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Features calibration of the dynamic force transducers

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Abstract. The article discusses calibration methods of dynamic forces measuring instruments. The relevance of work is dictated by need to valid definition of the dynamic forces transducers metrological characteristics taking into account their intended application. The aim of this work is choice justification of calibration method, which provides the definition dynamic forces transducers metrological characteristics under simulation operating conditions for determining suitability for using in accordance with its purpose. The following tasks are solved: the mathematical model and the main measurements equation of calibration dynamic forces transducers by load weight, the main budget uncertainty components of calibration are defined. The new method of dynamic forces transducers calibration with use the reference converter "force-deformation" based on the calibrated elastic element and measurement of his deformation by a laser interferometer is offered. The mathematical model and the main measurements equation of the offered method is constructed. It is shown that use of calibration method based on measurements by the laser interferometer of calibrated elastic element deformations allows to exclude or to considerably reduce the uncertainty budget components inherent to method of load weight.

1. Introduction

Now the status of machines, mechanisms, their nodes and separate details is estimated by measurements of their vibration characteristics (vibration rate, vibration acceleration, vibration displacement). However, in some cases it is more expedient to measure directly the dynamic forces arising by operation of this or that mechanism [6]. Calibration methods of dynamic forces transducers known today do not allow to define the valid metrological characteristics researched transducers. It is explained by the distinctions of the metrological characteristics taking place in real operating conditions where their response frequency characteristics do not match that, defined in the lab. Distinctions are caused by the fact that in lab determination of dynamic forces transducers metrological characteristics produced by forces which different from those in real operating conditions. In lab make calibration impulse, quasistatic or by a load mass method that does not provide the broad picture of the dynamic response transducer under test (TUT). The conducted researches showed that the metrological characteristics of dynamic forces transducers determined by a range of their impulse response on different forms of exciting signals have more reliability in comparison with the characteristics determined by a method of the load mass where excitation is made at single frequency on the sinusoidal law of force change. The current situation restricts a possibility of creation full-fledged system of metrological support in the field of dynamic forces measurements.

2. Problem definition

Thus, the task of creation new calibration methods and the measurement techniques allowing to make determination of dynamic force transducers metrological characteristics in the conditions reproducing conditions of real operation on subject to measurements in case of excitation by harmonic complex waves, including, impulse in all the range of operating frequencies in case of broad static load

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variability is relevant. For achievement of a theoretical measurements accuracy limit, as reference quantities of comparing it is necessary to use physical constants, such as wavelength of laser radiation, matter elastic modulus of the reference transducer "force - deformation".

3. Theory

Methods of static calibration [1], [5] do not allow to define response dynamic characteristics calibration of dynamic force transducers with an acceptable accuracy in the range of operating frequencies therefore in this article are not considered. Now for calibration of dynamic forces transducers the main method is the method of the load mass providing idea of dynamic properties transducers under test. According to this method, for determination of metrological characteristics (a sensitivity at a basic frequency, frequency response) of dynamic force transducers, use the set loading mode by force changing under the sinusoidal law [3]. The transducer under test with the load mass of the known weight established on it is subjected to harmonic oscillations of the known frequency and acceleration, and force operating at the same time on transducer under test, determine in the estimated method by the second law of Newton. An acceleration of a sheaf "transducer under test + the load mass" in case of mechanical oscillations can be measured by means of the reference piezoelectric accelerometer, however, for achievement of higher accuracy, it is necessary to use methods and means of a laser interferometry.

The general diagram of a calibration method and its composition by the load mass is shown in Figure 1.



Figure 1. A general view of installation for calibration of dynamic force transducers by load weight method [4]

The mathematical model of calibration process by load mass can be presented in the following form:

$$S_f = \frac{q_f}{(m_i + m_l) \cdot [(x_b - x_t)] f''(t)}$$
(1)

 S_f is the sensitivity of transducer under test (TUT);

 q_f is the output signal TUT;

 m_i is the internal mass of a sensitive element TUT;

 m_l is the load weight;

 x_b , x_t is the initial and final coordinates of a vibration displacement.

The main equation of measurements by this method can be presented in a general view as:

$$S_{f} = \frac{\sqrt{\sum_{i=1}^{n} (q) u_{sign}^{2}}}{\sqrt{\sum_{i=1}^{n} (m) u_{mass}^{2} \cdot \sum_{i=1}^{n} (a) u_{acc}^{2}}}$$
(2)

 $\sum_{i=1}^{n} (q) u_{sign}^2$ is the result of measurements for output signal (charge) TUT;

 $\sum_{i=1}^{n} (m) u_{mass}^2$ is the result of measurements for weigh mass; $\sum_{i=1}^{n} (a) u_{mass}^2$ is the result of measurements for acceleration.

Measurements uncertainty for acceleration consists of two groups: total standard uncertainty of measurements for acceleration by the laser interferometer and total standard uncertainty reproduction of acceleration by an electrodynamic shaker:

$$u_{a} = \sqrt{\sum_{i=1}^{n} u_{meas}^{2} + \sum_{i=1}^{n} u_{rep}^{2}}$$
(3)

We will consider the structure of these groups in more detail:

$$u_{a} = \sqrt{\frac{u_{cos}^{2} + u_{quad}^{2} + u_{f}^{2} + u_{noice}^{2} + u_{phase}^{2} + u_{Ab}^{2} + u_{drift}^{2} + u_{ref}^{2} + u_{ref}^{2} + u_{ras}^{2} + u_{res}^{2} + u_{mag}^{2} + u_{grad}^{2} + u_{sign}^{2} + u_{mass}^{2}}$$
(4)

 u_{cos} is the Cosine uncertainty; u_{quad} is the SDE uncertainty; u_f the is uncertainty caused by instability of laser radiation frequency; u_{noice} is the uncertainty caused by electronic noise of the laser interferometer; u_{phase} is the uncertainty caused by phase noise of an interferometer output signal; u_{ab} is the uncertainty caused of Abbe shift; u_{drift} is the uncertainty of interferometer setup drift; u_{ref} is the uncertainty of changes air refraction index; u_{rrans} is the uncertainty caused by cross motion of shaker; u_{rock} is the uncertainty caused by unevenness of the shaker movement; u_{rel} is the uncertainty caused by the relative movement of the interferometer; u_{mag} is the uncertainty caused by influence of a shaker magnetic field on an TUT output signal; u_{grad} is the uncertainty of TUT output signal measurements; u_{mass} is the uncertainty of TUT output signal measurements; u_{mass} is the uncertainty of load weight measurements

On the basis of the analysis listed calibration uncertainty budget components of the of dynamic force transducers by load mass method it is possible to draw a conclusion that the main components of the calibration uncertainty budget are the specified method is consequence of acceleration reproduction and measurements of the transducer under test and the load mass. Therefore, for minimization of the most part of the specified uncertainty components, the failure from an inertial method of excitation of dynamic forces by means of the electrodynamic shaker and transition to their excitation by a inertialess principle would be logical. The inertialess principle of dynamic force excitation (the variable mechanical strength causing proportional deformations) identical to the fastened together reference transducer and transducer under test is the base of this method.

In the offered method the deformation direct measurement of the calibrated elastic element performing function of the reference transducing "force-deformation" by method of a laser interferometry is used. Inertialess dynamic force excitation by means of a piezoactuator use of the calibrated elastic element as the reference transducer "force-deformation" and measurement of this deformation by the laser interferometer allows to exclude most a part of the uncertainty budget components inherent in a method of the load mass. The functional diagram explaining the offered principle is figured in Figure 2.



Figure 2. Calibration of dynamic forces transducers by the inertialess method, with use the laser interferometer [2]

1 – PC; 2 – coherent light source (laser); 3 – laser interferometer; 4 – photodetector and encoder of the laser interferometer; 5 – ring pro-point; 6 – calibrated elastic element; 7 – housing; 8 – dynamic force TUT; 9 – measuring amplifier; 10 – power amplifier; 11 – piezoactuator; 12 – signal generator; 13 – reflective coating.

The mathematical model of calibration process can be presented this method in the following form:

$$S_f = \frac{q_f}{s \cdot (E_{max} - E_{min}) \cdot d_{rev}}$$
(5)

 S_f is the sensitivity of TUT;

 q_f is the output signal (charge) of TUT;

s is the stifness of the reference converter "force-displacement";

 E_{max} , E_{min} is the maximum and minimum strengths of the piezoactyuator electric field;

 d_{rev} is the piezoelectric modulus.

The main equation of measurements can be presented in the deformation method in a general view as:

$$S_{f} = \frac{\sqrt{\sum_{i=1}^{n} (q) u_{sign}^{2}}}{\sqrt{\sum_{i=1}^{n} (k) u_{conv}^{2} + \sum_{i=1}^{n} (s) u_{strain}^{2}}}$$
(6)

 $\sum_{i=1}^{n} (q) u_{sign}^{2}$ is the measurements result of an TUT output signal (charge);

 $\sum_{i=1}^{n} (k) u_{conv}^{2}$ is the transformation uncertainty of force to deformation coefficient;

 $\sum_{i=1}^{n} (s) u_{strain}^{2}$ is the measurements result of elastic element deformation by laser interferometer.

Finally, it is possible to write down expression of total calibration standard uncertainty by the deformation method in the following look:

$$u_{a} = \sqrt{u_{cos}^{2} + u_{quad}^{2} + u_{f}^{2} + u_{noice}^{2} + u_{phase}^{2} + u_{Ab}^{2} + u_{drift}^{2} + u_{ref}^{2} + u_{hist}^{2} + u_{creep}^{2} + u_{sign}^{2}}$$
(7)

Apparently, in a formula (7) there are no uncertainty components inherent in a method of load weight caused by reproduction and vibration acceleration measurements: the uncertainty caused by a cross component of shaker motion u_{trans} , uncertainty, caused by unevenness of the shaker movement u_{rock} , the uncertainty caused by the relative movement of the interferometer u_{rel} , uncertainty, caused by influence of shaker magnetic field on an TUT output signal u_{mag} , uncertainty owing to an acceleration gradient along an axis of TUT u_{grad} . At the same time, there is measurements uncertainty of the reference converter "force-deformation" by the laser interferometer, measurements uncertainty of the TUT output signal and the uncertainty components of piezoactuator such as a hysteresis and drift. Uncertainty components inherent to a piezoactuator such as hysteresis, in control mode with a charge feedback it can be reduced to negligible size.

4. Results of experiments

The main components numerical values of the calibration dynamic force transducers uncertainty budget by load weight and by a deformation method listed in the section III are presented in comparative Table 1 in the form of the maximum values obtained as a result of an experiment and passport data of the laser interferometer.

Component of uncertainty	Method of load weight	Deformation method
a	b	с
Cosine uncertainty u_{cos}	0.017 %	
SDE uncertainty u_{quad} (passport data)	Periodic, 158 nм	
The uncertainty caused by instability of frequency of laser radiation u_f (passport data)	± 0.05 ppm/hour	
The uncertainty caused by electronic noise of the laser interferometer u_{noice} (passport data)	0.1 пм	
The uncertainty caused by phase noise of an interferometer output signal u_{phase} : uncertainty of an arctangent u_{arc} , time of a delay and jitter u_{del} , random uncertainty u_r (passport data)	1.4 %	
The uncertainty caused by Abbe shift u_{ab}	be absend for RLE10	
The uncertainty caused by working point drift of the interferometer due to conditions fluctuations of the environment u_{drift} (passport data)	100 пм/°С	
The uncertainty caused by fluctuations of air index refraction u_{refr} (passport data) temperature fluctuations atmospheric pressure fluctuations humidity fluctuations	1 ppm/°C 0.3 ppm/мBar 0.1 ppm/%	
Total standard uncertainty of measurements by the laser interferometer (passport data)	1.2%	
Uncertainty caused cross component of shaker motion u_{trans}	0.5%	0%
Uncertainty caused by unevenness of shaker motion u_{rock}	0.27%	0%
The uncertainty caused by the relative movement of the interferometer u_{rel}	0.04%	0%
a	b	с
The uncertainty caused by influence of a shaker magnetic field on an output signal of the TUT u_{mag} .	0.06%	0%
The uncertainty caused by an acceleration gradient along an axis of the TUT excitations u_{grad}	0.01%	0%
Uncertainty of load weight measurements u_{mass}	0.01%	0%
Uncertainty of the output signal TUT measurements u_{sign}	1% (when using the instrument amplifier 2626 of Bruel & Kjaer, Denmark	
Total standard uncertainty	1.768%	1.2%

Table 1.

5. Discussion of the results

On the basis of the comparative analysis of uncertainty budget components for calibration method by load weight and a deformation method, it is possible to draw the following conclusion: along with the identical values of uncertainty components for the laser system [7] which is used in both methods and presented to items 1 - 8 of Table 1, the uncertainty components such as caused by a cross component of a shaker fluctuations u_{trans} , the uncertainty, caused by unevenness movement of shaker u_{rock} , the uncertainty caused by an acceleration gradient along an axis of TUT u_{grad} , the uncertainty caused by the relative movement of the interferometer u_{rel} , the uncertainty, caused by influence of shaker magnetic field on an TUT output signal u_{mag} , the measurement uncertainty of load mass u_{mass} , in the offered deformation method are reduced to negligible size or are absent thanks to the inertialess principle of dynamic forces excitation by means of a piezoactuator and to lack of TUT free oscillations and the most load weight.

6. Outputs and inference

In the present article a brief description of the scientific rationale and solution of urgent scientific and technical tasks of creating a new high-precision calibration method of dynamic forces transducers, the mathematical model is defined and listed the most significant components of the calibration uncertainty budget.

Comparative analysis of both dynamic forces transducers calibration methods by load weight and strain method determined the main components of the uncertainty budget for these methods.

It is determined that the main contribution to the uncertainty budget of a load mass method is made by the components directly or indirectly connected to reproduction and measurement of the movement characteristic (acceleration). The offered new calibration method for dynamic force transducers by inertialess force excitation principle by means of an piezoactuator with use the calibrated elastic element as the reference transducer "force-deformation" and a laser interferometer for measurements of this deformation allowed to reduce calibration uncertainty of on comparing to a load mass method, to expand the frequency range of calibration and made possibility calibration by forces which law of change is excellent from sinusoidal (the polyharmonic, a pulse sequence, etc.). The offered new calibration method for dynamic force transducers and the experimental gage installation created on its basis allow to make calibration of dynamic force transducers in the range of forces from 0,1 N to 300 N with uncertainty no more than 1.2% in the frequency range from 1 Hz to 10 kHz.

Theoretical reasons and the received experimental results allow to consider the offered calibration method for dynamic force transducers and the experimental gage installation as a prototype of special standard for unit of dynamic forces allowing to reproduce a unit of measure with the initial accuracy, with a binding to wavelength of the stabilized He – Ne laser and elastic modulus of the reference transducer "force-deformation".

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