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Instruments and Measuring Systems Based On Acoustic, Optical and Radio Waves

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Microaccelerometer on Surface Acoustic Waves with a Ring Resonator on Anisotropic Material

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Abstract

Introduction. Diagnostic systems are designed to monitor the condition of operational components (for example, on the railway). It is imperative that micro-electromechanical systems (MEMS) equipped with acceleration sensors (accelerometers) be used as part of measuring diagnostic systems. It is known that accelerometers are operated under increased vibration and repeated shock loads. This imposes a limitation both on the accelerometer design and the properties of materials from which these devices are produced.

Aim. To develop a micromechanical accelerometer (MMA) for surface acoustic waves (SAW), capable of measuring shock effects.

Materials and methods. The theoretical part of the study was carried out using the mathematical theory of differential equations, theoretical mechanics, finite element analysis and elements of SAW theory. In the course of the work, the following methods of mathematical processing were applied: MATLAB, Mathcad, Maple, COMSOL Multiphysics, OOFELIE: Multiphysics, Bluehill3 software, CorelDRAW. Experimental studies were also conducted using the INSTRON 5985 floor automated test system.

Results. An original design of MMA on a SAW capable of measuring shock effects in hundreds of g was proposed. A sensing element (SE) of the sensor was developed. An analysis of the plate materials for their use as part of the SAW-based MMA design showed that SE from the quartz ST-cut material has a wider range of measured accelerations and a higher sensitivity threshold than SE from the YX-128˚ cut-off lithium niobate material. Requirements were developed to increase the SE sensitivity threshold. Design requirements were developed, and an interdigital transducer (IDT) topology in the form of a ring resonator was proposed. The following output characteristics were assessed: sensitivity threshold, dynamic range and scale factor. In addition, a procedure was developed for calculating MMA on a SAW with a ring resonator on an anisotropic material. It was found that the developed SE is characterized by a high sensitivity threshold, a wide dynamic range and a low transverse sensitivity.

Conclusion. The technique proposed for designing a sensing element for use in solid-state linear acceleration sensors facilitates, depending on technical requirements, selection of construction materials and sensor design. Due to the originality of the design and engineering solutions, the proposed accelerometer allows measurements to be carried out across a wide range of impact loads.

Key words: microelectromechanical systems, micromechanical accelerometer, sensitive element, surface acoustic waves, interdigital transducer, anisotropic material

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Приборы и системы измерения на основе акустических, оптических и радиоволн

Оригинальная статья

Микроакселерометр на поверхностных акустических волнах с кольцевым резонатором на анизотропном материале

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Аннотация

Введение. Состояние объектов эксплуатации (например, на железной дороге) контролируется системами диагностики. В их составе используются микроэлектромеханические системы, комплектуемые датчиками ускорения (акселерометрами). В процессе эксплуатации акселерометры подвергаются значительным вибрациям и многократно повторяющимся ударным воздействиям. Это накладывает ограничения на конструкцию и материалы, из которых изготавливаются акселерометры.

Цель работы. Разработка микромеханического акселерометра (ММА) на поверхностных акустических волнах (ПАВ), способного измерять ударные воздействия.

Материалы и методы. Теоретическая часть работы выполнялась с применением математической теории дифференциальных уравнений, теоретической механики, конечно-элементарного анализа и элементов теории ПАВ. В ходе работы применялась математическая обработка в программах MATLAB, Mathcad, Maple, COMSOL Multiphysics, OOFELIE::Multiphysics, ПО Bluehill3, CorelDRAW. Экспериментальные исследования проведены с привлечением напольной автоматизированной испытательной системы INSTRON 5985.

Результаты. Разработана концепция построения и предложена оригинальная конструкция ММА на ПАВ, способного измерять ударные воздействия в сотни g. Разработан чувствительный элемент (ЧЭ) сенсора. Анализ материалов для пластин в составе конструкции ММА на ПАВ показал, что ЧЭ из кварца ST-среза отличается более широким диапазоном измеряемых ускорений и более высоким порогом чувствительности, чем ЧЭ из ниобата лития среза YX-128°. Выработаны требования и исследована возможность повышения порога чувствительности датчика. Сформулированы требования к проектированию и предложена топология встречно-штыревого преобразователя (ВШП) в виде кольцевого резонатора. Предложена оригинальная топология резонатора с неэквидистантным ВШП для учета анизотропии материала чувствительного элемента. Оценены выходные характеристики: порог чувствительности, динамический диапазон, масштабный коэффициент. Предложена методика расчета ММА на ПАВ с кольцевым резонатором на анизотропном материале. ЧЭ ММА такой конструкции имеет высокий порог чувствительности, широкий динамический диапазон и малую поперечную чувствительность.

Заключение. Предложенная методика проектирования ЧЭ твердотельного датчика линейных ускорений позволяет выбрать материал и систему съема измерительной информации в зависимости от технических требований. Благодаря оригинальности конструкторско-технологического решения предложенный акселерометр позволяет проводить измерения в широком диапазоне ударных воздействий.

Ключевые слова: микроэлектромеханические системы, микромеханический акселерометр, чувствительный элемент, поверхностно-акустические волны, встречно-штыревой преобразователь, анизотропный материал

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Introduction. In recent decades, microelectromechanical systems (MEMSs) have become an integral part of modern technology [1–3]. As well as being widely used in personal electronics devices, they have important applications in heavy industry and military equipment. MEMSs are actively used in techniques with special operating conditions, in control and measuring equipment, for example, as part of railway diagnostics systems, where it is necessary to measure the impact of hundreds of *g* [4–6]. The above applications determine the relevance of the design of such devices.

As a result of the analysis of the main types of MEMS sensors [7–17], it was concluded that the following recommendations should be followed for a micromechanical accelerometer (MMA) to be capable of withstanding high overloads and measuring high accelerations:

– the sensing element (SE) must be firmly fixed;

– to reduce transverse sensitivity, it is necessary to use axisymmetric SE structures and their uniform fastening;

– to increase the sensitivity threshold, it is necessary to load the SE with inertial mass (IM).

To meet these recommendations, it is proposed to develop a solid-state sensor on surface acoustic waves (SAWs) using molecular kinetics of a solid body.

Previously, an MMA on SAWs was developed at the Department of Laser Measurement and Navigation Systems (LMNS) of the Saint Petersburg State Electrotechnical University [18]. This comprised a pendulum-type accelerometer, whose SE was realised in the form of a console made of single-crystal ST-cut quartz. The SE was rigidly fixed on the one side and loaded with IM on the other. On the opposite sides of the element, SAW resonators were located.

The generalised structural scheme of the differential SAW accelerometer is shown in Fig. 1. It includes a SE *1*, which is rigidly fixed at the left end and loaded with the IM *m* on the right. It is equipped with two SAW resonators *2*, included in the circuit of self-oscillators *3*. Output signals of self-oscillators are fed to the mixer *4*, the output of which includes two bandpass filters *5*, *6*.

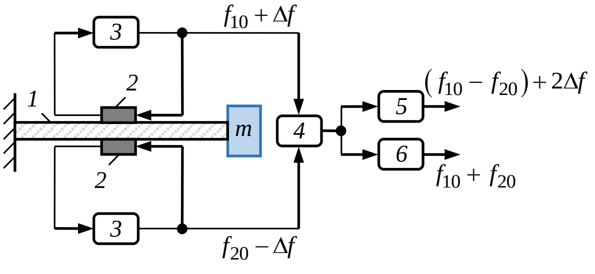


Fig. 1. Structural diagram of a SAW-accelerometer

Under the influence of acceleration, the cantilever-type SE experiences bending load. In this case, the resonant frequencies of the resonators *2* change causing the frequencies of the output signals of the generators *3* to change by a value Δf, proportional to the effective acceleration. Harmonic oscillations of the self-oscillators *3* are fed to the mixer *4*, where signals of the total frequency $f_{10}+f_{20}$ and difference frequency $f_{10}-f_{20}+2\Delta f$ are formed. The difference frequency depends on the acceleration value, while the total frequency can be used to reduce the influence of destabilising factors, especially temperature, through the generator frequency auto-adjustment channel.

One of the most important criteria determining the sensitivity of an MMA on SAWs is the relative SE deformation. In the case of a rectangular console, the distribution of relative deformations taking place on the linear SE dimension under the action of acceleration along the sensitivity axis of the sensor is heterogeneous. In the case of the asymmetrical arrangement of SAW resonators, this leads to different sensitivity of the differential circuit arms and, consequently, to additional errors. In order to reduce these errors, a triangular console is proposed [18], the relative deformations of which are uniform.

At the same time, a rectangular SE is characterised by a significant sensitivity to accelerations along the axes perpendicular to the measuring axes, while an SE with a triangular shape of the console is practically insensitive to such influences.

Taking these properties into account, it was concluded that a triangular console is more promising for further development, since it provides a uniform distribution of relative deformations in the area of application of the SAW resonator, as well as having a low transverse sensor sensitivity. The disadvantage of this design is the small dynamic range, which prevents the measurement of impacts.

In 2009, a Russian-German research team proposed a high-quality SAW resonator in the form of an extended, ring-closed single-pass resonator applied to the substrate of the Z-cut aluminium nitride [19–21].

In the present article, it is proposed to combine these two developments in order to create an MMA on SAWs with a ring resonator on an anisotropic material capable of measuring shock effects of hundreds of *g*. The objective is achieved by solving the following tasks:

– selection of the design and material of the SE for the MMA on SAWs for impact measurements;

– analysis of the internal stresses and distribution of relative deformations of the SE;

– increasing sensitivity by using an interdigital transducer (IDT) topology and loading the SE with IM;

– assessment of the dynamic range, sensitivity threshold, scaling factor;

– calculation of the IDT topology for the anisotropic substrate and assessment of the influence of technological errors on the output signal;

– analysis of the features of the output signal pickup.

Based on the solution of these problems, an MMA on SAWs with a ring resonator on anisotropic material is proposed (Fig. 2). The SE of such an MMA consists of a round plate fixed on the generatrix with SAW resonators affixed on both sides. This solves two problems simultaneously – uniform distribution of relative strains and reasonable use of element dimensions [22].

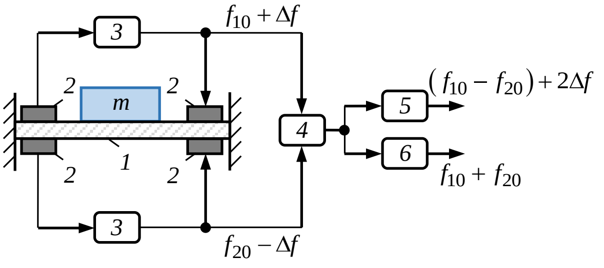


Fig. 2. Structural diagram of the MMA using the SAW with ring resonator

The principle of operation of such an accelerometer is precisely the same as that of the MMA described earlier.

At the first stage of MMA design, it is necessary to assess the optimal material for the sensing element, in this case ST-cut quartz or YX-128°-cut lithium niobate. As materials for substrates of acoustic and electronic devices, each of these materials has its advantages and disadvantages. Therefore, it is necessary to study how these materials will behave as a suspended structure of the MMA.

Material parameters. The characteristics of any accelerometer are the threshold sensitivity and dynamic range. In an MMA on SAWs, these parameters are determined (in the first approximation) by the mechanical part of the SE; in the MMA under consideration, by a round plate rigidly fixed on the generatrix.

The dynamic range of the MMA is determined by the ultimate strength of the mechanical part of the SE. It is assumed that the proposed SE will be able to withstand heavier loads than the pendulum-type SE [18]. As a result of the analysis of the stress-strain state of the SE fixed on the generatrix, it is determined that the maximum stress depends on two variables: acceleration a and the ratio of the square radius of the plate R to its thickness h:

$$\sigma_{\max} = (3/4)\rho a\left(R^2/h\right),$$

where ρ is the density of the material.

When selecting the SE dimensions for the accelerometer, the penetration capacity of the acoustic wave is decisive. SAWs have a weak penetrating capacity of about 3λ (λ – SAW length). Assuming that the IDT will be located on opposite sides of the SE, the quartz element must have a minimum thickness of 7λ. For example, for a sensor with dimensions of not larger than 10×10×10 mm, the ratio $R_{\max}^2/h_{\min}$ must be no more than 500 for quartz and 400 for lithium niobate ($R_{\max}$, $h_{\min}$ – the maximum radius and minimum thickness of the plate, respectively). All further calculations and graphs are given for the values $R_{\max}^2/h_{\min}=$ 25, 100, 200 и 400.

Maximum material strength. The MMA on SAWs retains its measurement capability up to fracture, i.e., the measuring range of the sensor and the maximum overloads it can withstand are the same. As a result, to assess the dynamic range, it is necessary to determine the mechanical capabilities of the SE in terms of the maximum bending strength, which is understood as the load leading to sample destruction.

Static tests of ST-cut quartz and YX-128°-cut lithium niobate samples were performed to determine the maximum material strength.

On the experimental INSTRON 5985 installation, crossheads with clamps were installed with the supporting surfaces aligned in parallel (Fig. 3). ST-

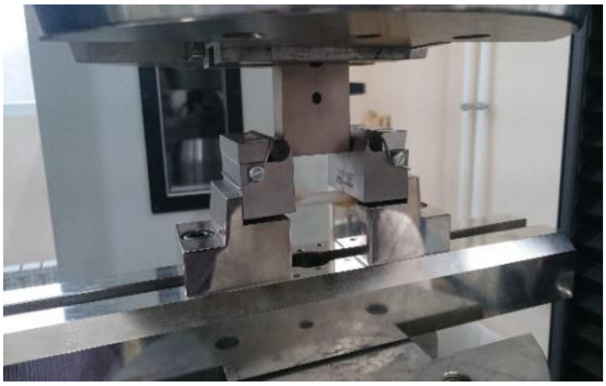


Fig. 3. Experimental installation INSTRON 5985 with the testing sampler

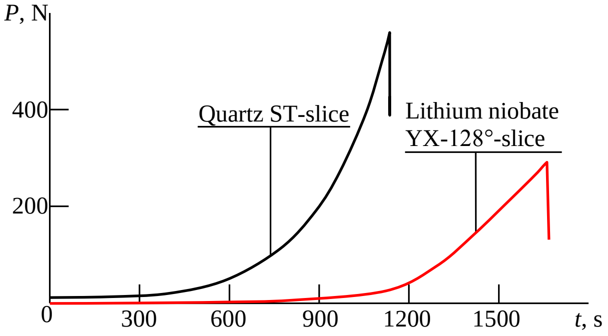


Fig. 4. Graph of the load in the experiment to determine the ultimate strength of the samples

cut quartz plates and YX-128°-cut lithium niobate samples were rigidly fixed by clamps in the experimental installation and were subjected to mechanical influence in the form of pressure "from top to bottom" uniformly distributed by the load *P* to the destruction of the material (Fig. 4). Based on the test results, the maximum strength of the materials was calculated: 141.8 MPa for ST-cut quartz and 106.8 MPa for YX-128°-cut lithium niobate [23–25].

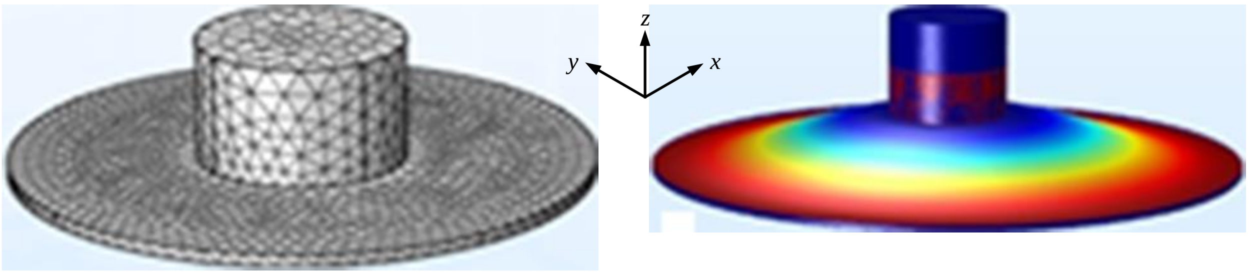
Thus, under identical operating conditions, typical for the SE IDT (overload of thousands of *g*, rigid fastening of the SE along the perimeter), quartz is a more durable material in comparison with lithium niobate, which justifies its use as a material for the SE accelerometer.

Sensitivity threshold. The sensitivity threshold was defined in terms of a signal 3 times higher than the noise level. When assessing the threshold sensitivity of the MMA on SAWs, relative deformations at the resonator location play an essential role. An increase in these deformations increases the frequency change and hence the output signal of the transducer. The results of measurements showed that the sensitivity threshold for the MMA on SAWs with s pendulum-type SE previously developed at the LMNS Department [18] is 0.21 kHz.

In order to increase the relative deformations leading to an increase in the sensitivity threshold, it was decided to load the SE with IM and analyse the stress-strain state. It is possible to achieve the highest accuracy of measurements, the simplicity of the sensor design and the required frequency range by varying the IM parameters and the IDT structure. Due to the complicated and time-consuming nature of analytical calculation of relative deformations, computer modelling was carried out for optimisation. The design process additionally required an assessment of the limiting performance of the sensors. Since the impact resistance of SAW sensors is exceptionally stringent, its experimental evaluation is costly, if not impossible in some cases.

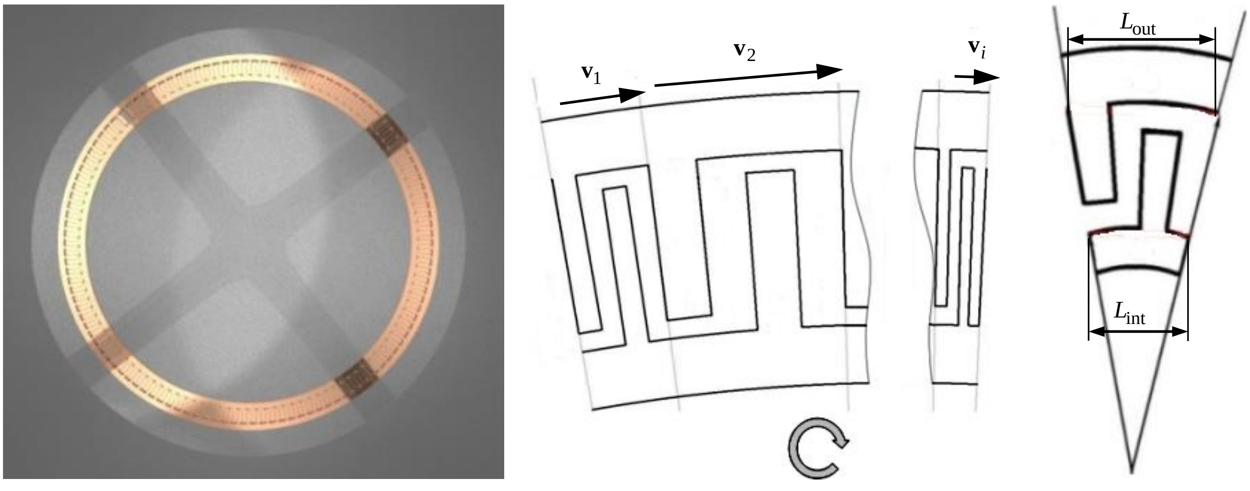
The modelling of the MMA on SAWs was performed in the COMSOL Multiphysics software package. With the help of the built-in geometry editor, models were built, consisting of round plates rigidly fixed to the generatrix, in the centre of which the IMs were placed. The models were divided into finite elements by a triangular grid (Fig. 5, *a*). The dimensions of the plates satisfied the previously selected ratios $R_{\max}^2 / h_{\min} = \; = 25,\ 100;\ 200;\ 400$. The calculation was made for two types of materials: ST-cut quartz and YX-128°-cut lithium niobate. The anisotropic properties of these materials were considered in the modelling process. The IM consisted of a cylinder of non-magnetic heavy tungsten-nickel-copper (TNC) alloy having the following characteristics: high density $\rho = 18\,000\ \mathrm{kg/m^3}$, Young's modulus $E = 350\ \mathrm{GPa}$, and Poisson's ratio $\gamma = 0.29$. The program allowed the effects of different acceleration values to be simulated (Fig. 5, *b*) and the SE deformation characteristics (deformation, internal stresses, elongation) calculated under the influence of acceleration along the *z* sensitivity axis.

Ring SAW resonator. Both considered SE materials – quartz ST-cut and lithium niobate YX-128°-cut – are anisotropic. The phase velocities of SAWs in them in terms of electromechanical coupling fac-



a *b*

Fig. 5. Model of a sensitive element (SE): *a* – breakdown into finite elements; *b* – SE under load along the *z* axis



a *b* *c*

Fig. 6. Ring interdigital transducer (IDT): *a* – general view; *b* – scheme of the non-equidistant unapodized IDT; *c* – determination of the periods of a ring IDT

tors (ECFs) vary depending on the direction of acoustic wave propagation in the material.

When calculating and constructing the IDT topology (Fig. 6, *a*), it is crucial to consider changes in phase velocity and ECFs in order to increase the reliability of the results. In order for the operating frequency of the acoustic device to remain constant, it is necessary to consider the phase velocity within each period of the ring resonator topology separately. Then the anisotropy of SE material properties is compensated by the non-equidistance of the unapodised IDT ring (Fig. 6, *b*).

Calculation of the linear equidistant resonator topology is reduced to determining the period, the length of the transducer and the aperture. The IDT period is determined by the condition of acoustic synchronism: the equality of the topology period to the SAW length $\lambda = v_{m.s} / f_{op}$, where

$$v_{m.s} = \frac{1}{d/v_m + (1-d)/v_s}$$

– SAW speed on partially metalised substrates, and v_s, v_m – SAW speed on free and metalised surfaces, respectively; $d = 0.5$ – the metallisation ratio.

The length of the whole transducer is a product of the period of topology L on the quantity N: $L_{IDT} = LN$.

In a non-equidistant IDT, this period changes. Then:

$$L = \sum_{i=0}^{N} L_i,$$

where i is the number of the topology period defined as

$$L_i = v_i / f_{op}.$$

Here v_i is the SAW phase velocity on the i-th pair of pins; f_{op} – the operating frequency equal to 433 MHz.

When selecting the aperture of the transducer, it is necessary to consider possible diffraction losses associated with the divergence of the acoustic beam of the limited aperture. Therefore, the aperture of the IDT electrodes should not be smaller than the value determined by the Fresnel zone limit:

$$W = \sqrt{\lambda L_{IDT} |1+\gamma|},$$

where γ is the anisotropy parameter.

The length of the transducer ring resonator is the circumference length: $L_{IDT} = 2\pi R,$ where R is the middle radius of the ring.

The aperture will be equal to:

$$W = \sqrt{(v/f_{op}) 2\pi R |1+\gamma|} = M\sqrt{R},$$

where $M = \sqrt{(v/f_{op}) 2\pi |1+\gamma|}$. The maximum aperture corresponds to the maximum SAW speed, so M_{max} is achieved at v_{max}. The maximum phase velocity of the surface wave in the quartz ST-cut is 3569.53 m/s, $\gamma = +0.378$. In the niobate lithium YX-128°-cut, the maximum phase velocity is 3739.2 m/s, $\gamma = -0.37$. Hence $W > 0.009\sqrt{R}$ for quartz, $W > 0.006\sqrt{R}$ for lithium niobate. If for both materials $M_{max} = 0.01$, then $W > 0.01\sqrt{R}$.

In the IDT, the aperture is $W = (R_2 - R_1)$. Considering that it is much smaller than the average ra-

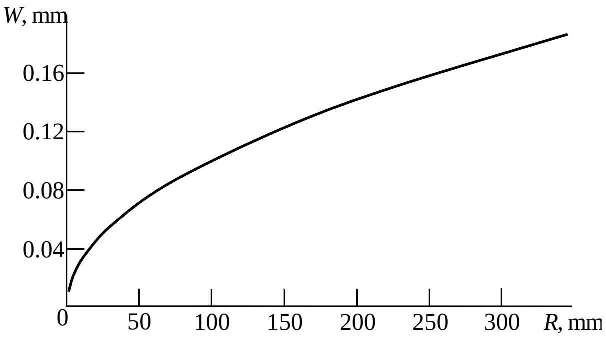


Fig. 7. The dependence of the IDT aperture on the average ring radius

dius $R = (R_2 - R_1)/2$, the ring resonator aperture requirement can be obtained:

$$R \gg W > 0.01\sqrt{R}.$$

The dependency of the IDT aperture on the ring radius is shown in Fig. 7. This curve is the limit of the minimum aperture value relative to the radius of the ring resonator.

Obviously, the amplitude-frequency response of the transducer should have a narrow peak for better information acquisition. However, the periods of IDT topology are flabellate: the distance between the symmetry axes of the pins changes monotonically along its width, which expands the amplitude-frequency response (AFR) employing a resonator topology.

Although the SAW phase velocity on the anisotropic material is variable, it can be assumed that the velocity is constant and known at each period of the topology since the resonator is non-equidistant. Then the AFR width:

$$\Delta\omega = f_{\text{out}} - f_{\text{int}},$$

where

$$f_{\text{out}} = v_{\text{m.s}}/L_{\text{out}}, \quad f_{\text{int}} = v_{\text{m.s}}/L_{\text{int}}$$

– SAW frequency near the outer and inner radius, respectively, and (L_{out}, L_{int} – the width of the topology period near the inner and outer radius, respectively, see Fig. 6, *c*).

Due to the small width of the topology period compared to the length L of the transducer, let us equate its arc length with the corresponding radius:

$$L_{\text{int}} = \theta_{\text{p}} R_1; \quad L_{\text{out}} = \theta_{\text{p}} R_2,$$

where θ_{p} – угловой период. Тогда

$$\Delta\omega = f_{\text{op}} \frac{R_2 - R_1}{R} = f_{\text{op}} \frac{W}{R}$$

and a condition for a narrow peak of AFR: $W/R \to \min$.

Calculation results. Dynamic range. Deformation and internal stress values were converted into sensor output values for all proposed size / material ratios. Fig. 8 shows the output characteristics for the SE made of two materials and four different size ratios: the square of the radius to the SE thickness.

Table 1 presents the results of the calculations:

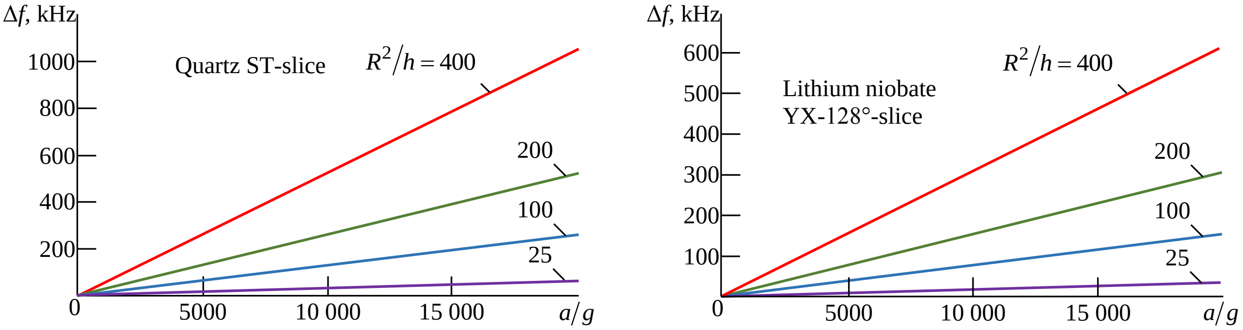


Fig. 8. The output characteristics of the sensing elements

Table 1. Characteristics of MMA on SAW

Parameter	R^2/h, mm			
	25	100	200	400
ST-cut quartz				
Scale factor (differential mode), kHz/*g*	0.0063	0.0259	0.0523	0.1053
Measured acceleration range, *g*	±200 or more	±200 or more	±200 or more	±200 or more
Sensitivity threshold, *g*	68	17	9	4
YX-128°-cut lithium niobate				
Scale factor (differential mode), kHz/*g*	0.0035	0.0151	0.0304	0.0612
Measured acceleration range, *g*	±200 or more	±200 or more	±200 or more	±200 or more
Sensitivity threshold, *g*	120	29	14	7

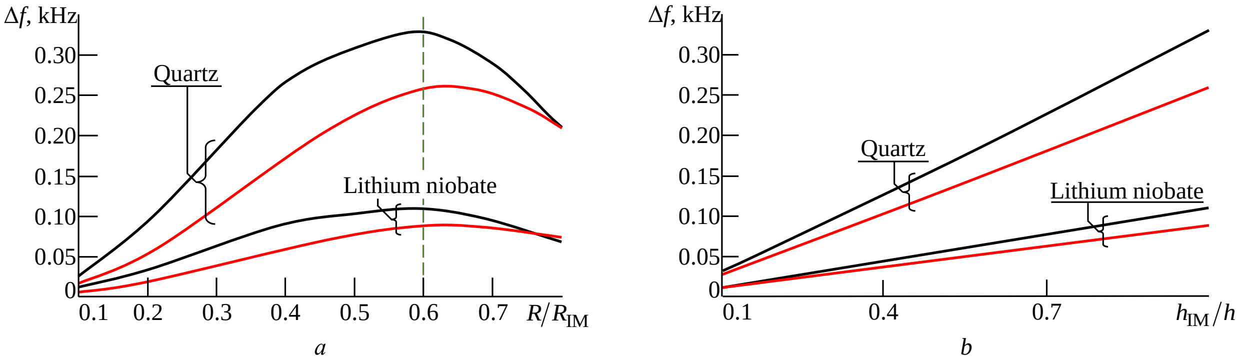


Fig. 9. Dependency of the frequency shift for the studied SE on the ratio of the plate radius and the IM radius (*a*) and on the ratio of IM to the SE height (*b*).
Black curves - near SE attachment; red curves - near IM attachment

scale ratios in differential mode, ranges of measured accelerations, sensitivity thresholds.

The model experiment has shown that at SE loading by IM of the cylindrical form placed on SE coaxially on the *z*-axis (see Fig. 5, *b*), IDT sensitivity increases. At the same time, with the growth of IM, the frequency increment also increases. In this connection, an analysis of SE characteristics in the stress-strain IM state was carried out.

Under the same conditions for the two materials of the plate, the maximum sensitivity is observed if $R_{\text{IM}} < H$ (where R_{IM} – the IM radius; H – the IM height) and the ratio $R_{\text{IM}}/R < 1,$ and the zone of the highest sensitivity of the element shifts to the place of attachment and reaches its maximum at $R_{\text{IM}}/R = 3/5,$ after which there is a decrease (Fig. 9, *a*).

Thus, the IM radius should be 60% of the SE radius. On the contrary, the dependency of sensitivity on the ratio of SE and IM heights (Fig. 9, *b*) has no extreme. Therefore, the IM height is limited only by the expediency and design of the device.

It can be concluded from the described results that it is recommended to provide a higher sensitivity threshold of the sensor built with both ST-cut quartz and YX-128°-cut lithium niobate when using the IM:

– the location of the ring resonator near the SE attachment;

– the ratio of the IM radius to the plate radius $R_{\text{IM}}/R = 3/5.$

Having obtained the optimal IM size (the optimal size is the size at which the maximum SE sensitivity is achieved) and determined the sensitivity zone, it is possible to estimate the dynamic range.

Thus, the placement of the resonator topology on the opposite sides of the SE, as well as on the circumference and near the place of SE attachment to the body, together with the location of the cylindrical IM in the centre of the SE, ensuring the ratio of the IM radius to the radius of the plate is equal to 3/5, leads to an increase in the threshold sensitivity.

Similar to Table 1, Table 2 presents the results of calculations for the IDT with an SE in the stress-strain inertial state at the optimal size of the IM for each material, as well as the location of the resonator in the zone of highest sensitivity.

The results of converting the internal voltages into the sensor output signal values with an SE in the stress-strain state are shown in Fig. 10.

Based on the results of this work, a flowchart of the method of calculation of the MMA on SAWs with a ring resonator on anisotropic material is proposed (Fig. 11).

Table 2. Characteristics of the MMA on SAW with sensing element in the tense deformed state

Parameter	R^2/h, mm			
	25	100	200	400
ST-cut quartz				
Scale factor (differential mode), kHz/*g*	1.48	6.69	13.81	27.58
Measured acceleration range, *g*	±200 or more	±200 or more	±177	±95
Sensitivity threshold, *g*	0.29	0.063	0.031	0.016
YX-128°-cut lithium niobate				
Scale factor (differential mode), kHz/*g*	0.39	1.73	3.70	7.43
Measured acceleration range, *g*	±200 or more	±200 or more	±167	±84
Sensitivity threshold, *g*	1.08	0.24	0.11	0.06

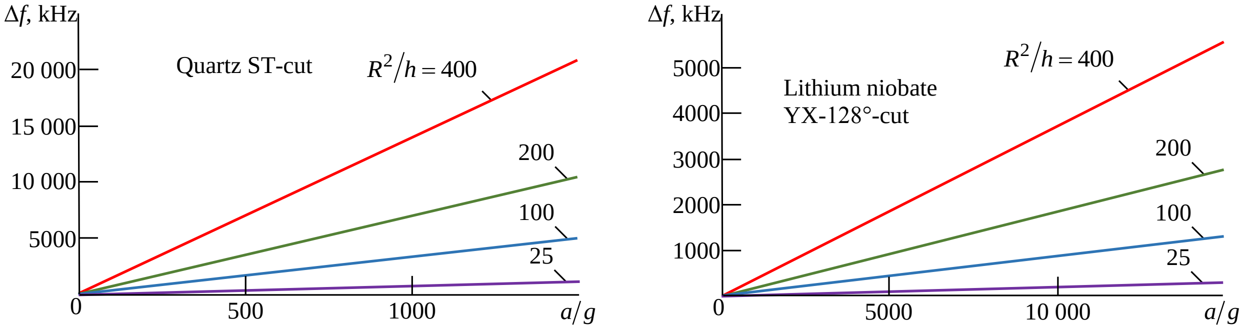


Fig. 10. Output characteristics of the sensing element in in the tense deformed state

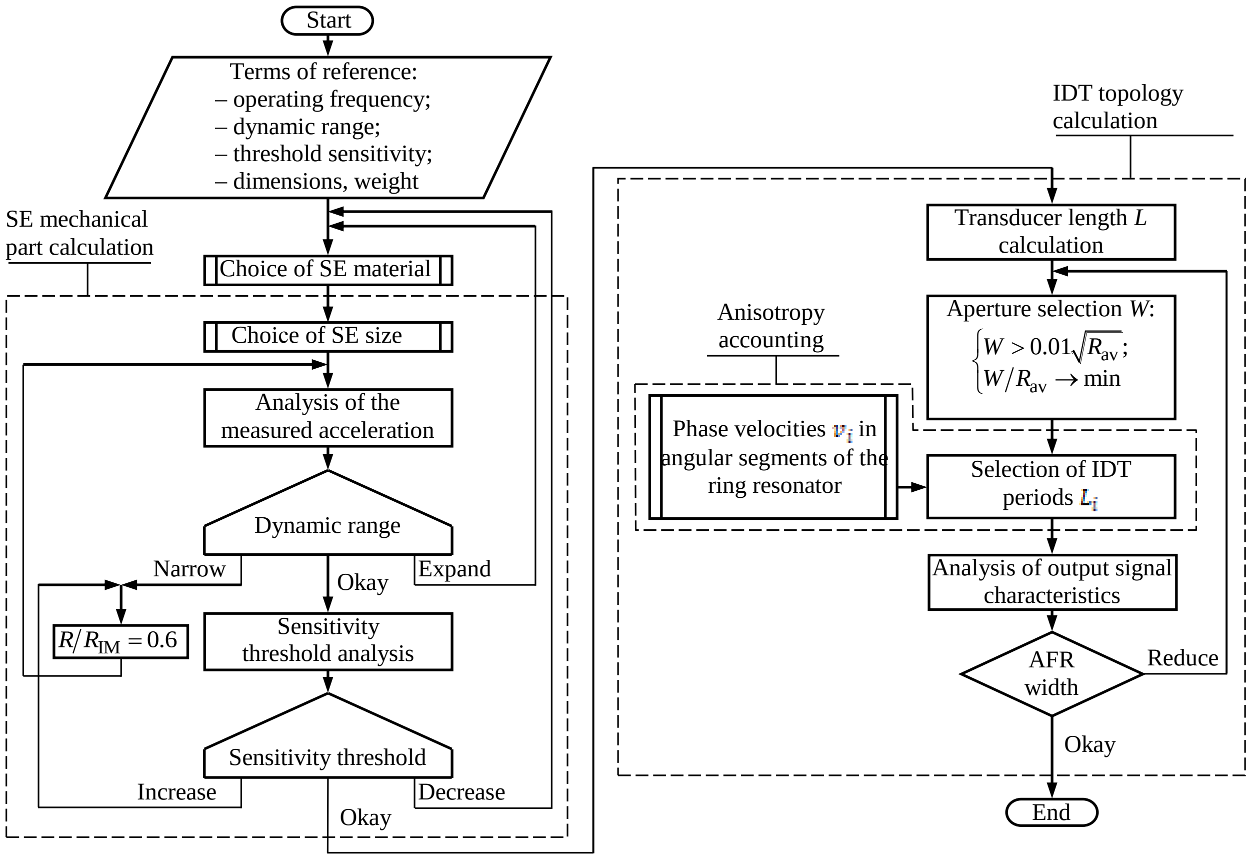


Fig. 11. Flowchart of the calculation method for MMA on SAW with a ring resonator using an anisotropic material

The method breaks down the calculation into 2 consecutive steps: calculation of the mechanical part of the SE and calculation of the IDT topology. First, it is required to set the necessary conditions: the operating frequency of the device, as well as its dynamic range, threshold sensitivity, dimensions and weight. Then it is necessary to select the SE material and size, as well as calculate the dynamic range. The dynamic range can be extended by selecting other materials or the size of the SE; to narrow it down, an IM can be added.

The next step is to perform a sensitivity threshold analysis, which can be increased by loading the IM sensing element. Here it is advisable to proceed to the calculation of the IDT topology following the calculation of the mechanical part of the SE, since the length of the transducer depends on its result. The quality of the output signal depends on the aperture and IDT period calculations, which are consequently the most critical steps in the design process.

Conclusion. In this work, the authors investigated the materials for the SE of the MMA on SAWs: ST-cut quartz and YX-128°-cut lithium niobate. The analysis of substrate materials to be used as a part of the design of the MMA on SAWs has shown that an SE from quartz ST-cut has a wider range of measured accelerations and a higher sensitivity threshold than a YX-128°-cut lithium niobate SE with all other conditions being equal.

To raise the sensitivity threshold, it is necessary to place the IDT resonator topology on the opposite sides of the SE, on the circumference and close to the place of fixing the SE to the body, as well as to load the SE by cylindrical IM, located coaxially on the vertical with the SE. The ratio of the IM radius to the plate radius must be 3/5.

In order to obtain the narrowest peak of the amplitude-frequency response of the SE accelerometer resonator, it is necessary to consider the anisotropy of the SE material by the non-equidistance of the interdigital transducer. The following conditions must be met when designing the IDT: $R_{\text{av}} \gg W > 0.01\sqrt{R_{\text{av}}}$; $W/R_{\text{av}} \to \min$.

Authors' contribution

Dmitry P. Lukyanov, a review of the use of MMA on SAW as part of a railway diagnostic system; substantiation of the principle of building MMA on SAW.

Alexander M. Boronakhin, a review of the use of MMA on SAW as part of a railway diagnostic system; formulation of technical requirements for MMA on SAW, taking into account operating conditions as part of the diagnostic system.

Sergey Yu. Shevchenko, review of existing MEMS; fundamentals of the concept of building MMA on SAW.

Mariya A. Khivrich, the concept of building MMA on SAW with a ring resonator on anisotropic material; calculations; block diagram; output characteristic.

Temurmalik A. Amirov, review of existing MEMS.

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Лукьянов Дмитрий Павлович – обзор использования ММА на ПАВ в составе системы диагностики железной дороги; обоснование принципа построения ММА на ПАВ.

Боронахин Александр Михайлович – обзор использования ММА на ПАВ в составе системы диагностики железной дороги; формулировка технических требований к ММА на ПАВ с учетом условий эксплуатации в составе системы диагностики.

Шевченко Сергей Юрьевич – обзор существующих МЭМС; основы концепции построения ММА на ПАВ.

Хиврич Мария Александровна – концепция построения ММА на ПАВ с кольцевым резонатором на анизотропном материале; расчеты; блок-схема; выходная характеристика.

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