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A new approach to assessing the dynamic uncertainty of measuring devices

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ABSTRACT

A spectral method for estimating the dynamic uncertainty of measuring instruments based on a mathematical model of the frequency characteristic of a measuring instrument and a model of the spectral function of an input signal is presented. The model equation for estimating the amplitude value of the dynamic measurement uncertainty is obtained, which is caused by the limited properties of the measuring devices when a measuring signal passes through it in dynamic operation modes. A mathematical simulation of the characteristic of the dynamic uncertainty variation during the passage of a measuring signal through a measuring transducer is performed using the dynamic model of a vibration transducer as an example.

Keywords: dynamic measurements, dynamic uncertainty, frequency characteristic, spectral function

1. INTRODUCTION

When compiling a report on the results of dynamic measurements, it is necessary to demonstrate quantitative values of the quality of measurements so that their reliability can be correctly assessed[1-10]. Without such values, the results of dynamic measurements cannot be compared, neither with each other nor with reference values. Therefore, it is necessary to propose methods for estimating the quality characteristics of dynamic measurements. In this case, it is necessary to take into account the fact that during dynamic measurements a transient mode of operation of the measuring devices (MD) will also be present at some stage, during which the signal from the output of the measuring device changes significantly over time. These circumstances are due to the inertial properties of the MD, since they consist, as a rule, of a set of different masses and springs, capacitances and inductances, and other inertial elements that lead to the manifestation of dynamic uncertainty. The equation of the transformation of the MD, which displays its statics properties, is unacceptable in a dynamic mode. In this case, we must go to the differential equations that describe the dynamic relationship between the output y(t) and the input x(t) values of the measuring devices[11,12].

In view of the above, there is a need to develop methods for estimating the uncertainty of dynamic measurements that would meet international requirements for estimating the characteristics of the quality of measurements, which is a topical scientific task in the field of metrology.

2. MAIN MATERIALS OF THE RESEARCH

If the equation of the transducer under measurement can be represented in the form

$$Y = K_C X, \tag{1}$$

where X is the measured value of the physical quantity (input signal); K_C is the coefficient of the conversion of the measuring device and Y is the measurement result (output signal), then the mathematical expectation for the input signal will be equal to M[X], and the mathematical expectation of the output signal will be equal to

$$M[Y] = K_C M[X], \tag{2}$$

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where *M[Y]* and *M[X]* are the corresponding mathematical expectations of the output and input signals of the measuring device, respectively[9]. The spectral density of the input signal X(t) has the form

$$H_X(\omega) = \lim(2T)^{-1}|X(j\omega)|^2 \text{ when } T \to \infty, \tag{3}$$

where $X(j\omega)$ is the Fourier image obtained by replacing the value in the operand of the image $X(s)$ by the values of s for $j\omega$; T is the time of observation; $\omega = 2\pi f$.

The expression for the spectral density of the output signal can be represented by the expression

$$H_Y(\omega) = \lim(2T)^{-1}|Y(j\omega)|^2 \text{ when } T \to \infty. \tag{4}$$

The relationship between the images of the output and input values gives us an expression for the transfer function of the measuring device

$$\boldsymbol{K_C}(s) = \frac{Y(s)}{X(s)} = \frac{\sum_{k=0}^{m} B_k s^k}{\sum_{q=0}^{n} A_q s^q}, \tag{5}$$

where $Y(s)$, $X(s)$ are the operator images of $Y(t)$ output and $X(t)$ input signals, respectively; k, q are the order of the derivatives of Y and X, respectively; A_q, B_k are the coefficients of the differential equation[11].

Therefore, we can write that

$$\boldsymbol{H_Y}(\omega) = |K_C(j\omega)|^2 H_X(\omega), \tag{6}$$

where $K_C(j\omega)$ is the frequency characteristic of the measuring transducer[13].

The spectral density of the error signal, reduced to the input, will be equal to

$$H_{\Delta X}(\omega) = \left|\frac{K_C(j\omega)}{K_C} - 1\right|^2 H_X(\omega), \tag{7}$$

K_C - frequency characteristic of the measuring device for ω = 0.

The dispersion of the output signal σ_Y^2 for dynamic measurements can be defined as the square root of the integral of the spectral density of the output signal over all frequencies

$$\sigma_{\boldsymbol{Y}} = \pi^{-1/2}\left(\int_0^\infty H_Y(\omega)d\omega\right)^{1/2}. \tag{8}$$

Taking into account the equations (3) and (6) above, the dispersion of the output signal σ_Y^2 (8) can be represented on the basis of the spectral density of the input signal and the frequency characteristic of the measuring channel used (measuring means)

$$\sigma_{\boldsymbol{Y}} = \pi^{-1/2}\left(\boldsymbol{T}^{-1}\int_0^\infty |K_C(j\omega)|^2 |X(j\omega)|^2 d\omega\right)^{1/2}, \tag{9}$$

where $|K_C(j\omega)|$ is the frequency response module of the measuring device, used for dynamic measurements.

Similarly, the variance of the error signal, reduced to the input, will be equal to

$$\sigma_{\Delta X} = \pi^{-1/2}\left(\int_0^{\infty}\left|\frac{K_C(j\omega)}{K_C}-1\right|^2 |X(j\omega)|^2\, d\omega\right)^{1/2}. \tag{10}$$

The frequency response module of the measuring device is determined by the formula

$$|K_C(j\omega)| = \left(\boldsymbol{a}^2(\omega)+b^2(\omega)\right)^{1/2}, \tag{11}$$

where $\boldsymbol{a}(\omega)$, $\boldsymbol{b}(\omega)$ are respectively, the real and imaginary parts of the frequency response MD $K_C(j\omega)$[9].

The spectral function of the incoming signal $X(j\omega)$ is related to its time function $X(t)$ by the Laplace expression

$$\boldsymbol{X}(\boldsymbol{j}\omega) = \int_0^{\infty} X(t)e^{-j\omega_0 t}\, dt, \tag{12}$$

where ω_0 is the cyclic pulsations of the harmonic signal under study (input signal)[9].

The cyclic pulsations ω_0 is the pulsations of the fundamental harmonic of the investigated input signal, which passes through the measuring device (measuring channel) and is distorted due to the limited properties of the measuring channel. This frequency ω_0 is allocated from the whole spectrum of frequencies ω to investigate the uncertainty of the measurement, which is due to the limited propertie of the measuring device when passing through it a periodic signal at a certain frequency.

For a finite time interval, the infinity sign may be replace by the total observation time T.

The dynamic error of the measuring transducer, brought to the input, in the time domain can be represented by the expression

$$\Delta X(\boldsymbol{t}) = \pi^{-1/2}\int_0^{\infty}\sigma_{\Delta X} e^{j\omega t}\, d\omega = \pi^{-1/2}\left[\int_0^{\infty}\sigma_{\Delta X}\boldsymbol{cos}(\omega\boldsymbol{t})d\omega + j\int_0^{\infty}\sigma_{\Delta X}\boldsymbol{sin}(\omega\boldsymbol{t})d\omega\right]. \tag{13}$$

Thus, the dynamic error that is introduced due to the limited properties of the measuring device used for the dynamic measurements can be estimated in the time domain, based on the model equation of the spectral function of the input signal and the frequency response of the measuring instrument used by formula (13).

Since expression (13) consists of real and imaginary parts, and in assessing the error we are interested in the amplitude value of dynamic error, expression (13) may now be written as

$$|\Delta X(\boldsymbol{t})| = \left[\left(\int_0^{\infty}\pi^{-1/2}\sigma_{\Delta X}\boldsymbol{cos}(\omega\boldsymbol{t})d\omega\right)^2 + \left(\int_0^{\infty}\pi^{-1/2}\sigma_{\Delta X}\boldsymbol{sin}(\omega\boldsymbol{t})d\omega\right)^2\right]^{1/2}. \tag{14}$$

When, for instance, prior knowledge about the amplitude of the frequency spectrum of the measurand is available in terms of a frequency function, then equation (14) can be rewritten in the form

$$|\Delta X(\boldsymbol{t})| = \left[\left(\int_0^{\pi\boldsymbol{F_s}}\pi^{-1/2}\sigma_{\Delta X}\boldsymbol{cos}(\omega\boldsymbol{t})d\omega\right)^2 + \left(\int_0^{\pi\boldsymbol{F_s}}\pi^{-1/2}\sigma_{\Delta X}\boldsymbol{sin}(\omega\boldsymbol{t})d\omega\right)^2\right]^{1/2}, \tag{15}$$

with $F_s = 1/T_s$ the sampling frequency.

According to GUM Supplement 2 [3], the uncertainty associated with the estimation error is then given as the variance of the corresponding rectangular probability distribution, i.e. the dynamic uncertainty of the measuring device can be estimated from the formula

$$u_D(t) = \sqrt{\left(\int_0^{\pi F_s} \pi^{-1/2}\sigma_{\Delta X}\boldsymbol{cos}(\omega t)d\omega\right)^2 + \left(\int_0^{\pi F_s} \pi^{-1/2}\sigma_{\Delta X}\boldsymbol{sin}(\omega t)d\omega\right)^2} \bigg/ \sqrt{3}\,. \tag{16}$$

To confirm the proposed theoretical basis for estimating the dynamic uncertainty of measuring instruments, we will perform a study of the characteristics of the change in dynamic uncertainty by the example of a vibration acceleration measurement using an accelerometer.

The differential equation describing the dynamic relationship of the input and output values of the vibration acceleration measuring transducer has the form

$$\frac{d^2X_s(t)}{dt^2} + 2h\frac{dX_s(t)}{dt} + h_k^2 X_s(t) = \frac{F_0}{m}\cos(\omega_0 t), \tag{17}$$

where $F(t) = F_0\boldsymbol{cos}(\omega_0 t)$ is the harmonic forced power of the oscillation of the surface of the object (input value); F_0 is the force amplitude; ω_0 is the angular frequency of forced power; $X_s(t)$ represents the the mechanical vibrations of the inertial mass; m is the mass of the accelerometer; c is the damping variable; k is the equivalent rigidity of the piezoelements, $h = c/2m$ is the damping coefficient; $h_k = \sqrt{k/m}$ is the critical value damping coefficient.

The uncertainty budget of the constituent elements of the measuring channel of the acceleration in relative units is shown in Table 1. On the basis of an experimental study of the uncertainty budget of the measurement channel of the vibration acceleration (Tab. 1), a the relative value of the combined standard uncertainty was calculated without taking into account the dynamic component of the uncertainty, which is 0.36%.

Table 1. Uncertainty budget of the constituent elements of the measuring channel of vibration acceleration.

Elements	**Value of relative uncertainty, %**	**The expanded uncertainty** (coverage factor 1.96 at confidence level 95%), %	Distribution
Accelerometer	0.3	0.59	Uniform (rectangular)
Preliminary charge amplifier	0.02	0.04	Uniform (rectangular)
Bandpass filter	0.2	0.39	Uniform (rectangular)
Scale converter	0.01	0.02	Uniform (rectangular)
ADC	0.005	0.01	Uniform (rectangular)
Background noise	$2.14 \cdot 10^{-6}$	$4.19 \cdot 10^{-6}$	Normal
The ccombined standard uncertainty ($\tilde{u}_s$)	0.36	0.71	Normal
Mean value			2.93 m/s^2

The transfer function of the measuring device will take the form of

$$H(s) = \frac{K_{MM}}{s^2 + 2hs + h_k^2}\,, \tag{18}$$

where K_{MM} is the coefficient of proportionality of the measuring channel of vibration acceleration.

Turning to the domains of frequency and separating the real and imaginary parts, we obtain an expression for the module of the frequency characteristics of the measuring device for vibration acceleration

$$|K_C(j\omega j| = \left|\frac{K_{MM}}{(j\omega)^2 + 2h(j\omega) + h_k^2}\right| = \left[\frac{K_{MM}}{\omega^4 - 2\omega^2 h_k^2 + 4\omega^2 h^2 + h_k^4}\right]^{1/2}, \tag{19}$$

$$K_C = \frac{mK_{MM}}{k}. \tag{20}$$

The input signal $F_0 m^{-1}\cos(\omega_0 t)$ of vibration acceleration has the form of

$$X(j\omega) = j\omega\omega_0\left(\omega_0^2 + (j\omega)^2\right)^{-1} m^{-1}, \tag{21}$$

where ω_0 is the cyclic frequency input vibration acceleration, which ranges from 6 to 10 kHz that is, with a minimum value of 18,849.5 and the maximum value is 31,415.9 radians/second.

The choice of the frequency range 6-10 kHz is attributed to the fact that it is in this frequency range that many nascent defects manifest themselves excitation of high-frequency vibration. It is these frequencies (first 6 kHz, and then 10 kHz) that will be used as the minimum and maximum input harmonic signals ω_0, which enters into the equation (14).

The module image of the input vibration acceleration is written as

$$|X(j\omega)| = \omega F_0\left(\omega_0^2 - \omega^2\right)^{-1} m^{-1}. \tag{22}$$

From source literature[13-22], it is known that the amplitude of forced harmonic power F_0 is $3 \cdot 10^{-4}$ m. The mass of the accelerometer is $m = 4 \cdot 10^{-2}$ kg. The damping variable for the piezoelectric accelerometers is equal to 0.5, equivalent rigidity of the piezoelements is k =2, and the minimum observation time T = 300 s. The proportionality factor or gain K_{MM} of the measuring channel of the vibration acceleration is 10^5.

Substituting the resulting values of the module of the frequency characteristics (19), (20) and the image of the input signal (22) in equation (10), we obtain an expression for the evaluation of the variance of the error signal of vibration acceleration in the spectral area, reduced to the input

$$\sigma_{\Delta X} = \pi^{-1/2}\left(\int_0^{\infty} \frac{\omega F_0\left[\left(k\left(h_k^2 - \omega^2\right) - m\left(h_k^2 - \omega^2\right)^2 - 4m\omega^2 h^2\right)^2 + 4k^2\omega^2 h^2\right]}{2Tm\left(\omega_0^2 - \omega^2\right)\left(m\left(h_k^2 - \omega^2\right)^2 + 4m\omega^2 h^2\right)^2} d\omega\right)^{1/2}. \tag{23}$$

To represent the characteristicsof the changes in the uncertainty in the dynamic measurement vibration acceleration in the time domain, which is caused by the inertial properties of the measuring transducer in its dynamic mode we must express a Fourier expression for inverse transformation in the form of (15).

Since expression (15) consists of real and imaginary parts, and in assessing the uncertainty we are interested in the amplitude value of dynamic uncertainty, expression to evaluate the dynamic uncertainty (16) can be written as

$$u_D(t) = \left[\left(\int_0^{\pi F_s} \pi^{-1/2}\sigma_{\Delta X}\cos(\omega t)d\omega\right)^2 + \left(\int_0^{\pi F_s} \pi^{-1/2}\sigma_{\Delta X}\sin(\omega t)d\omega\right)^2\right]^{0.5} \Big/ \sqrt{3}. \tag{24}$$

For the solution of equation (24) in the light of equation (23) we used the Maple 12 mathematical package. At the minimum frequency of the input signal of the vibration acceleration of 6 kHz, and with an observation time of 300 s, the value of dynamic uncertainty is 0.156 m/s^2 (Fig. 1). If the observation period increased to 600 s at a frequency of input signal of the vibration acceleration of 6 kHz, the value of dynamic uncertainty is reduced to 0.116 m/s^2 (Fig. 2). The nominal value of the signal for vibration acceleration of the bearings of the electrospindle of the motor is 2.93 m/s^2. Characteristics of the change of dynamic uncertainty of the measurement of vibration acceleration depending on the time variable which were obtained using the Maple 12 mathematical package are presented in Figures 1 and 2, with the minimum value of the frequency of the input signal of the vibration acceleration of 6 kHz with observation times of 300 s and 600 s, are respectively.

Substituting into expressions (23) and (24) the values for the impact coefficients given above, we obtained the amplitude value of the dynamic uncertainty of the measurement of vibration acceleration, which equals 0.088 m/s^2 when the frequency of the input signal of the vibration acceleration is 10 kHz, and time of observation of the vibration acceleration T = 300 s (Fig. 3). If the time of observation is increased to 600 s at the same frequency of the input signal of the vibration acceleration, the value of dynamic uncertainty decreases to 0.064 m/s^2 (Fig. 4). Characteristics of the change of dynamic uncertainty of the measurement depending on the time variable which were obtained using the Maple 12 mathematical package are presented in Figures 3 and 4, with the maximum value of the frequency of the input signal of the vibration acceleration of 10 kHz with observation times of 300 s and 600 s, are respectively.

Thus, based on the proposed spectral method of evaluation of uncertainty of dynamic measurements, the evaluation of the uncertainty of dynamic measurements of vibration acceleration of roller bearings of the electrospindle of the engine was achieved. This was achieved based on mathematical models of the spectral function of the input signal of the vibration acceleration and frequency characteristics of the measurement transducer for the vibration acceleration. This resulted in obtaining the opportunity to take into account the values of dynamic uncertainties when assessing combined total uncertainty of the measurement of vibration acceleration.

To calculate the maximum relative value of the uncertainty of the dynamic measurement of vibration acceleration, we divide the obtained maximum value of dynamic uncertainty 0.156 m/s^2 (Fig. 1) by the nominal value of the vibration acceleration of $\overline{X}$ = 2.93 m/s^2 [13], as a result of which we obtain

$$\tilde{u}_D = \frac{u_D(t)}{\overline{X}} 100\% = \frac{0.156}{2.93} 100\% = 5.32\%. \tag{25}$$

When calculating the relative value of the uncertainty of the dynamic measurement of vibration acceleration from formula (23) and (24) for the frequency of 6 kHz and the observation time 600 s, we obtain 3.96 % (Fig. 2). At a frequency of 10 kHz and an observation time of 300 s (Fig. 3), we get the relative dynamic uncertainty of the measurement of 3 %. At a frequency of 10 kHz and an observation time of 600 s (Fig. 4), we get the relative dynamic uncertainty of the measurement of 2.18 %.

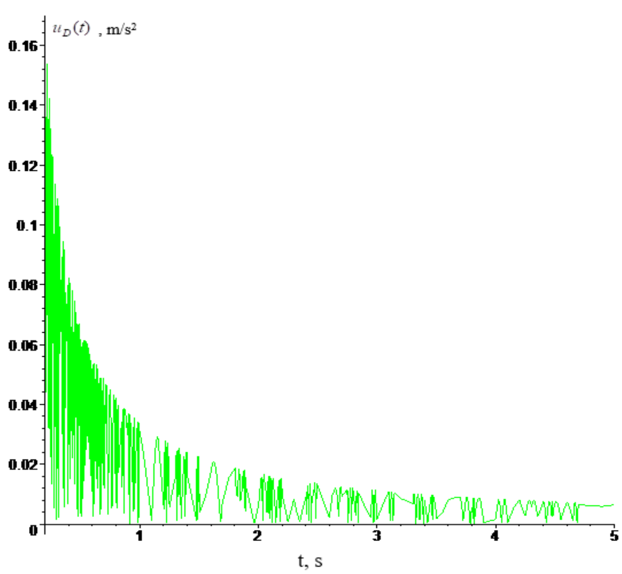

Figure 1. Uncertainty of dynamic measurement of vibration acceleration at a frequency of 6 kHz and observation time of 300 s.

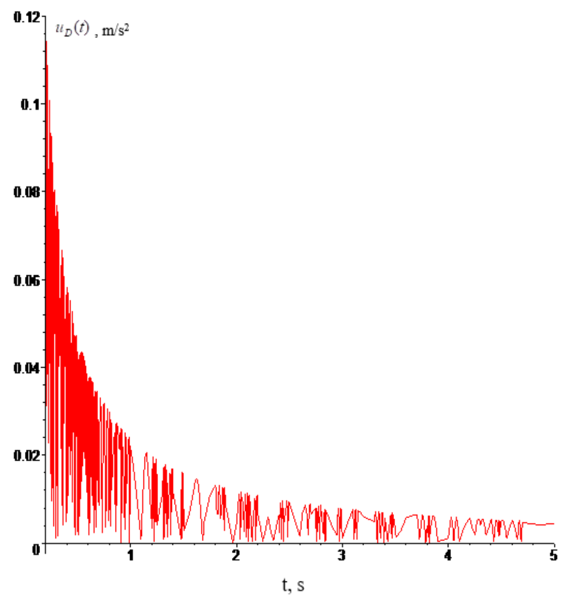

Figure 2. Uncertainty of dynamic measurement of vibration acceleration at a frequency of 6 kHz and observation time of 600 s.

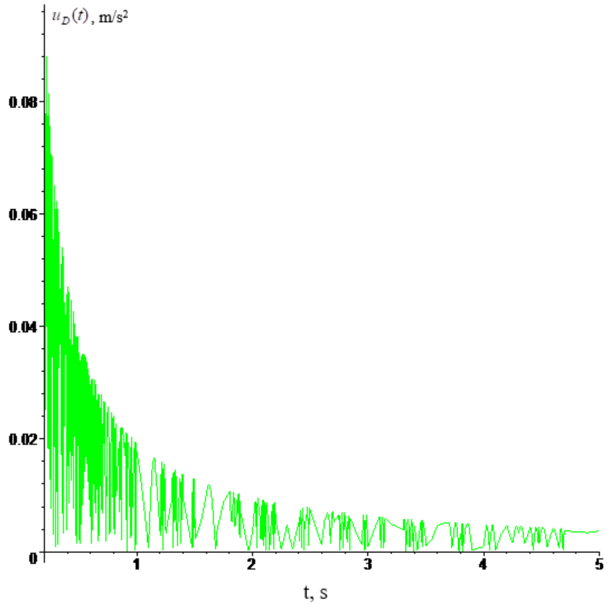

Figure 3. Uncertainty of dynamic measurement of vibration acceleration at a frequency of 10 kHz and observation time of 300 s.

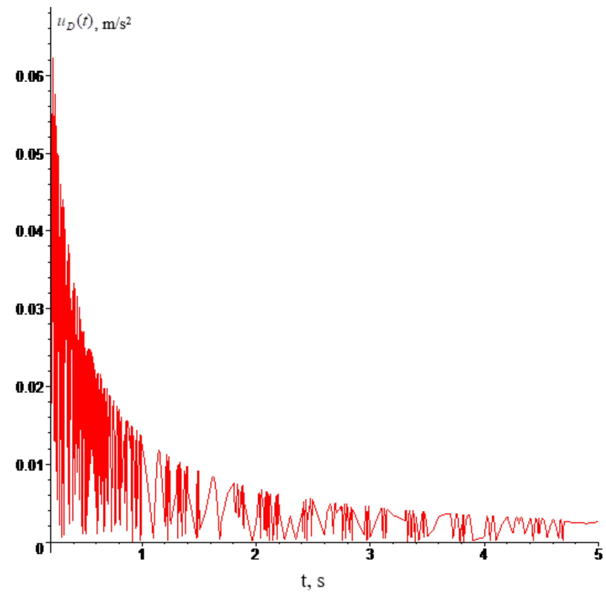

Figure 4. Uncertainty of dynamic measurement of vibration acceleration at a frequency of 10 kHz and observation time of 600 s.

The uncertainty budget of the dynamic measurement of the vibration acceleration for the observation time of 300 s and 600 s at frequencies of 6 and 10 kHz is shown in Table 2. The maximum value of dynamic uncertainty is 5.32 % at a frequency of 6 kHz at a observation time of 300 s (Tab. 2).

Table 2. Uncertainty budget of the constituent elements of the measuring channel of vibration acceleration.

Quantity	**Mean value, m/s^2**	**Frequency of the study, kHz**	**Observation time, s**	**Value of dynamic uncertainty, m/s^2**	**The expanded dynamic uncertainty** (coverage factor 1.96 at confidence level 95%), **m/s^2**	**Value of relative dynamic uncertainty, %**
The vibration acceleration	2.93	6	300	0.156	0.31	5.32
		6	600	0.116	0.23	3.96
		10	300	0.088	0.17	3
		10	600	0.064	0.13	2.18

The relative combined uncertainty measurement of the vibration acceleration, taking into account the relative dynamic uncertainties $\tilde{u}_D$ (Tab. 2) and the relative combined standard uncertainty $\tilde{u}_s$ (Tab. 1), is calculated by the formula

$$\tilde{u}_C = \sqrt{\tilde{u}_D^2 + \tilde{u}_s^2} = \sqrt{5.32^2 + 0.36^2} = 5.33\% \,. \tag{26}$$

Thus, the maximum value of the relative combined uncertainty of the vibration acceleration measurement is 5.33% with an observation time of 300 s and a frequency of 6 kHz. At a monitoring time of 600 s at a frequency of 6 kHz, the combined uncertainty value is 3.98%. At a frequency of 10 kHz at a observation time of 300 s, the combined uncertainty is 3.02% and at a observation time of 600 s at the same frequency of 2.21%.

3. CONCLUSIONS

The proposed spectral method of evaluating the uncertainty of dynamic measurements allows the calculation of the amplitude values of dynamic uncertainties, taking into account the international requirements for the evaluation of the quality of measurements - the concept of uncertainty. It helps to ensure the uniformity of measurements and enables comparison of the results of dynamic measurements made by different measuring devices and testing by different laboratories of leading countries. This method was tested when evaluating the dynamic uncertainty of the measurement of vibration acceleration of the roller bearing of the electric motor, which proved its validity and effectiveness.

The proposed approach to the evaluation of dynamic uncertainty of measurement means can be used for any measurement means characterized by dynamic components of any type.

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