Numerical Study of the Acoustic Efficiency of the Joint Operation of Sound-Absorbing Cells of Various Shapes

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Abstract. In the framework of the present work, numerical experiments were conducted to simulate an acoustic wave in a model channel with a group of various shapes resonators of the same volume. The mutual influence of closely spaced prismatic and biconical resonators in a rectangular model channel is revealed. It is proposed to consider the combination of various shapes resonators, which will allow, for one, to reduce the mutual influence of the resonators at their joint frequency, and also will increase the broadband band of the resonators group. Acoustically effective resonators combinations were revealed in the research.

1. Introduction
Currently, to reduce the noise of the aircraft engine fan, sound-absorbing structures (SAS) are widely used that installed on the inner side surfaces of the inlet and exhaust channels [1,2]. The SAS are subject to stringent requirements for a large number of parameters, the most important of which is the acoustic efficiency, which is determined by the maximum attenuation and the width of the frequency attenuation spectrum. At the same time, it is important that high efficiency is maintained at all standard operating modes of engines. Search and selection of the most effective SAS is based on solving the equation of sound propagation in a channel with an inhomogeneous subsonic flow with the right-hand side determined by a given noise source [3].

The principle of resonant SAS operation is based on the effects of absorption (dissipation) and reflection of the incident sound wave by the resonator. In the first case, the incident wave excites air vibrations in the resonator neck, leading to absorption (energy transfer to translational degrees of freedom) [4–6]. In the second case, the wave entering the resonator, due to double passage in it, changes its phase to the opposite and, being added to the emitted source by the primary wave, suppresses the latter [6,7].

When using several closely arranged resonators, the interaction (compensation) of waves generated by neighboring resonators occurs. Which leads to a significant decrease in the acoustic efficiency of the resonator group [8].

To reduce or completely eliminate the mutual influence, it is necessary to study the effect of the resonant interaction of cells at distances that are multiples of the acoustic wave half-length based on numerical simulation of acoustic processes in the channel and cells with varying geometric shapes and relative cells positions along the channel [7].

In addition, the use of traditional cellular SAS leads to the need to increase the number of sound-absorbing layers of honeycomb core to three or even four, or to the introduction of one or more membrane covers into each cell. Such decisions lead to a significant complication in the
manufacturing technological process, increasing the cost and lowering the competitiveness of aircraft engines developed using traditional approaches to SAS creation [9 – 14].

In the framework of this work, new approaches and methods for reducing noise in channels using new types of resonator cells are proposed. The processes of the interaction of acoustic waves propagating in channels with waves generated by resonant cells are studied. The influence of the cells group parameters on the effectiveness of reducing the intensity of acoustic waves in model channels is studied.

2. Numerical Model

To conduct a series of computational studies of the mutual influence of cells during joint operation, geometric models were constructed that can be divided into three groups: A1–4, B1–7. Description of the groups is given later in the text of the report. All geometric models contain a channel and free volumes of cells connected in the middle of the channel.

The general view of the groups A1–4 geometric models is shown in Fig. 1. Models A1 and A3 consist of one prismatic and one biconical resonator. Models A2 and A4 consist of two prismatic and biconical resonators, respectively. For models A2 and A4, as well as for subsequent groups of resonators, the distance between the axial lines (Δl) passing through the center of the resonator neck was taken to be 170 mm.

![Figure 1. General view of the geometric models A1–4.](image)

The general view of the group B1–7 geometric models is shown in Fig. 2. All models of group B consist of two resonators, the basic biconical resonator and the “auxiliary”: B1-cylindrical; B2-cubic; B3-prismatic (cellular); B4-conical.

![Figure 2. General view of the following geometric models (a) B1, (b) B2, (c) B3, (d) B4.](image)

Numerical experiments to determine the acoustic characteristics of the resonator were carried out by solving the Helmholtz equation [15 – 17]:

\[ -\nabla \left( \frac{\nabla P}{\rho_0} \right) - \frac{\omega^2}{\rho_0 c^2} P = 0, \quad \omega = 2\pi f \]

where \( p \) is the initial pressure in the computational domain (1 atm.), \( \omega = 2\pi v \) is the natural frequency of the resonator, \( \rho_0 \) is the air density, \( c \) is the speed of sound in the medium, and \( v \) is the frequency of the input signal.

The wave at the entrance to the model channel was set in the form of a harmonic pressure wave with the \( p_0 \) amplitude.
The output wave was described as:

$$n \frac{\nabla P}{\rho_0} = \frac{i \omega}{\rho_0 c} p - \frac{2 i \omega}{\rho_0 c} p_0$$  \hspace{1cm} (2)$$

The rigid wall of the model channel was described as:

$$n \frac{\nabla P}{\rho_0} = \frac{i \omega}{\rho_0 c} p_0$$ \hspace{1cm} (3)$$

The acoustic pressure loss coefficient at the outlet of the model channel was determined as:

$$TL = 10 \log \left( \frac{P_{in}}{P_{out}} \right);$$ \hspace{1cm} (5)$$

$$P_{in} = \int \frac{p_0^2}{\rho c} dA;$$ \hspace{1cm} (6)$$

$$P_{out} = \int \frac{p_c^2}{\rho c} dA.$$ \hspace{1cm} (7)$$

For better convergence of the solution and to reduce the errors in the results obtained when constructing the numerical model, a computational grid was generated, the cells of which have a shape close to the shape of an equilateral tetrahedron. The maximum element size was determined as $N_{max} = 343 \text{ [m/s] / 6 [kHz] / 10 = 0.0057m}$ [17], the minimum element size was taken to be $N_{min} = 0.0001m$, the total number of elements was 800 thousand elements.

3. The Study of the Acoustic Efficiency of Various Shapes Joint SAS Cells

According to the results of computational experiments for models A 1-4, the dependences of the acoustic pressure loss coefficient ($TL$) on the frequency were obtained. Fig. 3 shows the dependencies for the basic geometric models G1, 3.

![Figure 3](image_url)

**Figure 3.** Dependences of the acoustic pressure loss coefficient ($TL$) on the frequency $\nu$ for the basic geometric model (a) with a prismatic (b) biconical resonator.

The dependence analysis showed that the resonance frequency for the prismatic resonator is $\nu = 174$ Hz and the biconical resonator frequency is 201 Hz. The value of the acoustic pressure loss coefficient ($TL$) was 30 dB and 77 dB, respectively. An analysis of the acoustic pressure fields
distribution over the model channel longitudinal section revealed that a significant incident wave reflection is observed for the biconical resonator (Fig. 4).

![Figure 4](image-url)

**Figure 4.** The field of acoustic pressure distribution over the model channel longitudinal section C-C equipped with (a) a prismatic (b) biconical resonator.

Considering the results of numerical experiments on modeling an acoustic wave in a model channel with two resonators, prismatic and biconical (models A2, 4), a significant mutual influence of the resonators was found. Fig. 5 shows the dependences of the acoustic pressure loss coefficient (TL) on the frequency of geometric models A, 2, 4.

![Figure 5](image-url)

**Figure 5.** Dependence of the acoustic pressure loss coefficient (TL) on the frequency \( \nu \) for a group of resonators (a) prismatic (b) biconical shape.

For a group of prismatic and biconical resonators, the value of the acoustic pressure loss coefficient \((TL)\) amounted to 29 dB and 26 dB at a resonant frequency of 174.6 Hz and 201.4 Hz, respectively.

The analysis of the acoustic pressure distribution fields along the model channel longitudinal section equipped with a group of prismatic biconical resonators is shown in Fig. 6, with the presence of mutual compensation during the interaction of waves generated by a group of resonators.

![Figure 6](image-url)

**Figure 6.** Field of acoustic pressure distribution over the model channel longitudinal section equipped with a group of (a) prismatic (b) biconical resonators.
It was revealed that the total acoustic efficiency for groups of prismatic and biconical resonators is lower than the acoustic efficiency of single resonators. This is because neighboring cells at the resonant frequency affect each other. In this case, the transmission coefficient of the main acoustic wave along the channel increases.

So, when comparing the results obtained for a single and for a group of resonators, it was found that the maximum decrease in the acoustic pressure loss coefficient ($TL$) was the largest for the group of biconical resonators and amounts to $\Delta TL_{\text{max}} = 48$ dB. In this case, a slight increase in the resonance frequency by $\nu = 0.4$ Hz is observed. At the same time, the minimal decrease in the acoustic pressure loss coefficient ($TL$) $\Delta TL_{\text{max}} = 1$ dB was observed for the group of prismatic resonators. The increase in the resonance frequency for the group of prismatic resonators was 0.4 Hz.

In the framework of computational experiments on models B1 – 4, the influence of the acoustic efficiency of the joint operation of a biconical resonator and resonators of various shapes and the same volume was studied. Fig. 7 (a–b) shows the graphs of the acoustic pressure loss coefficient ($TL$) dependence on the frequency $\nu$ for geometric models B1 - 4.

When considering the results of numerical experiments obtained using the models of group B, it was found that the greatest value of the acoustic pressure loss coefficient ($TL$) is observed for the calculated variant B3. In this case, the group of resonators operates at two different frequencies: at the frequency of the base (biconical) and auxiliary (prismatic) resonators (Fig. 7 c). For the base resonator, the value of the acoustic pressure loss coefficient is $TL_{\text{max}} = 101$ dB at the $\nu = 202$ Hz resonant frequency. For the auxiliary resonator, this value is 68 dB at a resonant frequency of 176 Hz.

![Figure 7](https://example.com/figure7.png)

**Figure 7.** Dependences of the acoustic pressure loss coefficient ($TL$) on the frequency $\nu$ for the B1 calculated variant.

Additionally, it is worth noting that when the biconical and prismatic resonators work together, an increase in the acoustic efficiency of the resonators is observed when compared with the acoustic...
efficiency of a single resonator. For the biconical resonator, the increase was 25 dB, and for the prismatic one - 40 dB.

The lowest value of acoustic pressure loss coefficients (\( TL \)) was observed for the group of calculated variant B2 resonators. In this case, the group of resonators operates at two different frequencies: at the frequency of the base (biconical) and auxiliary (cubic) resonators (Fig. 7 b). For the base resonator, the value of the acoustic pressure loss coefficient was \( T_{\text{max}} = 45 \) dB at the frequency of 201 Hz resonant frequency. The acoustic pressure loss coefficient For the auxiliary resonator was 43 dB at a resonant frequency of 175.5 Hz.

4. Conclusion

Based on the results of the studies, physical and mathematical models are formulated for predicting the effective acoustic properties of the SAS (Helmholtz resonator) cells during joint operation. Numerical experiments have been carried out to simulate an acoustic wave in a model channel with a group of various shapes resonators. The mutual influence of closely situated prismatic and biconical resonators in a rectangular model channel was revealed. It is proposed to consider the combination of resonators of various shapes, which will allow, for one, to reduce the mutual influence of the resonators at their joint frequency and will also increase the broadband band of the group of resonators. It was found that the most preferred combination is a combination of biconical and prismatic resonators, in which the highest values of the acoustic pressure loss coefficient are observed.

5. References

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