Numerical and Experimental Studies of Acoustic Processes in Model Channels for the Development of Wideband Single-Layer Sound-Absorbing Structures

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Abstract. In this paper, the results of numerical and experimental studies of the acoustic efficiency of a group of prismatic resonators of different volumes at an acoustic pressure level of 130 dB were presented. The prototype was developed, and representative samples of fragments of different-height sound-absorbing structures were manufactured by 3D-printing. Laboratory tests of the samples were carried out on the interferometer with normal incidence of sound waves. The acoustic efficiency of the developed sound-absorbing structures was experimentally confirmed. The different-height sound-absorbing structures allow to extend the broadband of the prismatic resonator group.

1 Introduction

Tightening of the ICAO standards on aircraft noise on the ground increases the relevance of the study. Since 2018, for medium-haul aircrafts weighing up to 55 tons, the noise limit requirements have been reduced by 7EPN dB, and the majority of foreign aircrafts, and all of the currently operated Russian-made aircrafts do not meet these standards. Consequently, the competitiveness of Russian civil aviation in the world market is endangered. To solve the problem, serious extra efforts in the development of approaches and systems to reduce aviation noise are required [1-8].

One of the effective ways to reduce the noise generated by aircrafts is the implementation of sound-absorbing structures (SAS). All SAS can be divided into the following types: by the number of layers (single-layer, double-layer, triple-layer), by the form of the elementary cell (rectangular, honeycomb, trapezoidal, chevron, etc.), by the type of filler (homogeneous, honeycomb, cellular, tubular, corrugated, etc.). The new direction in reducing the noise of aircraft engines is SAS with an irregular filler.

The use of the single-degree-of-freedom and two-degree-of-freedom (1-DOF, 2-DOF) resonator group [9], as well as the study of their combined operation, which is presented in [5, 10], is of particular interest.

At the same time, implementing the proposed solutions in the designs of nacelles of modern aircraft engines is very difficult. It requires serious investments. Therefore, it

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becomes necessary to carry out numerical and experimental studies aimed at the development of inexpensive, technological and acoustically effective SAS, working in a wide range of frequencies.

To solve this problem, the concept of single-layer broadband SAS with a different-height honeycomb filler is proposed in this work. The results of numerical and experimental studies of the acoustic efficiency of a group of prismatic resonators of different volumes at an acoustic pressure level of 130 dB are presented.

2 Numerical study of the acoustic characteristics of SAS in the channel with normal incidence sound wave

Geometric models of the periodicity cells of the prismatic-shaped SAS were constructed to perform a series of numerical simulations to determine the distribution of the sound wave in the interferometer channel.

The SAS periodicity cell was placed in a channel of circular cross-section (free volume of interferometer) with a diameter of 30 mm. Figure 1 shows a general view of the basic geometric model, where: 1 – channel of circular section, 2 - cells of prismatic shape, connected to the channel by 3 - "narrow" throat of cylindrical shape.

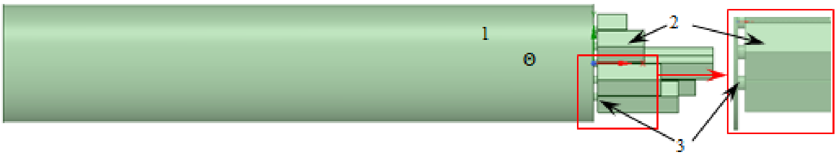

Fig. 1. General view of the geometric model.

As part of the numerical experiments, the acoustic efficiency of the group of prismatic resonators in the operating frequency range from 500 to 3000 Hz at a sound pressure level of 130dB was determined.

To solve the problem, the mathematical model for describing the processes of interaction of sound waves with each other, with the channel walls, and with the prismatic resonators operating at a sound pressure level of 130 dB was formulated. For the computational domain Θ (Figure 1), the mathematical formulation includes the system of nonlinear Navier-Stokes equations for a viscous heat conducting gas, a viscous stress tensor, and total energy.

To improve the convergence of the solution and reduce the errors in the results obtained, a computational grid with triangular prism-shaped cells was used. The grid was adapted in the area of the throat of the resonator in a way that 20 cells were distributed along the height of the throat. Moving from the throat, the linear size of the elements was increased until it reached an average linear size of 2 mm. Additionally, mesh refinement on the wall of 20 layers with a growth factor of 1.2 was used. The size of the wall cells was 0.0002 mm. The total number of elements was 496,861. Also, during the grinding of the grid, serious differences in the sizes of neighboring cells were avoided. The linear dimensions of neighboring cells did not differ by more than a factor of 2.

A signal simulating white noise in the frequency range from 500 to 3000 Hz was set on the end as the boundary condition.

To compute impedance using the transfer function method [11], sound pressure was recorded at the control points (P1, P2) of the area. The control points were placed at distances of 38 and 58 mm from the surface of the SAS, corresponding to the positions of the microphones on the interferometer during the laboratory experiment. The layout of the control points is shown in Fig. 2.

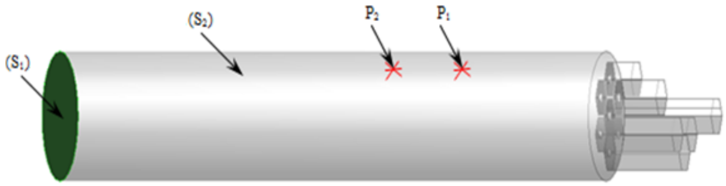

Fig. 2. Layout of control points.

As a result of numerical simulations, the dependence of the sound absorption coefficient on frequency was obtained (Fig. 3).

Fig. 3. The graph of the dependence of the acoustic efficiency on the natural frequency of the different-height SAS.

Analysis of the dependence of the sound absorption coefficient on the frequency of the different-height SAS revealed several peaks. The maximum value of the sound absorption coefficient was 0.93 at the resonance frequency of 1625 Hz. In the operating frequency range from 1375 to 2375 Hz, the sound absorption coefficient of the resonance cell SAS was 0.8.

3 Experimental studies of the acoustic characteristics of the SAS on the interferometer with normal wave incidence

The verification of mathematical models for evaluation the acoustic efficiency of SAS in the channel with normal incidence of waves was carried out on an interferometer with normal incidence of sound waves at a sound pressure level of 130dB. Then the results of the numerical experiments were compared with the laboratory tests.

Reference samples for full-scale tests were manufactured using FDM prototyping technology. The technology of manufacturing on this equipment consists of layer-by-layer extensions of the reference samples by extrusion of a threads from ABS plastic [12].

Acoustic tests in an interferometer with normal incidence of sound waves are widespread due to simplicity of conducting them. The experimental setup consists of a tube of circular cross-section, at one end of which there is a sample of a SAS, on the other: a speaker that irradiates the sample with acoustic waves. Also, microphones are installed flush with the wall at some distance from the sample in the interferometer channel. They record the acoustic pressure of the falling and reflected waves in time. Then, the recorded pressure is processed using the fast Fourier transform algorithm, which results in computation of the impedance of the SAS sample [13].

Impedance relates the pressure and the normal velocity at a boundary, describing the boundary acoustic properties. In most works, the effect of high sound pressure levels of the incident wave is described as the velocity of particles through the hole [14-15]. The majority of semiempirical models are based on the works of Crandall and Melling.

According to the definition, the dimensionless specific acoustic impedance is expressed as the ratio:

$$Z = X + iY = \frac{p}{\rho c u_n} \tag{1}$$

where p - acoustic pressure; ρ - air density; c - speed of sound in air; un - acoustic velocity.

Despite the apparent simplicity of expression (1), computation of the SAS impedance is a difficult task. Today, the impedance of the particular sample of SAS is determined primarily by experimental study.

Two microphones are usually used for measurements because the "transfer function method" is the easiest for computing the impedance. At the same time, this method can be implemented in a channel that has only piston mode, which results in the dependence of the frequency range of the installation on the size of the impedance tube channel.

The model cylindrical sample of the SAS with a diameter of 30 mm was made to conduct laboratory tests (Fig. 4).

Based on the results of the experimental studies, the dependence of the sound absorption coefficient on frequency was determined (Fig. 5).

Fig. 4. A sample of SAS after printing.

Fig. 5. The graph of the dependence of the sound absorption coefficient on the frequency of the different-height SAS.

Analysis of the dependence of the sound absorption coefficient on the frequency of the different-height SAS revealed several peaks corresponding to different volumes of the resonators. The maximum value of the sound absorption coefficient was 0.95 at the resonance frequency of 1496 Hz. In the operating frequency range from 1308 to 1856 Hz, the sound absorption coefficient of SAS resonant cell was 0.8.

The comparative analysis of the results of numerical studies with the results of experimental studies revealed that the difference in the coefficient of sound absorption is not more than 2% and not more than 7% in terms of frequency (at the first peak).

4 Conclusion

Based on the results of this research, the physical and mathematical models for predicting the effective acoustic properties of SAS (Helmholtz resonator) cells of different volumes were formulated. Numerical simulations to estimate the acoustic wave in the model channel of resonators were carried out. The acoustic efficiency of the developed different-height SAS was experimentally determined. It was revealed that the developed SAS allow to extend the broadband of the prismatic resonators up to the range from 1308 to 1856 Hz, with the sound absorption coefficient not less than 0.8.

The results are technically feasible and facilitate the creation of new and more efficient SAS for promising Russian aircraft engines, in particular the PD-35.

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