Simulation of measuring transducers based on interconnected piezoresonators

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Abstract. The article presents the results of simulation of the operating modes of measuring transducers based on interconnected piezoresonators. The article discusses modulation options as a function of the measured effects of the parameters of equivalent electrical equivalent circuits of piezoresonators and coupling elements between them. The article describes the features of using coupled oscillations in systems with two degrees of freedom for constructing differential-type sensors with a frequency and amplitude output. The article gave examples of the practical implementation of measuring devices based on coupled oscillations of piezoresonators.

1. Introduction

The development of automation and robotization systems in a wide variety of fields of activity increases the need for intelligent measuring instruments with high metrological characteristics and advanced functionality. The solution to this problem is the use of new materials, principles of construction of measuring instruments using firmware that are used for receiving, storing and processing of the primary measurement information. At present, piezoresonance sensors are widely used \cite{1, 2}. As shown by studies \cite{3-6}, the use of coupled oscillations in piezoresonant structures can significantly increase sensitivity, expand the operating range and operating conditions of primary measuring transducers (PMT) based on piezoresonators.

2. Simulation of mode of operation of a measuring transducer with strong coupling between piezoresonators

Figure 1 shows a simplified block diagram of a measuring transducer (MT) based on interconnected piezoresonators (PR) and its equivalent electrical equivalent circuit (EEES) in the form of two interconnected oscillatory circuits.

![Figure 1. Structural and equivalent electrical circuit of a measuring transducer based on interconnected piezoresonators.](image-url)
The operation of sensors of this type can be based on various mechanisms of sensitivity to measured influences. In this case, the modulated parameters of the measuring transducer may be resistors, inductances and capacitances of the equivalent electrical equivalent circuit (EEES) of oscillatory circuits and coupling element (CE) between them. As the coupling element may be the object of study, which can significantly expand the functionality and scope of measuring devices of this type. In order to optimize the structural and circuit solutions of the measuring transducer, determine the parameters of the used resonators and communication elements, it was necessary to analyze the operating modes of such devices. As is known from the theory of oscillations [7], an accurate analytical description of dynamic processes in nonlinear systems is a rather difficult task. In this regard, a simulation was performed of various options for constructing measuring transducers based on the use of coupled oscillations in systems with two degrees of freedom. Designs of measuring transducers, consisting of interconnected monolithic and composite piezoresonators, additional vibrator elements of the relationship between piezoresonators were considered.

Table 1 shows the amplitude-frequency characteristics (AFC) of the oscillatory system of the measuring transducer, reflecting the influence of active resistance and frequency-setting parameters (capacitance, inductance) in the slave circuit on the parameters of coupled oscillations in the system. At the same time, the leading circuit is a circuit with an exciting generator connected to this circuit.

Table 1. Amplitude-frequency characteristic of the oscillatory system of the measuring transducer when exposed to the parameters of the circuits and the coupling element between the circuits.

| Variable parameter in circuit | master | driven |
|------------------------------|--------|--------|
| Variable parameter in a coupling element | resistor | frequency setting |
| Variable parameter in circuit | resistor | frequency setting |
| Variable parameter in a coupling element | resistor | frequency setting |

This systematic representation of the amplitude-frequency characteristic of the measuring transducer, consisting of strongly coupled circuits, reflects a number of features of the reaction of the oscillatory system to a change in the parameters of this system:
- a change in the quality factor of the slave circuit causes a change in the amplitudes of the oscillations in both circuits at the normal synchronization frequencies (NSF) of the system, while the normal synchronization frequencies themselves change significantly less;
- a change in the active resistance in the coupling element also leads to a change in the oscillation amplitudes in both circuits at the normal cut-off frequency of the out-of-phase oscillations in the system, since the coupling element is involved in the process of energy exchange between the circuits;
- a change in the frequency-setting parameters in the slave circuit causes a change in the amplitudes and frequencies of the in-phase and antiphase oscillations in both circuits;
- a change in the frequency-setting parameters in the coupling elements leads to a change in the frequency of antiphase oscillations in the system. The oscillation amplitudes in the circuits change significantly less.

Table 2 shows the graphs reflecting the effect of changes in the parameters of the slave circuit on the output characteristics of the measuring transducer with amplitude and frequency output.

**Table 2.** Changes in the amplitude and frequency characteristics of the measuring transducer when exposed to the parameters of the slave circuit.

| Type of output characteristic of the measuring transducer | absolute values | ratio of values |
|----------------------------------------------------------|-----------------|-----------------|
| Resistor variable parameter in the slave circuit and output signal type of MT | ![Graph](image1.png) | ![Graph](image2.png) |
| Frequency-controlled variable parameter in the slave circuit and type of output signal of MT | ![Graph](image3.png) | ![Graph](image4.png) |
As a result, it is possible to make the following conclusions:

- The effect on the quality factor of the driven circuit, in which there is a change in its active resistance, can be the basis for creating a sensor with an amplitude output. When implementing a differential type sensor, the ratio of the amplitudes of coupled oscillations in the circuits can be used as the output signal. Since the normal cutoff frequency and their ratio change extremely weakly and non-linearly, therefore, this solution cannot be recommended for use as the output signals of a measuring transducer with a frequency output.

- When influencing the frequency-setting parameters of the driven circuit, the use of the ratio of amplitudes and frequencies of interconnected oscillations of the circuits can be recommended as the oscillation frequency of interconnected circuit.

Table 3 shows graphs that reflect the effect of changes in the parameters of the coupling element between the circuits on the output characteristics of the measuring transducer with amplitude and frequency output.

**Table 3.** Amplitude and frequency output characteristics of the measuring transducer when changing the parameters of the coupling element between the circuits.
The analysis of the obtained dependencies allows developing the following recommendations for the development of measuring transducers based on the control of the parameters of the coupling element between the circuits:

- When acting on the active resistance of the coupling element, the measurement of the oscillation amplitudes in the slave circuit at the normal cut-off frequency of the out-of-phase oscillations in the system can be recommended as the output signal of the sensor with the amplitude output.
- When influencing the frequency-setting parameters of a coupling element, it may be recommended to measure the ratio (difference) of the normal cutoff frequency in the system. The performance of this type of device will provide the sensitivity and linearity of the measurement conversion process.
- It is of interest to use simultaneously the amplitude and frequency output signals. In this case, one of them can be used as a measuring signal, and the second can be used as a correction signal. For example, if a measuring transducer with an amplitude output is implemented, the frequency output can be used to correct the influence of destabilizing factors on the frequency-setting parameters of the communication element.

3. Modeling of mode of operation of a measuring transducer with a predominant resistive coupling between circuits

Of practical interest is the idea when the prevailing resistive coupling between the interacting circuits in the oscillatory system of the measuring transducer is realized. Measuring transducers of this type can be used, for example, for measuring the viscosity of liquid, in devices for controlling the surface roughness of solids [7]. Figure 2 shows the amplitude-frequency characteristic of the oscillatory systems of the measuring transducer with resistive coupling between the loops.

![Figure 2. Amplitude-frequency characteristic of oscillatory systems of a measuring transducer with a resistive coupling, excited according to the scheme of one (a) and two (b) generators.](image)

From these graphs, it follows that the system may be implemented by transmitters with measuring transducers with frequency and amplitude output using both versions of the excitation of oscillations. Of particular interest is the case of a strong tuning of the natural frequencies of the interconnected circuits. However, a change in the level of resistive coupling between the circuits leads to changes not only in amplitudes, but also to significant changes in the frequencies of coupled oscillations in the system. This can be the basis for the development of measuring devices with a frequency output [8].

Table 4 shows the dependences reflecting the influence of changes in the level of resistive coupling between the circuits on the amplitude and frequency output characteristics of the measuring transducer excited by the scheme of two generators [9].

It can be seen from the graphs that the change in active resistance in the coupling element determines the nonlinear nature of the change in the amplitudes and frequencies of coupled oscillations, as well as in the relations of amplitudes and frequencies. For example, the oscillation amplitudes in the circuits first decrease, and then increase, with increasing coupling in the system. The oscillation frequencies in the circuits approach with increasing coupling in the system, and more
strongly with decreasing vibration amplitudes in the system. Therefore, the sensitivity of the measuring transducer with a resistive coupling between the loops depends on the magnitude of the measured effect and can be varied widely [10].

Table 4. Output characteristics of the measuring transducer with resistive coupling between circuits.

| Type of output characteristic of the measuring transducer | Absolute values | Ratio of values |
|----------------------------------------------------------|-----------------|-----------------|
| Resistor variable parameter in coupling element and type of output characteristics | amplitude       |                 |
|                                                           | frequency       |                 |

Figure 3 shows several variants for the practical implementation of measuring transducers (MT) based on the coupled oscillations of piezoresonators (PR), piezotransformers (PT).

Figure 3. Varieties of measuring transducers using interconnected oscillations in piezoresonance structures.

In these examples of practical realization of measuring devices based on coupled oscillations in piezoresonator structures of varying complexity, the excitation oscillation is performed at a resonant frequency using auto-generating circuits. The output voltages of the interconnected piezotransformers, the values of the normal synchronization frequencies in the system, the ratio and the difference of the output voltages and the frequencies of the coupled oscillations of the piezoresonators (piezotransformers) are used as the output signal of the measuring transducer [12, 13].
4. Conclusion

Summarizing the simulation results, when developing measuring transducers, it is necessary to take into account a number of features:

- The introduction of additional resonators, vibrators, and coupling elements into the structure of the measuring transducer complicates the dynamics of such systems. It is possible to implement different modes of operation of the measuring transducer, expanding the functionality of the measuring transducer, there are additional opportunities to improve the metrological characteristics of the measuring transducer;
- In a measuring transducer of this type, the coupling elements between the resonators can be solids, gaseous and liquid. In addition, the connection between the resonators can be inertial, elastic, and dissipative; external and internal; strong and weak. All this allows the development of measuring transducers of various designs, expanding the scope of measuring transducers;
- The mechanical quality factor of the resonators used in the measuring transducer affects the metrological characteristics of the measuring transducer, the degree of detuning of the fundamental frequencies of the resonators. It is possible to control the operating modes of the measuring transducer by changing the ratio of the levels of excitation of oscillations in the resonators, changing the metrological characteristics of the measuring transducer.

The advantages of measuring devices based on interconnected piezoresonators include the high sensitivity of the device, the simplicity of the device design, the low cost of manufacturing the device, the reliability of the device, the ability to use the device for operation in difficult operating conditions. It should be noted that sensors of this type require the use of modern microprocessor technology and the development of appropriate software.

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