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INVESTIGATION OF THE SOURCES AND CHARACTERISTICS OF ERROR COMPONENTS IN THE ADVANCED INDUCTION-BASED VIBRATION MEASUREMENT TRANSDUCER

Fayzullayev J.S.

Associate Professor, PhD, Tashkent State Transport University, Tashkent, Republic of Uzbekistan

Abstract

According to the results presented in the paper, lowering the amplitude dynamic error of the improved inductive vibration sensor can be accomplished by raising the device's natural frequency and by selecting an optimal level of relative damping. However, to minimize the phase dynamic error, the relative damping must be kept as small as possible-ideally approaching zero. During the parameter-optimization stage, intended to simultaneously reduce both amplitude and phase dynamic errors, it became evident that such dual optimization is essentially unachievable. This is due to the fact that the amplitude-frequency response and phase-frequency response are physically coupled, meaning that improving one characteristic inevitably worsens the other.

Keywords

Inductive-type vibration transducer, basic measurement error, additional measurement error, amplitude relative error, phase relative error, dynamic characteristic, amplitude-frequency response, phase-frequency response, natural resonance frequency, degree of calming (relative damping factor)

The determination of vibration parameters is a complex task, as it is inherently linked to the actual vibration behavior of the object under investigation. This behavior depends on factors such as the number of degrees of freedom of the monitored mechanical system, the width of the vibration spectrum, and whether the oscillations are periodic or non-periodic [1]. Consequently, it is practically impossible to propose a single universal approach that would be suitable for evaluating measurement errors under all possible conditions. Only when the vibration characteristics of the object and the specific measurement conditions are well known can the errors associated with measuring vibration parameters be assessed with sufficient completeness and accuracy [2].

Knowing all instantaneous values of the measured vibration quantity within the time interval $[t_1 \div t_2]$ means having complete information about the behavior of that quantity. However, in most practical situations, it is sufficient to determine only a limited set of parameters of the vibration signal. These include the amplitudes, frequencies, and initial phases of its harmonic components, as well as the range ("peak-to-peak" value), the average value, and the root-mean-square (RMS) value of periodic oscillations [3]. When evaluating measurement errors, these specific parameters of the vibration quantity must be taken into account, as they directly influence the accuracy and reliability of the measurement process [4].

In studying the errors of the developed induction vibration transducers, we assume that the vibration input applied to their terminals follows a harmonic law. This assumption is justified because, if the measured vibration signal contains any harmonic component whose period slightly differs from the period of the fundamental (first) harmonic, then the measurement error associated with that specific harmonic must be considered separately. In such a case, additional conditions would need to be introduced into the error-calculation procedure to account for the influence of that harmonic on the total resulting error [5].

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1. Error caused by the imperfection of the measurement method. When an induction vibration transducer (IVT) is used to measure the linear components of vibration parameters, a methodological error appears if the monitored object simultaneously exhibits rotational or torsional vibration components. In such cases, the presence of these additional vibration modes affects the measurement process and introduces extra inaccuracies [6]. To minimize this type of error, certain conditions must be fulfilled. For example, when the IVT is intended to measure the linear vibration component strictly along its own axis, the following requirement must be satisfied [7]:

$$\omega_0^2=\left(\omega_x^2+\omega_y^2\right)_{max}, \qquad (1)$$

here, ω_x, ω_y denote the angular frequencies of the torsional (rotational) vibration components of the monitored object around the ox and oy axes, respectively.

Although the dependence of the measurement error on the value of the measured quantity may exhibit a complex nature, in most practical cases it can be approximated sufficiently well by using the following two-term expression [8]:

$$\Delta=\Delta_0+\gamma_s a, \qquad (2)$$

here Δ, Δ_0, γ_s – Accordingly, the resulting error, which is functionally dependent on the measured vibration acceleration a, consists of two main components: an additive term (zero-shift error) and a multiplicative term (sensitivity error) that is proportional to the vibration acceleration a.

In this case, the value of the relative error is determined as follows:

$$\gamma=\frac{\Delta_0}{a}+\gamma_s. \qquad (3)$$

When the measurement errors of induction vibration transducers (IVTs) are evaluated under different operating conditions using a single device, the obtained results may vary significantly. The dynamic errors of IVTs arise because the transducers are unable to respond instantaneously to rapid changes in the measured vibration parameters, and also due to adverse dynamic influences acting upon them [9]. Let us now address the problem of determining these dynamic errors. Ultimately, such errors lead to nonlinearities in the transfer function of the IVT, affecting the accuracy and correctness of the measurement process [10].

2. Dynamic errors of the induction vibration transducer. The theoretical investigation of the dynamic characteristics of the developed IVT, as well as the amplitude-frequency characteristics derived from this analysis [11], shows that the amplitude error of the transducer depends on the ratio of the vibration frequency ω_m to the natural mechanical frequency of the vibration system ω_0, expressed as $\xi_m=\frac{\omega_m}{\omega_0}$ and also on the relative damping level of the IVT's mechanical structure, defined as $D_m=\frac{\delta_m}{\omega_0}$. The amplitude error under these dynamic conditions can be determined using the following expression [12]:

$$\delta_A=\left(\frac{1}{\sqrt{(1-\xi_м^2)^2+4\xi_м^2 D_м^2}}-1\right)\cdot 100\%. \qquad (4)$$

The phase error of the developed induction vibration transducers also depends on the values of ξ_m and D_m. This type of error is determined from the phase-frequency characteristic $\varphi(\xi_m)$, and it is evaluated as the deviation of this characteristic from the proportional (ideal) phase characteristic $\varphi_p(\xi_m)$. The phase error can therefore be calculated using the following expression [13]:

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$$\Delta\varphi=\varphi\left(\xi_{\text{м}}\right)-\varphi_{\text{п}}\left(\xi_{\text{м}}\right)=arctg\frac{2D_{\text{м}}\xi_{\text{м}}}{1-\xi_{\text{м}}^2}-\varphi_{\text{п}}\left(\xi_{\text{м}}\right). \qquad (5)$$

Using formula (5), the phase shift angle φ between the input and output quantities was calculated for different values of ξ_m and D_m. Based on these calculated results, the corresponding graphs were constructed, and they are presented in Figure 1.

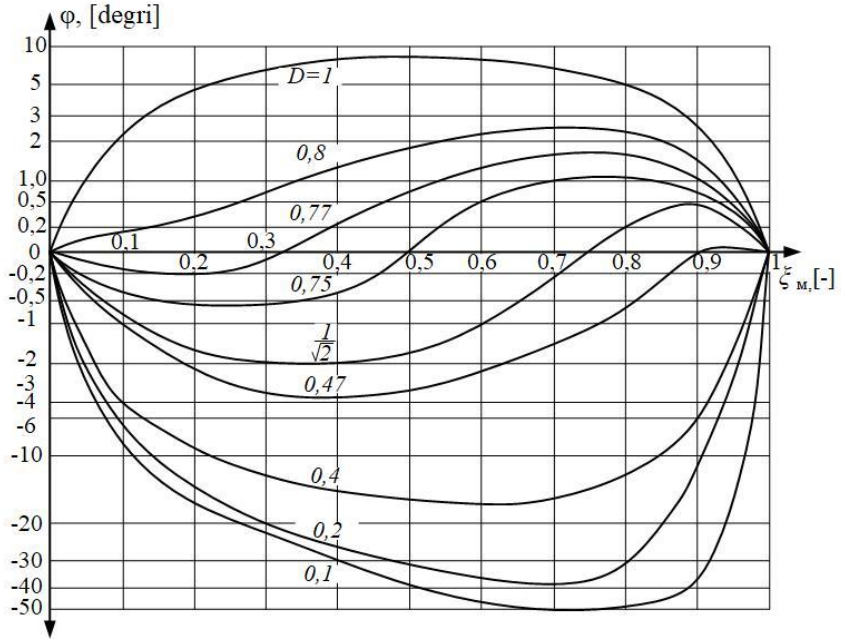

Figure 1. Graphs of the function $\varphi=f(\xi_m)$ for different values of D_m.

The figure illustrates the phase shift φ (in degrees) as a function of the frequency ratio ξ_m for various values of the relative damping coefficient D_m. Each curve on the graph corresponds to a specific value of D_m, ranging from 0.1 to 1.0. As the damping coefficient changes, the shape of the phase-frequency characteristic $\varphi=f(\xi_m)$ also changes. The curves demonstrate how the phase shift behaves under different dynamic conditions of the mechanical vibration system, showing increasing deviations as the frequency ratio approaches resonance ($\xi_m\approx1$).

Thus, when the newly developed induction vibration transducer is subjected to a harmonically varying vibration signal at its input, reducing the amplitude component of the dynamic error requires increasing the natural frequency of the measuring system and selecting an appropriate (optimal) value for the relative damping factor. In contrast, to minimize the phase error, the damping factor must be chosen to be very small, close to zero. The process of selecting optimal parameters with the aim of simultaneously decreasing both amplitude and phase errors demonstrates that this is practically unattainable, since the amplitude-frequency and phase-frequency characteristics are mutually dependent. As a result of this interrelation, it is not possible to minimize both types of dynamic error at the same time.

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