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

Приборы и системы измерения на основе акустических, оптических и радиоволн

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ANALYSIS OF ACOUSTIC PATH TRANSMISSION FACTOR FOR ANGULAR VELOCITY SENSOR[1]

Abstract. *The change in characteristics of ultrasonic waves' transmittion in solid rotating media is the basis for the operation of acoustic angular velocity sensor. The transmission coefficient of the sensing element (SE) of the acoustic path deter-mines the level of angular velocity sensor informative signal based on detecting changes in characteristics of bulk acoustic waves in solid media. In this regard, the efforts aimed at obtaining maximum transmission coefficient are relevant and represent an important stage in the design of such devices. The sensitive element of the acoustic path consists of radiating and receiving plate piezoelectric transducers, propagation medium (acoustic duct), contact layers and electrical load. The coefficient is identical to the path of ultrasonic delay lines on bulk acoustic waves. Although, many sources present the theoretical analysis of the path of this type, they carry out the analysis in so-called one-dimensional approximation, i.e. they perform the analysis without taking into account the limited transverse dimensions, whereas the path of the sensing element should have limited lateral dimensions, which can affect the value of transmission coefficient. The above-mentioned sources do not present the results of experiments. Thus, it is necessary to conduct a complex of simulation and experiments to analyze the acoustic path transmission coefficient of the angular velocity sensor. Authors of the paper developed a path-modeling program in Mathcad software to perform simulation. For implementation of the experiment, authors created the installation, as well as a number of proto-types with transducers made of piezoelectric quartz and piezoelectric ceramics. The results demonstrate that fundamental statements developed for one-dimensional approximation one can use to determine the transmission coefficient of the acoustic path with limited dimensions. Besides, the use of the matched electrical load gives the opportunity to increase the transmission coefficient. For example, in case of Y-cut piezoelectric quartz converter prototype the increase reached 20 dB.*

Key words: ultrasound waves, acoustic path, transmission coefficient, angular velocity sensor

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АНАЛИЗ КОЭФФИЦИЕНТА ПЕРЕДАЧИ АКУСТИЧЕСКОГО ТРАКТА ДАТЧИКА УГЛОВОЙ СКОРОСТИ

Аннотация. *Изменение характеристик ультразвуковых волн, распространяющихся в твердых вращающихся средах, лежит в основе функционирования акустических датчиков угловой скорости. Уровень информа-*

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тивного сигнала зависит от коэффициента передачи акустического тракта чувствительного элемента (ЧЭ) датчика такого типа, в связи с чем актуальны работы по достижению максимального коэффициента передачи. Акустический тракт ЧЭ на объемных волнах состоит из излучающего и приемного пластинчатых пьезопреобразователей, среды распространения (звукопровода), контактных слоев и электрической нагрузки. Он идентичен тракту ультразвуковых линий задержки. Теоретический анализ характеристик трактов такого типа широко представлен в литературе, однако анализ базируется на решении систем волновых уравнений в одномерном приближении. В этом случае расчеты выполняются без учета ограниченности поперечных размеров. На практике тракт ЧЭ должен иметь ограниченные поперечные размеры, которые могут повлиять на значение коэффициента передачи. Описания экспериментальных исследований в литературе не приводятся. Таким образом, потребовалось провести комплекс теоретических и экспериментальных исследований по анализу коэффициента передачи акустического тракта датчика угловой скорости. Для теоретического анализа разработана моделирующая тракт программа в системе Mathcad. Для экспериментальных исследований создана установка и изготовлен ряд макетов с преобразователями из пьезокварца и пьезокерамики. В результате показано, что теоретические положения, разработанные для одномерного приближения, могут применяться для определения коэффициента передачи акустического тракта ограниченных размеров. Кроме того, использование согласованной электрической нагрузки позволяет увеличить коэффициент передачи. Например, для макета с преобразователями из пьезокварца Y-среза это увеличение составило 20 дБ.

Ключевые слова: ультразвуковые волны, акустический тракт, коэффициент передачи, датчик угловой скорости

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Introduction. Studies of the possibility of using bulk acoustic waves (BAW) dissemination features in rotating solid medium for further creation of angular velocity sensors (AVS) are relevant both, in fundamental [1]–[4] and in practical terms [5]–[7].

Researchers of the Department of Electrical Acoustics and Ultrasonic Engineering of St. Petersburg Electrotechnical University "LETI" proposed a number of concepts for construction of AVS on BAW [5]–[7] within the frames of the studies carried out at the department. The solid-state acoustic duct (AD) presents the sensing element (SE) (Fig. 1) of the unit. On the opposite ends of the duct, locate ultrasonic vibrations radiating piezoelectric plate (Ra) and receiving piezoelectric plate (Re) with d_{ra} and d_{re} thicknesses respectively. The contact layers (CL) ensure the transfer of these oscillations between Ra and AD, and AD and Re.

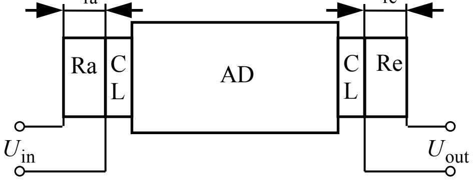

Fig. 1. Sensing Element Diagram

Researcher can determine the informative AVS output signal, regardless the proposed concepts, by the following correlation:

$$U_{\text{out}} = U_{\text{in}} K_{\text{g}} K_{\text{ac}} \Omega,$$

where U_{in} – voltage applied to Ra; K_{g} – transmission coefficient of the gyroscopic component, determined by the concept of building the sensor [6]; K_{ac} – transmission coefficient of the acoustic path of the sensor; Ω – angular velocity of rotation of the SE.

K_{ac} is largely determined by the properties of structural elements of SE: materials and the value of the resonant frequency transducers, the material and thickness of the CL, as well as the parameters of the electrical load. Thus, studies aimed to optimize the design of the acoustic path, providing the maximum transmission coefficient, are an integral part of the work on the creation of the considered AVS type. Researchers use piezoelectric plate transducers for the emission and reception of ultrasonic waves in the megahertz frequency range. Transducers of this type are widely used in flaw detection, ultrasonic thickness testing, medical diagnostics, studies of the physical and chemical properties of materials, as well as in acoustic electronics devices [8]. The acoustic system of the AVS is similar to the path of the ultrasonic delay line (UDL).

Researchers of the Department of Electrical Acoustics and Ultrasonic Engineering of St. Petersburg Electrotechnical University "LETI" carried out studies on the analysis of factors affecting the transmission coefficient of the acoustic path for a long time [9]–[16]. The main goal of the research was to optimize the constructive elements of the converter, taking into account the effect of the CL and electrical circuits on the transmission coefficient.

The performed works relate both, to the field of flaw detection [9]–[11] and to the task of the UDL design optimization [12]–[16]. The work [9] shows the expressions describing the transmission coefficient for a multilayer transducer consisting of the piezoelectric plate, the damper, and the number of matching layers.

One should note that the results of the obtained theoretical correlation are for the so-called one-dimensional approximation, which means, that the value does not take into account the limited transverse dimensions of the propagation medium and converters. The work [10] describes the possibility of constructing a consistent piezoelectric ceramic transducer, the sensitivity of which does not depend on the thickness of the CL. The results of simulation and experiments performed show that sensitivity of Ra made from piezoelectric ceramics is 20 times higher than one that quartz transducer has.

The work [12] describes studies on UDL bandwidth and solves the problem of ensuring uniform frequency response and low acoustic absorption in the acoustic duct. The work shows that in case of CL presence, the maximum of the transmission coefficient is located above the anti-resonant frequency of the X-cut of the piezoelectric quartz transducer. The work also studies the electrical load in the form of electric oscillatory circuit effect on the value of the pass band. In case of the CL absence, the resonant properties of the oscillating circuit reach a peak. With the thickness of the CL equal to 0.02 of Ra and Re thickness, the frequency dependence $K_{\mathrm{ac}}(f)$ has two peaks, and the pass band increases markedly. The resonant properties of the circuit in this case are less noticeable. The further increase of the CL thickness is inexpedient, since the resonant properties of the contour effect slightly, and the mechanical resonance in the "piezoelectric plate on CL" system effects sufficiently. Works [12], [14] observe similar issues for the Re of the *Y*-cut. The obtained results are consistent with previous research. The work [14] describes the entire system of waves in piezoelectric plates, CL and AD in radiation and reception modes. The work [16] gives the analysis of the oscillatory systems of the piezoelectric transducers of ultrasonic flaw detectors, as well as the basic correlations required for simulation and design of the oscillatory systems of such transducers.

A large number of works devoted to obtaining the optimal characteristics of the acoustic path confirm the relevance of the research. However, it is obligatory to note the following:

1. The works use expressions for the analysis of the acoustic path obtained for the so-called one-dimensional approximation, what means, without taking into account the limited transverse dimensions of the propagation medium and transducers, while the SE of the AVS has limited dimensions.

2. The majority of the listed works present the results of fundamental research, which do not have reliable experimental confirmation. In this regard, the data obtained from the experimental studies, and the conditions of the experiments are of greatest interest.

3. In most cases, the purpose of the analysis was to achieve a wide bandwidth of the acoustic path, therefore there was a requirement to use short pulses which provide high resolution (transducers converters), as well as to provide a bigger information capacity of the UDL. AVS on BAW use the pulse mode operation. Due to the condition of the standing waves formation absence, the pulse duration should be less twice times than the pulse passing time through the acoustic duct. This condition enables the sufficiently longer pulse duration and does not impose high demands to the bandwidth.

In this regard, it became necessary to conduct a set of experimental studies to determine the influence of the structural elements of the AVS SE acoustic path on the transmission coefficient. In addition, authors carried out the study of the limited transverse dimensions effect of the acoustic path on K_{ac} to assess the admissibility of the one-dimensional approximation. In the field of flaw detection, the propagation medium is considered semi-infinite, its' dimensions are bigger than the length of the ultrasonic wave. Therefore, researchers did not carry out the studies of this kind before. In the experiments carried out by the authors of this article, the prototypes have limited dimensions approaching to the dimensions of the SE of the designed AVS.

Analysis of the transmission coefficient of the acoustic path. Fig. 2. Represents the investigated AVS with SE path. Along with the SE, the diagram shows: R_{g} – the output resistance of the generator; C_{re} – the capacity of Re and external electrical circuit; L – the inductance of the external circuit; R – the load resistance.

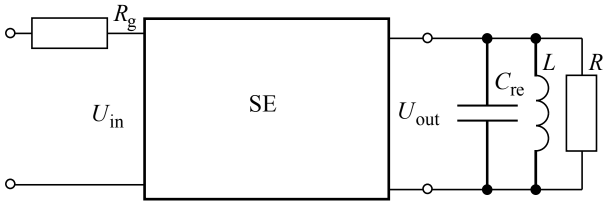

Fig. 2. The path of the angular velocity sensor with a sensitive element

The considered transmission coefficient of the $K_{ac} = U_{out}/U_{in}$ system is a multivariable parameter function, since it depends on a number of system characteristics: CL thickness, Ra and Re resonant frequencies, quality of the electric circuit at the output, acoustic impedances of the materials included in the system [16].

In order to determine K_{ac}, authors introduce the notation of elements' acoustic impedances of SE z_{ra}, z_{CL}, z_{AD} и z_{re} for Ra, CL, AD and Re, respectively, as well as acoustic impedances of the electric wave input transducer into acoustic wave $z_{0ra} = z_{ra} j \operatorname{tg} x_{ra}$ and output transducer of acoustic wave into electrical wave $z_{0re} = z_{re} j \operatorname{tg} x_{re}$[2]. The propagation of the acoustic wave over individual elements of the SE can be described with the introduction of the concept of the acoustic thickness of these elements $x_{ra} = k_{ra} d_{ra}$, $x_{CL} = k_{CL} d_{CL}$ and $x_{re} = k_{re} h_{re}$ for Ra, CL and Re respectively, ($k_I = 2\pi f / c_I$, $I \in \{\text{Ra, CL, Re}\}$ – are the radian wave numbers; c_I – the speed of the acoustic wave). Authors also introduce the concepts of impedance correlations $\alpha_{I|II} = z_I / z_{II}$, $I, II \in \{0, \text{Ra, CL, AD, Re}\}$.

K_{ac} is determined by the product of the amplitude conversion factors of the electric wave to the ultrasonic amplitude in the radiation mode K_{ra} and inverse conversion in the reception mode K_{re}, provided by the equality of waves displacement amplitudes (oscillatory velocity) at the boundaries of the Ra and Re:

$$K_{ac}(f) = K_{ra} K_{re} =$$
$$= \frac{2C_{re} f_{a.ra}}{Y + j2\pi f C_{re}} \frac{2k_{c.ra}^2 k_{c.re}^2 z_{re}}{z_{AD}} \sqrt{\frac{\varepsilon_{ra}\rho_{ra}}{\varepsilon_{ra}\rho_{ra}}} F_{ra}(x_{ra}) F_{re}(x_{re}),$$

where f – the frequency of ultrasonic vibrations; $f_{a.ra}$ – the frequency of the Re anti-resonance; Y – the conductivity of the load represented by the oscillating circuit $C_{re}L$; $k_{c.ra}$, $k_{c.re}$ – coefficients of electrical and mechanical coupling of Ra and Re respectively; ε_{ra}, ε_{re} – dielectric permeability of Ra and Re materials respectively; ρ_{ra}, ρ_{re} – density of Ra and Re materials respectively; F_{ra}, F_{re} – frequency-dependent parts of the Ra and Re transmission coefficients respectively.

Authors determine the frequency-dependent portions of radiation transmission coefficients by the following formulas:

$$F_{ra}(x_{ra}) = \left[1 - \cos(x_{ra}) - j\alpha_{0|ra} \sin(x_{ra})\right] / \Delta_{ra};$$

$$F_{re}(x_{re}) = \left[1 - \cos(x_{re}) - j\alpha_{re|0} \sin(x_{re})\right] / \Delta_{re}.$$

The denominators are determined as:

$$\Delta_{ra} = Q\cos(x_{ra}) + jR_1 \sin(x_{ra}) -$$
$$- j\left(k_{c.ra}^2 / x_{ra}\right)\left\{2R_0\left[1 - \cos(x_{ra})\right] - jQ\sin(x_{ra})\right\};$$

$$\Delta_{re} = Q\cos(x_{re}) + jR_1 \sin(x_{re}) -$$
$$- j\left(k_{c.re}^2 B / x_{re}\right)\left\{2R_0\left[1 - \cos(x_{re})\right] - jQ\sin(x_{re})\right\},$$

where

$$Q = \left(1 + \alpha_{0|AD}\right)\cos(x_{CL}) + j\left(\alpha_{0|CL} + \alpha_{CL|AD}\right)\sin(x_{CL});$$

$$R_1 = \left(\alpha_{0|ra} + \alpha_{ra|AD}\right)\cos(x_{CL}) +$$
$$+ j\left(\alpha_{ra|CL} + \alpha_{0|ra}\alpha_{CL|AD}\right)\sin(x_{CL});$$

$$R_0 = \alpha_{ra|AD}\cos(x_{CL}) + j\alpha_{ra|CL}\sin(x_{CL})$$

– coefficients determined by the circuit path $B = Y / \left(Y + j2\pi f C_{re}\right)$.

To carry out the analysis authors developed a program in "MathCad" system. The program gives the opportunity to carry out the analyses of the acoustic path in different modes of Re. The zero conductivity of the external circuit Y ensures the idling mode. The presentation of the conductivity Y in the form of a parallel connection C_{re} and L created a load on the resonant circuit. The authors did not take into account the losses due to diffraction divergence in the theoretical model, since the Ra operates in the near zone.

The experiment. Fig. 3 presents the block diagram of the installation for the experimental determination of the coefficient K_{ac} under investigation,

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[2] Authors do not take into account the influence of dampers and rear loads on the mentioned in [16] transducers due to the narrowband nature of the considered problem.

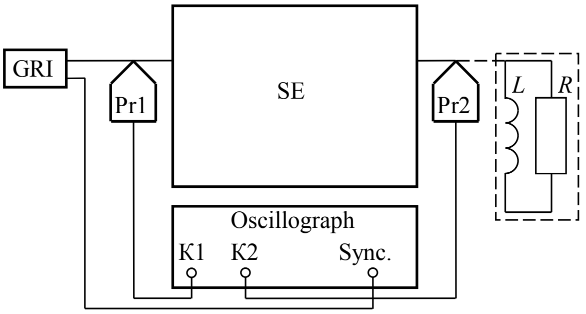

Fig. 3. Test Facility Block Diagram

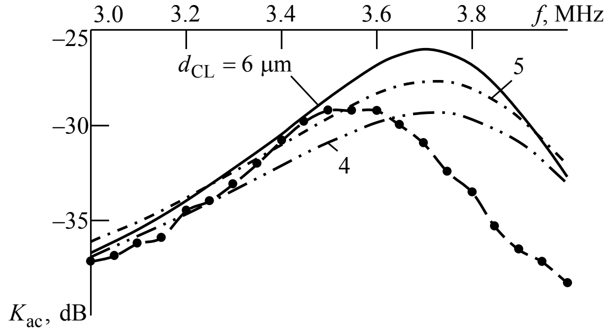

Fig. 4. Model 1 Transfer Factor. Idle running

where GRI is a generator of radio pulses; Pr1, Pr 2 – oscillographic probes (input capacitance 16 pF, input resistance 10 MΩ); K1, K2 – signal inputs, Sync – sync signal input. For conduction of experimental study authors of the article used GRI AKIP 3402, a Tektronix oscilloscope TDS 1002 V. Authors used salol material for CL, which provides the possibility of multiple gluing of piezoelectric transducers.

For the implementation of the experiments, authors took a number of identical acoustic ducts made of fused quartz and created acoustic paths on their basis. The table below shows the parameters of the mentioned acoustic paths.

Further authors present the results of a comparative analysis of the results of fundamental and applied research of these prototypes.

The prototype 1. Fig. 4 shows the frequency dependences $K_{ac}(f)$ of the first prototype in idle mode for several values of the CL thickness d_{CL}. Authors obtained the results presented with the dashed curve during the experiments. The analysis showed that a change in the CL thickness in the actually achievable limits leads to a change in the value K_{ac} within 6 dB. Authors observed the best convergence of the simulation and experimental results at thicknesses of the CL $d_{CL} = 4$ μm. On this basis authors can conclude that the equivalent thickness of the CL of the experimental sample is 4 μm.

Fig. 5 shows the analysis of the prototype operation in the oscillating circuit load mode with different values of inductance. Black curves show the results of the draft simulation results, gray – the results of experiments.

Curves for $L = 300$, 220 and 120 μH have two maxima. The first corresponds to the resonant frequency of the electric circuit, the second – to the mechanical system. At L = 82 μH there occurs the same resonance, since the frequencies of the contour and Re locate close to each other. The maximum value of the transmission coefficient is equal to – 6 dB, which is 20 dB higher than in case of the electrical load absence (Fig. 4).

Since, the capacity of the Re piezoelectric quartz is not significant, it is necessary to take into account the input capacity of the oscilloscope probe $C_{pr} = 16$ pF. Fig. 6 shows the diagram of measuring the resonant frequency of vibration circuit formed by

Model Parameters

Acoustic Duct Dimensions	Model				
	1	2		3	
Length, mm	23				
Diameter, mm	20				
Parameter	Radiating piezoplates/ receiving piezoplate	Radiating piezoplates	Receiving piezoplate	Radiating piezoplates	Receiving piezoplate
Material	Piezokvarts Y – cut	Piezoceramics LZT-19			
Form	Rectangular	Round			
Length and width, mm	10×16	–	–	–	–
Diameter, mm	–	15.7	15.7	15	15
Thickness, mm	0.6	0.95	1.0	0.32	0.32
Resonance Frequency f_p, MHz	3.25	2.0	1.94	5.9	6.25
Antiresonant Frequency f_a, MHz	3.26	2.33	2.17	7.00	7.3

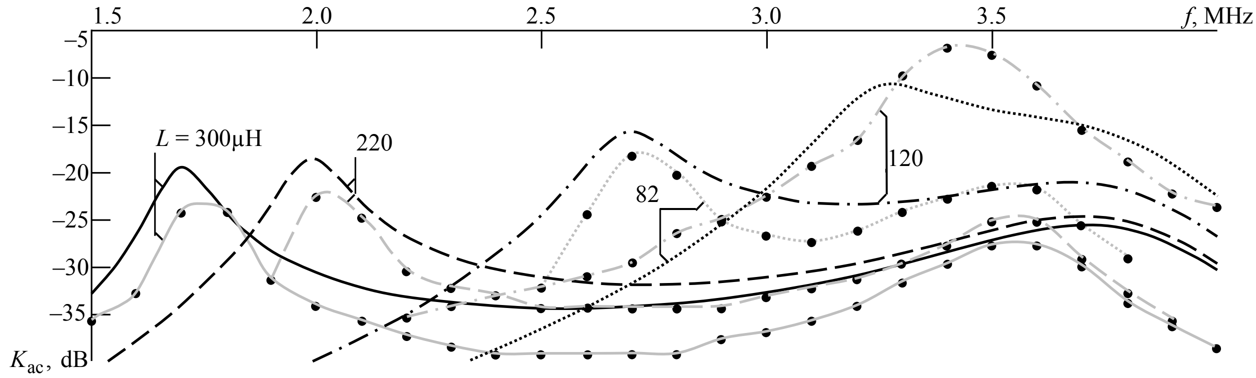

Fig. 5. Model 1Transfer Factor. Electrical Oscillating Circuit Load Operation

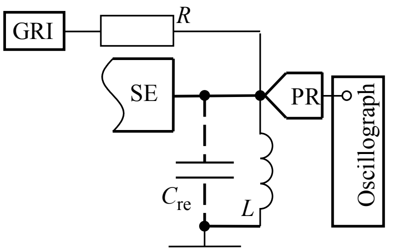

Fig. 6. Circuit Resonance Frequency Measuring Set Block Diagram

the capacity C_{re} with the regard to C_{pr} and the inductor of a known type.

In order to assess the parameters of the measuring stand, authors carried out the determination of the total capacity at R = 15 kΩ, L = 82 μH. The resonant frequency of the circuit is equal to $f_r = 3.3$ MHz, so the total capacitance has the value is equal to:

$$C_{\Sigma} = \frac{1}{(2\pi f_r)^2 L} = 29 \text{ pF}.$$

The prototype 2. Authors used plate transducers LZT-19 made from piezoelectric ceramics. Fig. 7 shows the results of studies of the frequency response in idle mode in for several values of CL thickness d_{CL}. The dashed curve demonstrates the results obtained during the experiments. The presented dependences show that for this prototype, there is no such significant change in the transmission coefficient in case of different CL thickness. The forms of the experimental and simulated curves coincide. The maximum value of K_{ac}, obtained during the experiment was equal to 0 dB, which is 30 dB higher than the corresponding value for the first prototype with piezoelectric quartz transducers (see Fig. 4).

Fig. 8 shows the results of the influence of the oscillatory circuit on K_{ac}. Authors constructed the curves representing the simulation results at CL thickness of 5 μm for several specified values of the resonant frequency of the circuit. The dashed curve presents the results of the experiment. The graphs show that the maximum value of the obtained transmission coefficient during the experiment is equal to 3 dB. Thus, the electrical load effect on K_{ac} is not so significant for a piezoelectric ceramic transducer. In addition, a distinctive feature of the path with transducers made from piezoelectric ceramics is the appearance of a dip at the resonant frequency of the oscillatory circuit [16].

The prototype 3. Authors used high-frequency plate transducers LZT-19 made from piezoelectric ceramics. Fig. 9 shows the K_{ac} frequency depend-

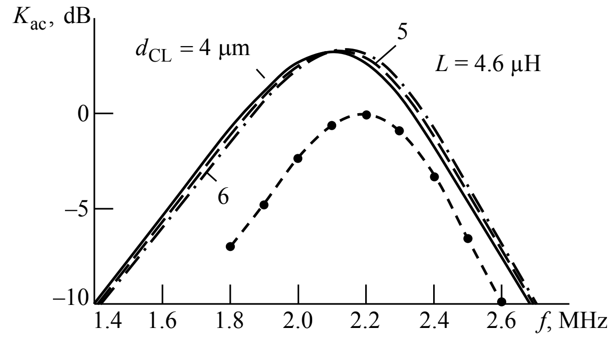

Fig. 7. Model 2Transfer Factor. Idle running

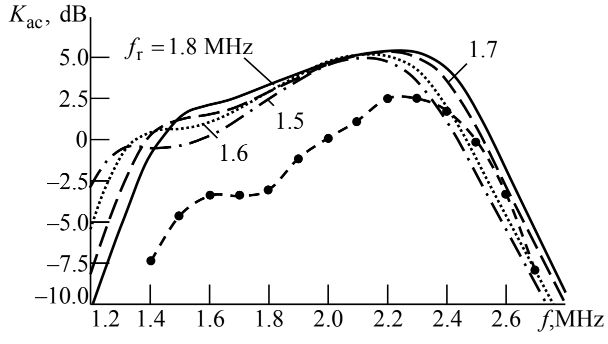

Fig. 8. Model 2 Transfer Factor. Electrical Oscillating Circuit Load Operation

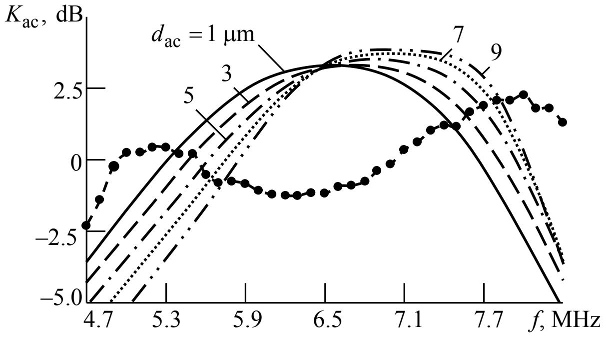

Fig. 9. Model 3 Transfer Factor. Idle running

ences obtained from simulation for the thickness of the CL d_{CL} in the range of 1...9 μm. The dashed curve demonstrates the results obtained during the experiments. The appearance of the oscillatory circuit formed by the parasitic inductance of electric circuits and the capacity of the Re explains a noticeable difference in the form of dependence.

Research results show that for the prototype with *Y-cut* piezoelectric quartz transducers (prototype 1), the maximum value of the transmission coefficient in idle mode is equal to minus 30 dB. For the prototype with LZT-19 piezoelectric ceramic transducers (prototype 2), the value obtained during the similar experiment is equal to 0 dB. The indicated experimental results correspond with the results of the previous modeling [9]–[15]. The presence of the oscillating circuit formed by the Re capacitance and the inductance of the external circuit, has a different impact on the maximum value K_{ac} for transducers made from piezoelectric quartz and piezoelectric ceramics. Therefore, from the comparison of experimental dependences presented in Fig. 4 and 5, it follows that for prototype 1, the use of the oscillating circuit with a resonant frequency close to its own resonant frequency Re leads to the increase of the maximum value of K_{ac} equal to 25 dB. For the prototype 2, the presence of oscillating circuit creates a noticeable decrease of the transmission coefficient value of at the circuit resonant frequency [16].

It is necessary to take into account the capacitance of electrical circuits for prototype 1, since the capacity of piezoelectric quartz plate consists of dozens of picofarads, while input capacity of the oscillograph probe $C_{pr} = 16$ pF. In this connection, when adjusting the oscillatory circuit, it is necessary to take into account the total capacitance of electrical circuits and Re.

The experiment shows formation of the oscillatory circuit with a resonant frequency equal to 6.5 MHz in idle mode in case of prototype 3 (the prototype with high-frequency transducers made from the LZT-19 piezoelectric ceramics. This effect is stipulated by the fact that the capacitance of Re made from piezoelectric ceramics has several nanofarads capacity. Therefore, for formation of the oscillatory circuit, parasitic inductance of external electric circuits for tenths of one microhenry is sufficient. Researches should consider this negative effect when developing acoustic paths with high-frequency transducers made of piezoelectric ceramics.

In addition, the work studied the effect of the implicitly specified parameter – the thickness of the CL – on the transfer coefficient. The variation of K_{ac} with varying of CL thickness locates within the frames of 6 dB for the prototype with piezoelectric quartz transducers. Researchers can consider this variation by construction the system of dependencies for different values of the layer thickness. For the prototype with piezoelectric ceramic transducers, researchers can neglect the effect of the CL thickness on the frequency dependence of the transmission coefficient.

Conclusion. The results of simulation and experiments performed show that researchers can apply theory developed for the one-dimensional approximation to calculate the transmission coefficient of paths with limited transverse dimensions.

The difference between experimental and simulation results, determined by the difference between the computational model and the real parameters of the prototype is insignificant in terms of the characteristics of the AVS prototypes.

The implemented studies to determine the design of the acoustic path, providing the maximum K_{ac}, allow developing the optimal design of SE of the angular velocity sensor on bulk acoustic waves. Despite the fact that authors performed the experiments on SE samples with specific sizes, researchers can transfer the results to the models of significantly smaller sizes. It is necessary to maintain the correlation between the dimensions of the Re, AD, Ra and the length of the ultrasound wave, determined by the choice of the operating frequency range.

REFERENCES

1. Schoenberg M., Censor D. Elastic Waves in Rotating Media. Quarterly of Applied Mathematics. 1973, vol. 31, no. 3, pp. 115–125. doi: 10.1090/qam/99708

2. Sarapulov S. A., Ulitko I. A. Rotation Influence on Body Waves in Elastic Medium and Their Use in Solid-State Gyroscopy. *Giroskopiya i navigatsiya* [Gyroscopy and Navigation]. 2001, no. 4, pp. 64–72. (In Russian)

3. Destrade M., Saccomandi G. Some Results on Finite Amplitude Elastic Waves Propagating in Rotating Medium. Acta Mechanica. 2004, no. 173, pp. 19–31. doi: 10.1007/s00707-004-0185-x

4. Khan A., Islam S., Khan M., Siddiqui I. Speed of Longitude and Transverse Plane Elastic Waves in Rotating and Non-Rotating Anisotropic Mediums. World Applied Sciences J. 2011, vol. 15, no. 12, pp. 1761–1769.

5. Durukan Ya., Lutovinov A. I., Peregudov A. N., Shevel'ko M. M. On Characteristics of Waves Propagating in Rotating Medium. *Izvestiya SPbGETU "LETI"* [Proceedings of Saint Petersburg Electrotechnical University]. 2014, no. 8, pp. 57–61. (In Russian)

6. Durukan Ya., Lutovinov A. I., Peregudov A. N., Shevel'ko M. M. On Designability of Rotational Motion Sensors on Bulk Acoustic Waves. *Izvestiya SPbGETU "LETI"* [Proceedings of Saint Petersburg Electrotechnical University]. 2015, no. 10, pp. 69–73. (In Russian)

7. Durukan Ya., Lutovinov A. I., Peregudov A. N., Popkova E. S., Shevelko M. M. The Characteristics of Acoustic Wave Propagation in Rotating Solid-State Media. A Materials of the 2018 IEEE Conf. of Russian Young Researchers in Electrical and Electronic Engineering (ElConRus), Saint Petersburg, Jan. 29 – Febr. 1, 2018. SPb., SPbGETU "LETI" Publ., pp. 461–464. doi: 10.1109 /ElConRus.2018.8317131

8. Domarkas V. I., Kazhis R.-I. Yu. *Kontrol'no-izmeritel'nye p'ezoelektricheskie preobrazovateli* [Piezoelectric Transducers]. Vilnius, Minthis, 1974, 258 p. (In Russian)

9. Ivanov V. E., Merkulov L. G., Yablonik L. M. Study of Ultrasonic Flaw Detector Piezo Transducer. *Zavodskaya laboratoriya* [Factory Laboratory]. 1962, no. 12, pp. 1459–1464. (In Russian)

10. Merkulov L. G., Yablonik L. M. Damped Piezoelectric Transducer Operation in the Presence of Several Intermediate Layers. *Akusticheskii zhurnal* [Acoustic magazine]. 1963, vol. 9, no. 4, pp. 449–459. (In Russian)

11. Yakovlev L. A. On Designability of Approximately Matched Piezoceramic Transducer. *Izvestiya LETI* [Proceedings of Leningrad Electrotechnical Institute]. 1970, no. 89, pp. 163–167. (In Russian)

12. Merkulov L. G., Fedorov V. A., Yakovlev L. A. On Delay Line Bandwidth with Multiple Reflections. *Izvestiya LETI* [Proceedings of Leningrad Electrotechnical Institute].1971, no. 95, pp. 17–22. (In Russian)

13. Merkulov L. G., Fedorov V. A., Yakovlev L. A. Electrical Load Influence on Delay Line Bandwidth with Multiple Reflections. *Izvestiya LETI* [Proceedings of Leningrad Electrotechnical Institute]. 1972, no. 112, pp. 43–47. (In Russian)

14. Yablonik L. M. On Electrical Load Influence on Multilayer Converter Operation. *Akusticheskii zhurnal* [Acoustic magazine].1964, vol. 10, no. 2, pp. 234–238. (In Russian)

15. Merkulov L. G., Fedorov V. A., Yakovlev L. A. Operation of Solid Elastic-Anisotropic Medium Loaded Piezoelectric Transducer. *Akusticheskii zhurnal* [Acoustic magazine]. 1973, vol. 19, no. 1, pp. 53–59. (In Russian)

16. Golubev A. S. *Preobrazovateli ul'trazvukovykh defektoskopov* [Ultrasonic Flaw Detector Transducers] / LETI, Leningrad, 1986, 80 p. (In Russian)

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СПИСОК ЛИТЕРАТУРЫ

1. Schoenberg M., Censor D. Elastic waves in rotating media // Quarterly of Applied Mathematics.1973. Vol. 31, № 3. P. 115–125. doi: 10.1090/qam/99708

2. Сарапулов С. А., Улитко И. А. Влияние вращения на объемные волны в упругой среде и их ис-

пользование в твердотельной гироскопии // Гироскопия и навигация. 2001. № 4. С. 64–72.

3. Destrade M., Saccomandi G. Some results on finite amplitude elastic waves propagating in rotating medium // Acta Mechanica. 2004. № 173. P. 19–31. doi: 10.1007/s00707-004-0185-x

4. Speed of longitude and transverse plane elastic waves in rotating and non-rotating anisotropic mediums / A. Khan, S. Islam, M. Khan, I. Siddiqui // World Applied Sciences J. 2011. Vol. 15, № 12. P. 1761–1769.

5. К вопросу о характеристиках волн, распространяющихся во вращающейся среде / Я. Дурукан, А. И. Лутовинов, А. Н. Перегудов, М. М. Шевелько // Изв. СПбГЭТУ "ЛЭТИ". 2014. № 8. С. 57–61.

6. О возможности построения датчиков вращательного движения на объемных акустических волнах / Я. Дурукан, А. И. Лутовинов, А. Н. Перегудов, М. М. Шевелько // Изв. СПбГЭТУ "ЛЭТИ". 2015. № 10. С. 69–73.

7. The characteristics of acoustic wave propagation in rotating solid-state media / Ya. Durukan, A. I. Lutovinov, A. N. Peregudov, E. S. Popkova, M. M. Shevelko // A Materials of the 2018 IEEE Conf. of Rus. Young Researchers in Electrical and Electronic Engin. (ElConRus), Saint Petersburg, Jan. 29 – Febr. 1, 2018. SPb.: SPbGETU "LETI" Publ. P. 461–464. doi: 10.1109 /ElConRus.2018.8317131

8. Домаркас В. И., Кажис Р.-И. Ю. Контрольно-измерительные пьезоэлектрические преобразователи. Вильнюс: Минтис, 1974, 258 с.

9. Иванов В. Е., Меркулов Л. Г., Яблоник Л. М. Исследование пьезопреобразователя ультразвукового дефектоскопа // Заводская лаборатория. 1962. № 12. С. 1459–1464.

10. Меркулов Л. Г., Яблоник Л. М. Работа демпфированного пьезопреобразователя при наличии нескольких промежуточных слоев // Акустический журн. 1963. Т. 9, № 4. С. 449–459.

11. Яковлев Л. А. О возможности построения приближенно согласованного пьезокерамического преобразователя // Изв. ЛЭТИ. 1970. Вып. 89. С. 163–167.

12. Меркулов Л. Г., Федоров В. А., Яковлев Л. А. О полосе пропускания линии задержки с многократными отражениями // Изв. ЛЭТИ. 1971. Вып. 95. С. 17–22.

13. Меркулов Л. Г., Федоров В. А., Яковлев Л. А. Влияние электрической нагрузки на полосу пропускания линии задержки с многократными отражениями // Изв. ЛЭТИ. 1972. Вып. 112. С. 43–47.

14. Яблоник Л. М. К вопросу о влиянии электрической нагрузки на работу многослойного преобразователя // Акустический журн. 1964. Т. 10, № 2. С. 234–238.

15. Меркулов Л. Г., Федоров В. А., Яковлев Л. А. Работа пьезопреобразователя, нагруженного на твердую упруго-анизотропную среду // Акустический журн. 1973. Т. 19, № 1. С. 53–59.

16. Голубев А. С. Преобразователи ультразвуковых дефектоскопов / ЛЭТИ. Л., 1986. 80 с.

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