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REDUCTION OF TECHNOLOGICAL RISKS OF FLIGHT OPERATION BY ARTIFICIAL FORMATION OF THE BUFFER ZONE TO PENETRATING ACOUSTIC RADIATION

Аналізується можливість зменшення технологічних ризиків від впливу проникаючого акустичного випромінювання на бортову апаратуру льотних виробів. Вивчається найбільш складна, поліагрегатна конструкція поплавкового диференційючого гіроскопа, який знайшов широкого вжитку як пілотажний прилад. Експериментально доведена діалектична єдність переваг поплавкового підвісу для підвищення точності вимірювань і, в той же час, стрімкого росту додаткових похибок в акустичних полях.

Ключові слова: *аберація, зона каустики, хвильове співпадання, буферна зона, поліагрегатна конструкція.*

1. Introduction

Fluctuations in air pressure very often cause oscillations in the body of flight elements and cause, perhaps, most of the irregular vibrations of the fuselage. Random pulsations due to instability of the air flow contain areas that cause intense pressure pulsations near the flight elements.

In the case of acoustic pressures, waves moves with a local sound speed through the environment. However, due to the movement of flight elements, the velocity of the pressure waves on the surface will be determined by the sum of the local velocity of sound and the velocity of flight. And since the latter varies greatly, and the sound waves approach the flight product at different angles, it becomes evident that the velocity of the pressure waves relative to the body of the flight article can take on a variety of meanings.

Let's briefly describe the cause of the appearance of pressure pulsations on the surface of a flight element from the standpoint of the general theory of generation of an acoustic field by an unstable aerodynamic flow. The theory of pressure pulsations originates from two classical works [1, 2]. They note that, in actual conditions, sound is acoustically equivalent to the sound generated in an ideal medium by a system of distributed sources, quadrupoles.

The nature and degree of acoustic impact, as well as the choice of the mechanical design model of disturbed motion, are directly dependent on the ratio of the dimensions of the product and half the length of the sound wave. In that case, when this value is within unity, then the acoustic load is equated to a uniformly distributed, and the design model – to a rigid body on elastic bonds. If the overall size is several times larger than half the length, then the external effect is considered as a wave, and the entire structure is treated as a system with distributed parameters.

The achievements of science in combating against noise of low and medium intensity (not higher than 130 dB) are quite fully reflected in the literature [3–6]. As for the study of the properties of structures under the influence of high-intensity acoustic fields (160...180 dB), they are analyzed in a few publications [7–9], mainly with respect to aircraft structure elements. The issue of the acoustic stability of some types of on-board equipment and their components is discussed in [10].

At present, in the engineering practice of noise isolation of high intensity fields, the same methods and means are used as for acoustic fields of medium and low levels. However, the effectiveness and universality of these methods is quite low. So, for example, passive methods have a number of significant shortcomings, and prospective compensation methods have not been developed at all.

At the same time, the power acoustic loading leads to a qualitatively new state of many structures, on-board electronic equipment and instruments of command and measurement systems. Some of them are in a state of alternating reversible deformations, others are experiencing strains exceeding permissible values, and others – can't function at all in the nominal mode. Scattering of sound energy in structural elements with oscillations of mechanical systems leads to a violation of acoustic stability.

2. The object of research and its technological audit

The object of research is the process of elastic interaction of an ultrasonic beam with a metal bush in the form of two identical lengths and different shell radii, connected at the ends by flat rings, the internal gap between them is filled with liquid. The conditions of radiation of the surface of the outer shell into the liquid of sound waves and the formation on their basis of a zone of increased energy turbulent in structure are analyzed. The conditions for the emission of sound waves into inter-shell spaces are determined with the obligatory fulfillment of the condition of a large wave size of the outer shell surface. The structure of the energy state of the caustic zone, which functions as a buffer zone to external penetrating acoustic radiation, is disclosed.

A certain disadvantage of the proposed technical solution is a certain increase in the mass-dimensional char-

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acteristics of the instrument and the need for additional complementation with an ultrasonic radiator.

3. The aim and objectives of research

The aim of research is semi-realistic implementation of the proposed technical solution using a commercially available two-stage gyroscopic device class ДУСУ2. In addition, it is advisable to perform a comparative analysis of instrument errors in an acoustic medium without a buffer zone and with an artificially formed buffer zone at the resonance level of the wave channel.

To achieve this aim, the following tasks are performed:

1. To construct a calculated model of the phenomenon under the condition of a large wave size of the outer shell.
2. To experimentally investigate the magnitude of the zero shift of the device for the most sensitive incidence angle of radiation and the resulting measurement errors of the instrument.
3. To experimentally investigate the additional errors of the device during the artificial formation of the buffer zone by means of an ultrasonic radiator.
4. To investigate the incidence angle of the ultrasonic radiator, in which the maximum efficiency of the buffer zone is manifested and to calculate the zero offset of the instrument and the error of the instrument with the existing, artificially generated, buffer zone.

4. Research of existing solutions of the problem

In [11], the nature of the manifestation of resonant phenomena in the gimbal of a float two-stage gyroscope in the sound fields of a hypersonic flight is revealed, which is based on a critical change in the permeability of the instrument.

An experimental study of turbulent flow with an open channel between two built-in hemispherical obstacles on the surface in a tandem arrangement is given in [12]. A series of experiments is performed with the combined interaction of the wave current with seven relative intervals:

L/h,

where L is the distance from the center to the center, and h is the obstacle height for the Reynolds number $Re=5.88\times10^4$ (Re=Reynolds number (dimensionless)). The observation is mainly focused on the changes induced in the average components, velocity, intensity of turbulence and the Reynolds displacement stress due to the superposition of surface waves on the surrounding flow and are compared with changes in the flat surface and one hemisphere. The paper also investigates the dominant turbulent fracture events that contribute to the Reynolds displacement stress for different relative depths under the influence of the hemispheres.

The sound insulation of a single-layer wall, due to a spherical wave, is considered in [13]. Theoretically, the sound field of an infinite elastic plate is transmitted when the spherical wave falls and the isolation mechanisms are considered. The displacement of the plate is formulated using the Hankel transform in the space of wave numbers, and the transmitted sound pressure in the far field is obtained by the Rayleigh formula in explicit closed form. The mass law for the incidence of a spherical wave differs from the law of normal plane wave. So, doubling the weight of the wall or frequency gives an increase of 3 dB (of 6 dB for the normal incidence of a plane wave), which is also less than the law of the mass field.

Detailed convective heat transfer is observed on a flat surface where the cylinder is installed in a supersonic flow [14]. During the test, the thermal image of the wall temperature distribution is received by an infrared camera with a constant heat flux on a flat surface. From the information of the measured wall temperature, the heat transfer coefficients are calculated. Shadow chart and oil flow tests are conducted to study the structure of the shock wave and the surface displacement flow around the protruding body, respectively. The entire flow is also modeled numerically. Mach number in flow, total pressure and Reynolds number are about 3.600 kPa and 2.3×10^6 (Re=Reynolds number (dimensionless), respectively. The effect of an approximate flow cylinder is considered in the range from 0° to 30°. It can be seen from the results that in the interaction region of the shock wave/turbulent boundary layer a large increase in heat transfer is observed, and peak heating is manifested especially in the region of repeated attachment of the flow.

In the technique of an ideally selected layer (ISL), an artificial layer is introduced in modeling the wave propagation as a boundary condition, which absorbs all the incident waves without any mapping [15]. It is believed that such layer is impossible because of its complex formation of material. In this paper, a new method of ISL designing for elastic waves is proposed on the basis of transformational elastodynamics and complex coordinate transformation. Applying the method of conformal transformation, the proposed ISL is formulated in terms of conventional constitutive parameters, and then can be easily implemented by functionally graded viscoelastic materials.

The models for calculation of loss of sound transmission on layered composite cylindrical shells on the basis of three-dimensional equations of anisotropic elasticity are presented in [16]. This model includes a multilayer composite cylindrical shell with an infinite length, as well as an air gap, falls on an inclined plane wave and is immersed in a liquid. The equations of motion for each monoclinic anisotropic layer of both walls of a multilayer component of a cylindrical shell are proposed.

An analytical model is considered in [17], which is ideally suited for layers of bending waves within elongated rod designs. The model is based on the methods of transformation of optics. It is considered how this model will work during the harmonious and transitional regime. A detailed comparative analysis is made between bending and longitudinal waves. It is proved that bending waves require special conditions for the solution.

In [18], sound transmission through double walls of a cylindrical shell with porous substrate material in the active zone, which is disturbed by pressure oscillations through external turbulent boundary layers, is investigated. The Bayot model is used to describe a sound wave propagating in a porous material. Three types of structures: forced communications; related – unrelated; bound – unrelated. The spectral power density (SPD) of the kinetic energy of the inner shell is considered for two models of turbulence in the boundary layer of different air gap depths and three types of polyamide foams, respectively.

A computational scheme for the elastic interaction of acoustic radiation with a float gyro is constructed in [19] under operational use in hypersonic motion. It is proved that at low frequencies, much lower than the cut-off frequency, a circular wave in the gyro casing generates a wave coincidence of the resonant type when the body of the instrument becomes acoustically transparent.

Materials [20] give the results of an analysis of wave coincidence appearance in the gimbal of a two-stage float gyroscope under hypersonic flight conditions. A design model of the elastic interaction of an ultrasonic beam with a polyaggregate gimbal is constructed and the conditions for the appearance of the phenomenon of "acoustic transparency" in the device case for two types of generated waves are determined.

5. Methods of research

One of the technical options for protecting the float gyro from penetrating acoustic radiation is proposed.

The laboratory installation MINI ULTRASONIC CLEANER MODEL 3560 manufactured by PRC (Fig. 1) provides a practical assessment of the effectiveness of the proposed design, as a buffer zone, from the effects of external penetrating acoustic radiation. Ultrasonic unit «model 3560» consists of:

– power supply voltage of 220 V (110 V) and frequency of 50 Hz (60 Hz);
– double choice of vibration mode with a power of 30 W (50 W);
– operating frequency 42 kHz;
– operating time 1–30 min (adjustment possible);
– settings of operating modes – push-button;
– information is displayed on a non-crystal display;
– radiator is flat, piezoceramic;
– intelligent MCU drive;
– the unit is only used when there is water in the bath.

Appearance of the test bench is shown in Fig. 2.

Fig. 1. Ultrasonic installation MINI ULTRASONIC CLEANER MODEL 3560 made in China

The design is a float gyro (FG). FG contains a cylindrical body with an internal cylindrical, partially filled working liquid, cavity. In the cavity of the body is a sealed float gimbal with a hydraulic motor and angle and torque sensors for determining the course, mounted on the supports in the ends of the body. On the outer part of the body there is a thermal casing. Outwardly it is enclosed by a bush of two coaxial, identical lengths, circular shells and rigidly connected to each other at the ends by flat rings, the inter-shell space is hermetically sealed and filled with liquid. The inner radius of the bush is equal to the radius of the thermal jacket. The large shell is equipped externally with an acoustic radiator with a beam direction adjustable relative to its normal (Fig. 3). This creates a caustic zone in the inter-shell, liquid-filled space in the form of a coaxial with the outer shell of a cylindrical surface of radius r [21]:

$$r = \frac{D_2}{2}\cos\alpha,$$

with an increased energy state. Thus, the caustic zone will greatly increase the resistance to penetrating acoustic radiation and its further passage into the device and will create an extremely high dispersion of its energy.

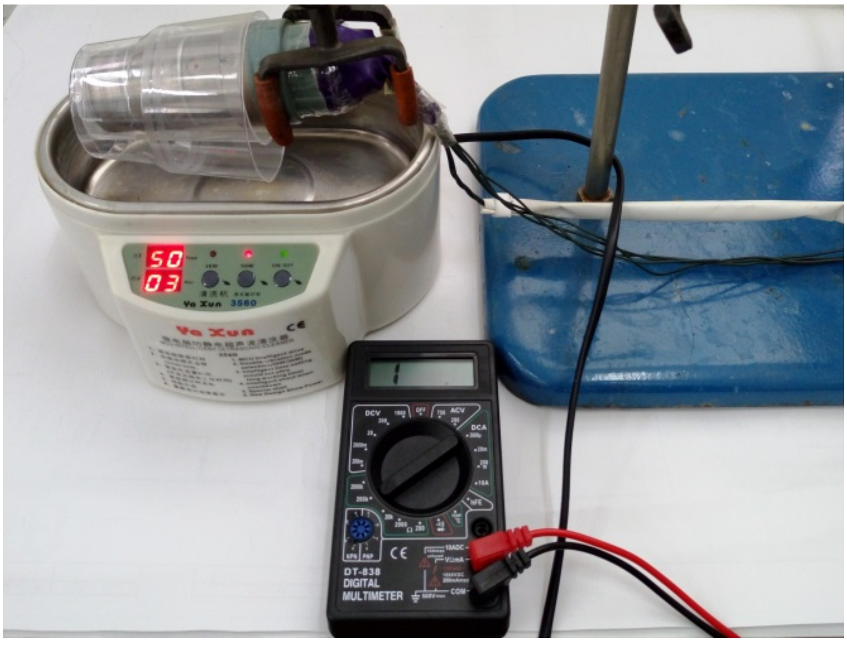

Fig. 2. Appearance of the test bench

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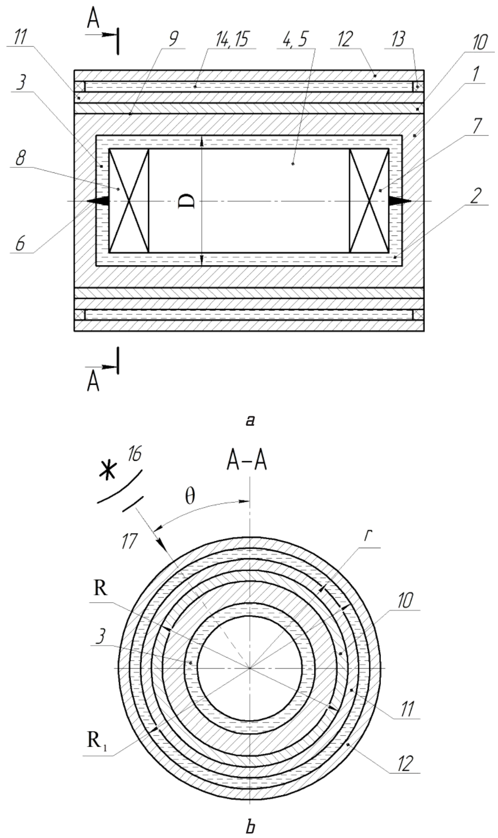

Fig. 3. Construction of the float gyro: *a* – in the longitudinal section; *b* – section AA: 1 – float gyro body; 2 – internal cavity of the body with diameter D; 3 – working liquid; 4 – gyro unit; 5 – gyro motor; 6 – supports; 7 – angle sensor; 8 – gauge of the moments; 9 – outer surface of the shell; 10 – thermal cover; 11 – ahell of radius R; 12 – large shell of radius R_1; 13 – flat rings; 14 – hermetic inter-shell space; 15 – liquid in the inter-shell space 14; 16 – sound emitter; 17 – ultrasonic beam

The artificial formation of the wave coincidence of an ultrasonic beam with a circular wave of a larger envelope is achieved as follows. The incidence angle θ of the ultrasonic beam changes to the value of the coincidence angle θ_c, when the ultrasonic wave and the circular wave in the shell follow the same [22]. When the magnitude of the incidence angle θ of the ultrasonic beam is equal to the coincidence angle θ_c, that is, the formation of a resonant situation, the energy state of the liquid turbulent in structure is instantaneously increased. Thus, a «buffer zone» is created in the path of propagation of penetrating acoustic radiation, in which intense suppression of sound waves of penetrating acoustic radiation is carried out, as shown by semi-actual tests – to a safely low level.

Such increase in the energy of the initial static liquid will make it impossible for further free propagation of external penetrating radiation into the device, and thus eliminates the additional error of the instrument from the penetrating acoustic measurement.

When the beam 17 is acting at a float gyro with a frequency below the limit, circular waves are generated on the surface of the larger shell 12. The frequency ω of the beam 17 is regulated by the sound emitter 16 to the extent that the inequality is satisfied:

$$1 \ll \left(\frac{\omega}{c} R_1\right),$$

where $\frac{\omega}{c}$ – the wave number; c – the sound velocity in the liquid 15 of the inter-shell spaces 14 of the thermal cover 10, ω – the frequency of the ultrasonic radiator; R_1 – radius of the outer larger shell 12 (Fig. 3, *b*). Fulfillment of this condition allows the elementary segment of the larger shell 12 to perceive a flat fragment that will radiate sound waves into the liquid 15 of inter-shell spaces 14 at an angle [22]:

$$\sin\alpha = \frac{c}{V},$$

where V – velocity of the circular waves in the larger shell 12, which, in turn, over the entire volume, will construct a caustic surface coaxial with the inner surface of the outer larger shell 12, that is, in the form of a circular cylinder [21]:

$$r = R_1 \cos\alpha,$$

which will change the initial static state of the liquid 15 of inter-shell space 14 to a high-energy, turbulent in structure. This gap, in the form of a caustic zone, will create an insurmountable obstacle to the propagation of external acoustic radiation into the device, by dissipating the energy of external sound waves and will be, in its own way, a «buffer zone». By changing the direction of the beam 17 generated by the sound emitter 16 to a value (coincidence angle), one can form a resonant situation in the form of wave coincidence, when the waves of the incident ray 17 and the circular wave are the same [21]. This phenomenon will lead, on the one hand, to the manifestation of «acoustic transparency» of the surface of the larger shell 12 on the other, considerably increase the energy of the ultrasonic beam passing through the interior. Thus, without any residue, the energy of beam 17 will go to a sharp increase in the energy state of liquid 15 in the form of the maximum possible, which will completely dissipate the energy of the incident external radiation in the caustic zone (Fig. 4).

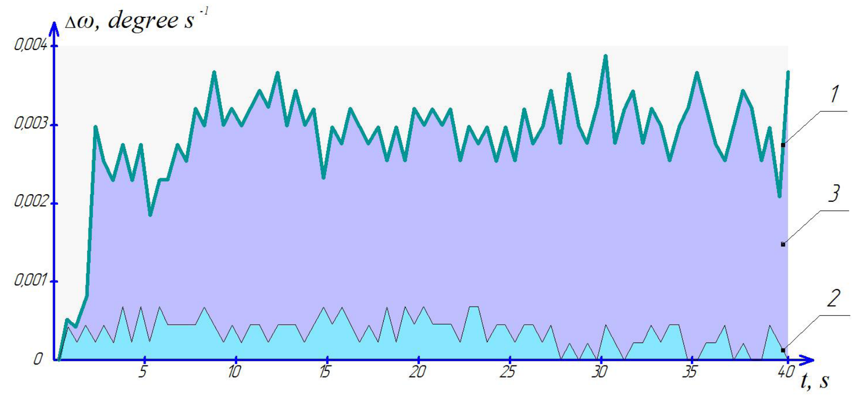

Fig. 4. Influence of acoustic radiation on the output signal of the float gyroscope: 1 – without a buffer zone; 2 – with a buffer zone; 3 – degree of error reduction

Thus, the caustic surface, which is artificially formed in the inter-shell space 14, functions as a «buffer zone». Almost absolutely complete dissipation of the energy passing through the outside of the acoustic radiation is provided. The degree of turbulence of the caustic zone of the liquid 15 in the inter-shell space 14 is decreased [22].

6. Research results

Studies on the test bed (Fig. 2) proved:

– the most vulnerable angle relative to the longitudinal axis of the device, $\varphi = 45^{o}$ degree.

– with the action of an ultrasonic beam with a frequency of 42 kHz with the off gyro, the polyaggregate gimbal of the gyroscope reacts in a certain way to the resulting vibration. The average integral shift of the output signal of the device is 1.24 mV, which corresponds to the average measurement error $\Delta\omega_{av} \approx 0.00282$ degree s^{-1}.

The polyaggregate gimbal of the gyroscope, surrounded by coaxial cylindrical shells, which are separated by a liquid, reacts in a certain way to the arising vibration. The polyaggregate gimbal of the gyroscope forms an average integral shift of the output signal of the device of 0.156 mV, which corresponds to the average measurement error $\Delta\omega_{av} \approx 0.00035\,\deg ree\ \mathrm{s}^{-1}$ (Fig. 4).

7. SWOT analysis of research results

Strengths. The original side of the proposed technical realization is that, in fact, in the caustic zone of the liquid-static part of the gyroscope gimbal, another, external caustic zone in the liquid of the bushing is artificially formed. An ultrasonic irradiator with a controlled beam direction allows, within certain limits, to regulate the density of this caustic zone, in fact, becomes the antipode of the caustic of the float gimbal.

Weaknesses. The proposed technical implementation of the device for extinguishing the influence of penetrating acoustic radiation slightly complicates the design of the device and requires additional energy to support the operation of the ultrasonic radiator.

Opportunities. Increasing the accuracy of constructing a tri-orthogonal coordinate system on mobile objects, in which, among other things, float gyroscopes are used as sensors. Also it is used to stabilize radars and lidar on mobile objects, which require the highest possible accuracy in the construction of coordinate axes. The proposed technical implementation of devices will allow without any financial complications, although it will slightly complicate the design, but achieve high measurement accuracy. The final solution to this issue depends on what is most important for this device – high accuracy of the coordinate system and the accuracy of the equipment, which is on a stabilized platform, or the minimum dimensions.

Threats. Additional costs when creating the proposed protective block, associated primarily with the layout of the bush on the thermal cover and providing a control system for an artificial ultrasonic radiator relative to the surface of the outer larger shell.

8. Conclusions

1. Prediction of the experiment results proved that the experimental model of the investigated phenomenon corresponds to the realities of laboratory experiments, both in the usual mode and in the presence of a resonant situation in the gimbal-wave coincidence.

2. Experiments under the condition of the large wave size of the outer shell and the presence of a resonant situation in the form of wave coincidence show that the displacement of the output signal of the device is 1.24 mV (Fig. 4).

3. Experimental and analytical errors in measurement were obtained $\Delta\omega_{av} \approx 0.00282$ degree s^{-1}. It is obvious that the presence of a buffer zone artificially formed by an ultrasonic radiator decisively reduces the influence of penetrating acoustic radiation 10 times due to the scattering of the energy of the incident wave in the caustic zone (in the buffer zone).

4. The regulated situation of the resonance manifestation in the gimbal of the gyroscope, namely the geometric resonance, in the form of wave coincidence, shows that the approach to the coincidence angle $\theta_c = 10$ degree, when the emitter waves track and the circular wave track of the outer shell coincide. Strongly increases the energy state of the buffer zone, significantly increases the turbulent structure with the available cavitational manifestations and, accordingly, intensively dissipates the energy of the incident waves to a level where they are unable to shift the zero of the device (Fig. 4).

Thus, the effectiveness of the proposed design for artificially creating obstacle to external acoustic radiation is practically proved.

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СНИЖЕНИЕ ТЕХНОЛОГИЧЕСКИХ РИСКОВ ЛЕТНОЙ ЭКСПЛУАТАЦИИ ИСКУССТВЕННЫМ ФОРМИРОВАНИЕМ БУФЕРНОЙ ЗОНЫ ПРОНИКАЮЩЕМУ АКУСТИЧЕСКОМУ ИЗЛУЧЕНИЮ

Анализируется возможность уменьшения технологических рисков от влияния проникающего акустического излучения на бортовую аппаратуру летных изделий. Изучается наиболее сложная, полиагрегатная конструкция поплавкового дифференцирующего гироскопа, который нашел широкое применение как пилотажный прибор. Экспериментально доказано диалектическое единство преимуществ поплавкового подвеса для повышения точности измерений и, в то же время, стремительного роста дополнительных погрешностей в акустических полях.

Ключевые слова: аберрация, зона каустики, волновое совпадение, буферная зона, полиагрегатная конструкция.

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