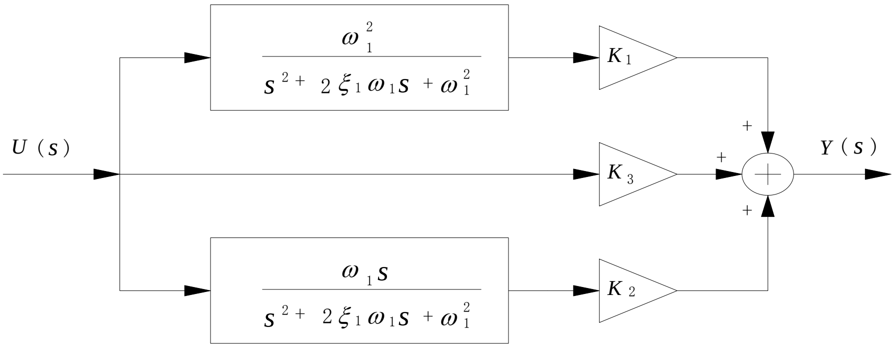


Figure 2. Functional block diagram of correcting segment

After correcting, the natural frequency decreases, and the normalization transfer function between vibration velocity input and system voltage output can still expressed by Eq. (1).

The vibration displacement is often interested in engineering ultra-low frequency test. The voltage output should be integrated once. But simple integral will lead to the accumulation of zero shifting, therefore it is difficult to realize. So the integral segment is replaced by a first order inertia segment. In addition, stopping direct current segment is also added in circuit. The functional block diagram which using output Y(s) to express corrected amplitude is shown in Figure 3.

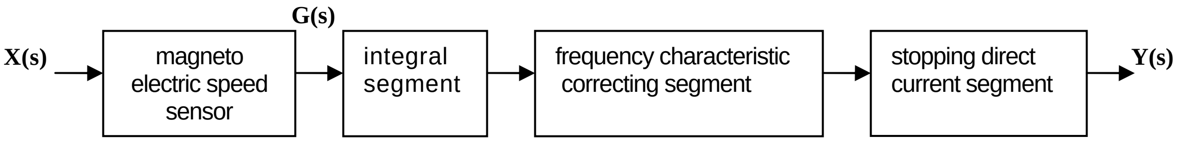


Figure 3. Functional block diagram of ultra-low frequency displacement

3.2. Correcting Circuit and Transfer Function.

The signal adjustment circuit of ultra-low frequency displacement sensor that has been corrected includes integral, low frequency compensation and stopping direct current segments. It is shown in Figure 4.

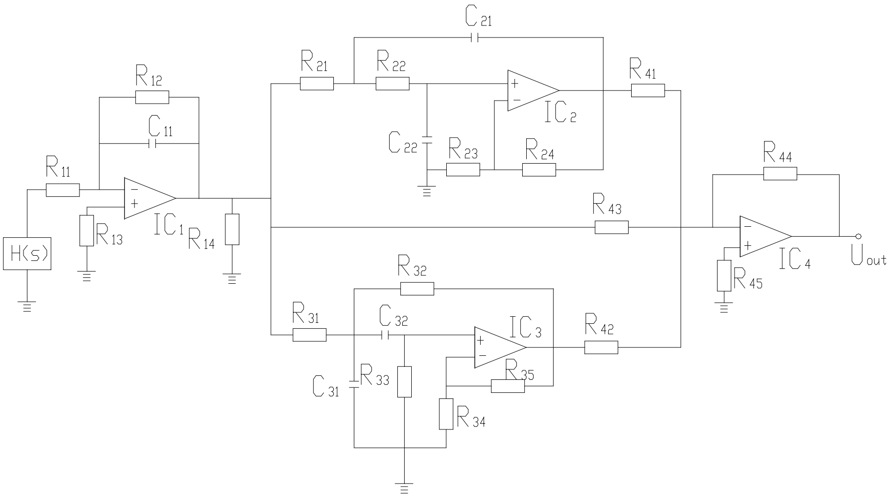


Figure 4. Signal adjustment circuit of corrected displacement sensor

In figure 4, the low pass amplifying circuit is constituted by IC2, C21, etc. and its transfer function is shown as follows:

$$\frac{\dfrac{R_{23}+R_{24}}{R_{21}R_{22}R_{23}C_{21}C_{22}}}{s^2+(\dfrac{1}{R_{21}C_{21}}+\dfrac{1}{R_{22}C_{21}}-\dfrac{R_{24}}{R_{22}R_{23}C_{22}})s+\dfrac{1}{R_{21}R_{22}C_{21}C_{22}}} \tag{5}$$

IC3 constitute a band pass amplifying circuit, and its transfer function is shown as follows:

$$\frac{\dfrac{R_{34}+R_{35}}{R_{31}R_{34}C_{31}}s}{s^2+(\dfrac{1}{R_{31}C_{31}}+\dfrac{1}{R_{33}C_{31}}+\dfrac{1}{R_{33}C_{32}}-\dfrac{R_{35}}{R_{32}R_{34}C_{31}})s+\dfrac{R_{31}+R_{32}}{R_{31}R_{32}R_{33}C_{31}C_{32}}} \tag{6}$$

The expected ratio of natural frequency to damping depends on the denominator of above two transfer functions, i.e. corresponding resistances in circuit.

The summing amplifier circuit is constituted by IC4, R44, etc. The adjustment of R41, R42 and R42 will change the enlargement factor of circuit to the output signals of low-pass, band-pass and all-pass segments. Therefore, the counteraction of correcting segment’s zero point to original sensor’s pole is realized.

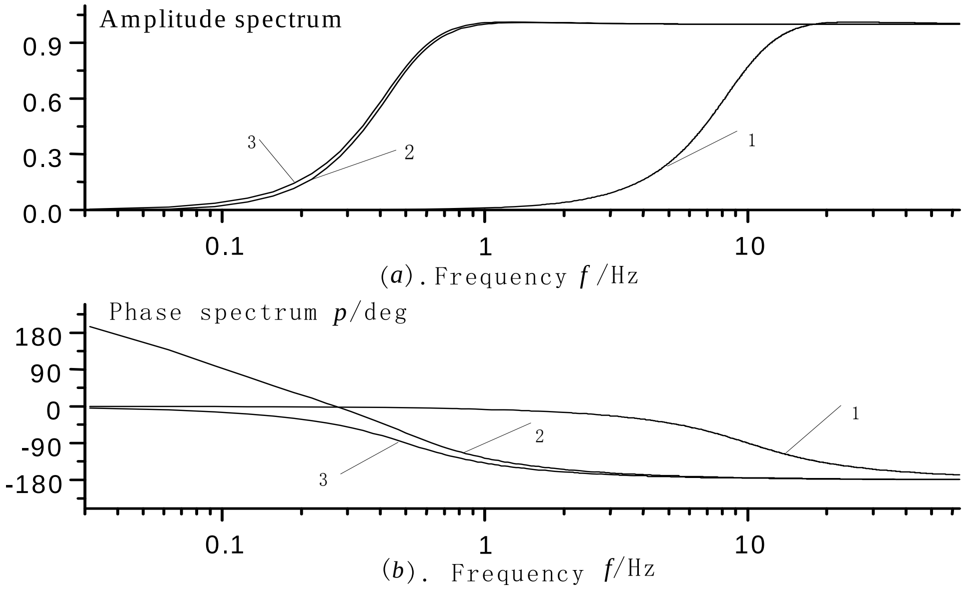
The integral segment is realized by integrating amplifying circuit which constituted by IC1 and R11, R12, R13, C11. Because the integral segment is critical instable, it is replaced by an inertia segment in practice. The transfer function of this segment is $-\dfrac{R_{12}}{R_{11}}\cdot\dfrac{1}{1+R_{12}C_{11}s}$, and the integral time constant is $\tau_i = R_{12}C_{11}$. In addition, two first order stopping direct current segments are added to restrain the affect of low frequency noise and deviation.

The normalization transfer function between output Y(s) of corrected ultra-low frequency sensor and vibration displacement is shown as follows:

$$H(s) = \frac{Y(s)}{X(s)} = \frac{s^2}{s^2 + 2\xi_1\omega_1 s + \omega_1^2} \cdot \frac{\tau_i \cdot s}{1 + \tau_i \cdot s} \cdot \left(\frac{\tau_d \cdot s}{1 + \tau_d \cdot s}\right)^2 \quad (7)$$

4. Output Characteristic Comparison Before and After Correcting

The curves of amplitude-frequency characteristic and phase-frequency characteristic (normalization) before and after correcting that plotting in accordance with Eq. (7) are shown in Fig.5. Curves named 1 are normalization amplitude-frequency characteristic curve and phase-frequency characteristic curve of low frequency displacement sensor before correcting. Curves named 2 are normalization amplitude-frequency characteristic curve and phase-frequency characteristic curve of ultra-low frequency displacement sensor after correcting (natural frequency of output characteristic after correcting is 0.5Hz, damping ratio is 0.65, integral and stopping direct current time constant is 2.2s). We can find from Fig.5 that the lowest frequency before correcting is greater than 15Hz, and the lowest frequency after correcting is about 0.6Hz.



(*a*). amplitude-frequency characteristic (*b*). phase-frequency characteristic

Figure 5. Amplitude-frequency characteristic and phase-frequency characteristic of speed sensor before and after correcting

Curves named 3 are amplitude-frequency characteristic curve and phase-frequency characteristic curve of second order high pass segment which contains stopping direct current segment.

Comparing curve 2 and curve 3 in Figure 5 (a), we can find that because of the affect of time constant of first order inertia segment and stopping direct current segment, the amplitude of curve 2 decays a little greater than curve 3 at the frequency range near 0.5Hz and lower than 0.5Hz. In corresponding phase frequency curve, the phase angle of working frequency range which natural frequency is greater than 0.5Hz is -180^{o}, the 0.5Hz phase shift of curve 3 is -90º, and the 0.5Hz phase shift of curve 2 reaches -65º (After 180º reverse phase, the phase angle of working frequency range of corrected sensor is 0º.).

If the requirement of measurement signal to phase is not high, the affect by integral and stopping direct current segments will be not obvious. But if the signal with high requirement on phase distortion is tested, for example ultra-low frequency transient signal, waveshape will be distorted because of the affect by integral and stopping direct current segments. Therefore, time constant of integral and stopping direct current segments should be selected a little bigger.

5. Conclusion

(1) Magnetoelectric vibration speed sensor has the characteristic of second order high pass, and has the advantages of stable physical construction, good performance on anti interference and resistance to impact. But the lowest frequency that can be tested by it depends on the physical natural frequency of sensor, and it is often several times to natural frequency.

(2) Based on the similarity of electromechanical system, we can design compensation network with analog circuit to correct the output characteristic of magnetoelectric vibration speed sensor. The corrected magnetoelectric vibration speed sensor becomes second order high pass system which has the same type transfer function of original sensor, and its natural frequency of output characteristic is usually reduced to 1/20-1/50 of original sensor's physical natural frequency.

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