Simulation modeling of composite piezotransformer measuring transducer with differential output

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Abstract. The article presents the results of using simulation modeling to study the output characteristics of composite piezotransformer measuring transducers with a differential output. The processes were simulated using the Micro-Cap software. The article presents options for controlling the parameters of the equivalent electrical circuit of the converter. The article presents the results of simulation of composite piezotransformer measuring transducers with two degrees of freedom. Structurally, they can include piezoelectric elements, additional vibrators and communication elements between them. This allows you to expand their functionality, scope of practical application. The advantages are applicable to work in difficult and even extreme conditions. On the basis of such measuring transducers, prototypes of highly sensitive sensors were developed for measuring pressures, forces, temperature and other physical quantities, for monitoring the physical and mechanical characteristics of solids, liquid and gaseous media.

1. Introduction
Piezoresonance sensors (PRS) are widespread, structurally simple, technological, and applicable for severe operating conditions measuring devices. On the basis of piezoelectric quartz, which has a high stability of properties, PRS with a frequency output are created. Based on the use of piezoceramic materials with a high piezomodule, piezotransformer sensors (PTS) with an amplitude output are created [1, 2, 3, 4]. The advantages of measuring devices of this type include simplicity of design, manufacturability, low cost, reliability in operation, and applicability for harsh operating conditions. The main disadvantage of PTS is the low measurement accuracy due to the low stability of the properties of the piezoelectric materials used in them [5, 6].

Using the methods of simulation modeling, options for controlling the parameters of interconnected resonators and elements of communication between them using an equivalent electrical equivalent circuit of the converter are considered. It is shown that the ratio of the output voltages of the composite piezotransformer measured at certain frequencies of coupled oscillations in the system, as well as the ratio of these frequencies, can be used to form the output signal of the sensor. The use of a ratiometric output will significantly reduce the effect of various destabilizing factors on the measurement accuracy, and increase the linearity of the device's output characteristics. Recommendations are proposed for the development and design of primary measuring transducers...
with a ratiometric output based on the use of coupled oscillations in composite piezotransformers with two degrees of freedom.

Structurally, they can include piezoelectric elements, additional vibrators and communication elements between them. This allows you to expand their functionality, scope of practical application. The measuring transducer (MT) is applicable to work in difficult and even extreme conditions. On the basis of such measuring transducers, prototypes of highly sensitive sensors were developed for measuring pressures, forces, temperature and other physical quantities, for monitoring the physical and mechanical characteristics of solids, liquid and gaseous media. For example, it is to control surface roughness, viscosity, density and elasticity of liquid media. Excitation of oscillations in the system can be carried out in the mode of forced or self-oscillations of oscillations at certain frequencies, using pulsed excitation. The operating modes of such converter can be synchronous, asynchronous, bifurcation. The ratio of amplitudes, frequencies, phases of interrelated oscillations in the system, as well as other parameters, can be used as an output signal. For example, there is a duration of transient processes in the system, the time of entry or exit into synchronism, the ratio of the number of in-phase and antiphase oscillations in the beating mode of oscillations with partial drag, the depth of amplitude, frequency and phase modulation of the output voltages of a piezoelectric transformer, etc. Rational use of the corresponding modes of coupled oscillations in the system allows one to significantly reduce the influence of destabilizing factors on the measurement results, at the same time to increase the sensitivity and other metrological characteristics of measuring devices of this type.

To increase the sensitivity, improve the metrological characteristics of piezotransformer sensors, expand their functionality, areas of practical application, measuring devices have been developed based on the use of coupled vibrations in piezoresonance systems with a finite number of degrees of freedom in systems with distributed parameters [7, 8, 9].

In the general case, measuring devices of this type can be oscillatory systems with a finite number of degrees of freedom, systems with distributed parameters. Structurally, a measuring transducers (MT) of this type can consist of piezotransformers (PT) interacting with each other, vibrators, coupling elements between them. Differences (ratios) of amplitudes, frequencies and other parameters of coupled oscillations in the system can be used to form a differential (ratiometric) output signal of the sensor [10, 11, 12]. The disadvantage of a MT with a differential output is the need to select pairs of piezotransformers with similar characteristics. The non-identity of changes in the properties of the used piezo materials (in time, with a change in temperature etc.) significantly affects the metrological characteristics of measuring devices.

2. Design features of a measuring transducer with two degrees of freedom based on a composite piezoceramic transformer with matched dimensions

The solution to this problem can be the creation of a measuring transducer with a differential output based on composite piezoelectric transformers (PET) with a ratiometric output. It is proposed to use the ratio of the parameters of coupled oscillations in the system, the frequency signals (FS) of one PET taken at different frequency signals in the system, as an output signal in the MT of this type. Special vibrators with consistent dimensions and a coupling element between the vibrator and the PET can act as sensing elements in such sensors. In accordance with the principle of equipartition of the vibration energy between the degrees of freedom, not only the resonators themselves, but also the modes of coupled vibrations between them can be considered as the degrees of freedom. This can be, for example, in-phase and anti-phase oscillations between the piezotransformer and the associated vibrator. This makes it possible to use the ratio of the output voltages of one PET, but measured at different frequencies of coupled oscillations in the system, as the output signal of the measuring transducer. Implementation of this type of MT will eliminate the need to use two piezoelectric elements with similar characteristics in the design of the measuring transducer, which are used to generate the ratiometric output signal of the sensor.

In general, the type and nature of couplings between resonators can be inertial, elastic, dissipative, mixed, as well as external and internal. The operation of the sensors can be based on tenso-thermo-,
acousto-, mass sensitivity, etc. Figure 1 shows a block diagram and design of a measuring transducer based on a composite PET. The sensing element of the measuring transducer consists of a disk piezoelectric transformer (PET) with a system of input and output plates on the surface, interacting through a coupling element (CE) with a metal vibrator (V). The measured impact can control the parameters of the vibrator and the coupling element.

Figure 1. The structural diagram of the MT (a) and the design of the sensitive sensor element (b).

Both a vibrator and a coupling element between the vibrator and the piezotransformer can act as a sensitive element of the sensor. This determines two possible options for the design of the sensor and the methods for generating the output signal of the sensor. To describe the possible modes of operation of the sensor, it is necessary to analyze the coupled oscillations in a composite piezotransformer with matched dimensions. In a simplified form, a measuring transducer of this type can be represented as a system with two degrees of freedom. It should be noted that the analytical description of nonlinear processes in such real dynamical systems is a rather difficult task [13]. The formulas describing the output characteristics of the measuring transducer of this type are cumbersome, not clear, and difficult to analyze. In this regard, simulation modeling of coupled oscillations in a strongly coupled system with two degrees of freedom was carried out. For this purpose, the method of electromechanical analogies was used, according to which the equivalent electrical equivalent circuit (EEEC) of the measuring transducer was presented in the form of two interconnected oscillatory circuits (figure 2).

Figure 2. The equivalent electrical equivalent circuit (EEEC) of the measuring transducer (MT) in the form of two interconnected oscillatory circuits.

3. Results of simulation of synchronous operating modes of a measuring transducer with two degrees of freedom and their analysis

Figure 3 shows the frequency response of a strongly coupled oscillatory system of a measuring transducer with two degrees of freedom.

To form a differential output signal of a measuring transducer with two degrees of freedom based on a composite piezoelectric transformer, the following parameters of coupled oscillations in the system can be used:

- \( A_1, A_2 \) - amplitudes of oscillations in the excited circuit at normal synchronization frequencies (NSF) of in-phase and antiphase oscillations in the system;
- \( a \) - amplitude of oscillations in the excited circuit at its partial frequency (PF);
• $n_1; \ n_2$ - normal synchronization frequencies of in-phase and antiphase coupled oscillations of the circuits;
• $n_a$ is the partial frequency of the excited circuit.

**Figure 3.** Amplitude-frequency response of the oscillatory system of the measuring transducer with two degrees of freedom.

Figure 4 shows graphs that reflect the nature of changes in the amplitude-frequency characteristics of the excited circuit, when parameters of the oscillatory system of the measuring transducers are affected.

**Figure 4.** Frequency dependences of the amplitudes of oscillations in the excited circuit (piezotransformer) when changing the active resistances and frequency setting parameters of the equivalent electrical equivalent circuit of the vibrator and the coupling element.

Analysis of the graphical dependencies obtained as a result of simulation modeling of the operating modes of the measuring transducer made it possible to draw the following conclusions:

• when influencing the Q-factor and frequency-setting parameters of the vibrator and the coupler to form the sensor output signal, it is of interest to use the ratio of the vibration amplitudes of the excited PET, measured at the normal and partial frequencies of coupled vibrations in the system;
• when acting on the capacitance / inductance of the EEEC of the vibrator and the coupling element, the ratio of the normal synchronization frequencies of in-phase and anti-phase oscillations in the system can be used as the output signal of the sensor.

**Figure 5.** shows graphs of changes in the amplitudes of oscillations in the excited circuit as a function of the variable parameters of the equivalent electric circuit for replacing the vibrator and the coupling element (the numerical values along the axes are expressed in relative units).
Change in the amplitudes of oscillations in the excited circuit when changing the parameters of the equivalent electrical equivalent circuit

Figure 5. Influence of the parameters of the electric power system of the vibrator and the coupling element on the amplitude of vibrations in the excited circuit:
- on the NCF of in-phase oscillations ($A_1$);
- on the NCF of antiphase oscillations ($A_2$);
- at a partial frequency (a).

From the graphs presented earlier in the article, it follows that a change in the parameters of the vibrator and the coupling element leads to significantly different changes in the amplitudes and frequencies of the associated oscillations in the system. As it was assumed, changes in the Q-factors of the vibrator and the coupling element cause, to a greater extent, a change in the amplitudes of oscillations in the excited circuit. At the same time, the frequencies of coupled vibrations in the system are more sensitive to changes in the frequency setting parameters of the vibrator and the coupling element. It should be noted that when controlling the frequency setting parameters of the vibrator at normal frequencies of in-phase and antiphase oscillations, the oscillation amplitudes in the excited circuit change in opposite directions, which can be used to create a sensor with a differential output.

To generate the output signal of a measuring transducer with a differential (ratiometric) output, it is of interest to use the ratios of the oscillation amplitudes (ROA) in the excited circuit at certain frequencies:

- $\chi_1 = A_2 / A_1$ – ROA oscillations on the NSF of in-phase and antiphase oscillations in the system;
- $\chi_2 = a / A_1$ – ROA on the PF and NSF of the in-phase oscillations in the system;
- $\chi_3 = a / A_2$ – ROA on the PF and NSF of the inverter oscillations in the system.

The following figure shows graphs of changes in the oscillation amplitudes (ROA) of oscillations in the excited circuit as a function of the parameters of the vibrator and the coupling element.

Figure 6. Dependences of the ratio of the oscillation amplitudes in the excited circuit to the change in the parameters of the EEES MT at two frequencies: ($\chi_1$; $\chi_2$; $\chi_3$).
The results of simulation of coupled oscillations in a composite piezotransformer allow us to draw the following conclusions:

- as the output signal of the measuring transducer with control of the vibrator Q-factor, it is possible to recommend the use of the ratio of the output voltages of piezoelectric transformers measured at one of the normal frequencies of coupled oscillations in the system and a partial frequency;
- when acting on the Q-factor of the coupling element to form the output signal of the measuring transformer, the best option is to use the ratio of the output voltages of piezoelectric transformers measured at normal frequencies of in-phase and antiphase oscillations in the system, as well as the ratio of voltages measured at the normal frequency of antiphase oscillations and partial frequency;
- when controlling the frequency setting parameters of the vibrator, you can use the amplitude version of the measuring transducer with an output in relation to the voltages of piezoelectric transformers measured at normal frequencies of coupled oscillations in the system;
- when influencing the frequency setting parameters of the coupling element, the best option is the version of the sensor with an output in relation to the NCF.

Figure 7 shows graphs reflecting the effect of changes in the EEES parameters of the vibrator and the communication element on the sensitivity of the MT.

**The sensitivity of the MT to changes in the EEES parameters**

These graphical dependences allow us to draw the following conclusions:

- as the output signal of the MT with the Q-factor control of the vibrator, we can recommend using the ratio of the output voltages of the PET measured at one of the normal frequencies of the associated oscillations in the system and the partial frequency;
- when the Q-factor of the communication element is affected, the best option for generating the MT output signal is to use the ratio of the PET output voltages measured at the normal frequencies of common-mode and anti-phase oscillations in the system, as well as the ratio of the voltages measured at the normal frequency of anti-phase oscillations and the partial frequency;
- when controlling the frequency-setting parameters of the vibrator, an amplitude version of the MT can be used with an output relative to the PET voltages measured at normal frequencies of coupled vibrations in the system;
- when exposed to the frequency-setting parameters of the communication element, the best option is the sensor option with an output relative to the NSF.

A comparative assessment of the metrological characteristics of the options for constructing piezotransformer measuring transducers with an amplitude output made it possible to formulate the following recommendations on the method of forming a differential output signal:
1. When influencing the quality factor of the vibrator, it is more preferable to use the ratio of the output voltages of the piezotransformers measured at the partial frequency and one of the normal frequencies of synchronization of oscillations in the system as the output signal of the sensor. In this case, the output characteristic of the measuring transducer is characterized by the presence of nonlinearity and low sensitivity.

2. When controlling the quality factor of the coupling element, a possible option for generating the output signal of the measuring transducer can be the use of the ratio of the output voltages of the piezotransformers, measured at the NCF of the in-phase and antiphase oscillations in the system. This provides a high linearity of the output characteristics of the measuring transducer, but at low sensitivity.

3. When influencing the frequency setting parameters of the vibrator, the highest sensitivity is characterized by a variant of constructing a measuring transducer based on the use of the ratio of the output voltages of piezotransformers measured at the NCF of the system as an output signal.

4. When modulating the frequency-setting parameters of the coupling element, the best option for constructing a measuring transducer with an amplitude output is to use the ratio of the output voltages of the excited piezotransformer, measured at the partial and one of the NCF.

Thus, we can recommend two main options for the formation of the output signal of a differential-type piezotransformer sensor with an amplitude output. Depending on which structural element of the measuring transducer and which parameter is affected by the measured physical quantity, the ratios of the output voltages of the piezotransformers measured on the partial and NCF of coupled oscillations in the system can be used as the output signal of the measuring transducer.

Figure 8 shows the load characteristics for the considered options for constructing the measuring transducer.

![Figure 8](image)

**Figure 8.** Changing the sensitivity of the IP: a - when acting on the active resistance of the vibrator (---) and the coupling element (---); b - when influencing the frequency setting parameters of the vibrator (---) and the coupling element (---).

4. Conclusions

The use of the ratio of the output voltages from one piezoelectric transformer measured at two frequencies as the output signal of the measuring transformer allows one, on the one hand, to reduce the influence on the measurement result of various destabilizing factors, such as: instability of the parameters of the exciting generator, change in the characteristics of the piezoelectric material in time, the influence ambient temperature, the presence of acoustic losses in the elements of the sensor. On the other hand, a rational choice of the method for generating the sensor output signal will improve the metrological and operational characteristics of measuring devices of this type and expand the area of their practical application.

The main disadvantages of sensors with a differential output based on composite piezotransformers include the following factors:

- complication of operating modes and principles of forming the output signal of the measuring transducer will lead to an increase in the cost of its software and hardware;
the speed will decrease, since at each measurement it is necessary to periodically switch the operating frequency.

Thus, the application of the simulation method to study the operating modes of the measuring transducer based on the composite piezotransformer made it possible to make a comparative assessment of various options for the formation of the differential output signal of the measuring transducer, to develop recommendations for optimizing the modes of their operation.

Measuring transducers based on composite piezoelectric transformers with amplitude output can be used to measure various physical quantities, physical and mechanical characteristics of liquid media, bulk materials, solids.

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