Paper No.348/2021

DETERMINATION OF THE IMPEDANCE OF A HONEYCOMB RESONATOR BY DEAN'S METHOD AND DIRECT METHOD IN A COMPUTATIONAL EXPERIMENT WITH GRAZING INCIDENCE OF WAVES

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Abstract*: The article considers the determination of the impedance of the acoustic liner sample on the basis of numerical simulation of physical processes in a honeycomb resonator with a grazing incidence of sound waves. The computational domain is the test section of a grazing incidence impedance tube with an acoustic liner sample. The liner sample is a single honeycomb resonator with a depth of 14 mm and an open area percent of 4.2%. Numerical simulation is performed based on the direct solution of the non-stationary compressible Navier-Stokes equations in a three-dimensional formulation. The pressure-time and velocity-time signals are recorded in the numerical simulation and processed by Dean's method and the direct method (from the ratio of acoustic pressure to normal acoustic velocity). The comparison of impedances obtained by the two methods demonstrates a good agreement with each other.*

Keywords: *Acoustic liner, acoustic impedance, grazing incidence impedance tube, Dean's method, direct method, numerical simulation*

DOI: *: 10.36336/akustika20214125*

1. INTRODUCTION

Acoustic liners are an effective means of reducing aircraft engine noise. The fundamental characteristic of the liners is the acoustic impedance, which is the ratio of the acoustic pressure to the acoustic normal velocity. This value depends on many parameters, which include: the sound pressure level, the presence of a grazing flow, the profile of the flow velocity, the signal spectrum, etc. Also, the impedance depends on the geometric characteristics (the size of the resonator cells, the thickness of the perforated sheets and their open area percent, the number of layers, etc.). The existing semi-empirical impedance models of the locally-reacting liners are based on a simplified description of physical processes and often lead to significant differences between the impedance predicted by these models from the experimental values [1].

In turn, the methods of experimental determination of the liner impedance also have some drawbacks. These methods are based on microphone measurements, while microphones are placed on the walls of experimental installations or test samples (in the case of multilayer liner sample, such placement of microphones is very problematic). At the same time, the results of the experimental determination of the liner impedance obtained by various methods at various installations differ not only from the results of impedance prediction but also among themselves [2-8]. This situation is partly due to insufficient information about the processes occurring inside the resonator cells, since measurements on the installation walls give an incomplete picture of the acoustic field inside the investigated area. The introduction of measuring probes into the channel of the installation or liner sample inevitably leads to a distortion of the values of the studied physical parameters.

In this regard, in recent years, much attention has been paid to the development of methods for predicting the impedance of the acoustic liners based on numerical simulation, which is able to more completely take into account the complex physical processes accompanying the liner operation. This approach allows both carrying out a direct simulation of a full-scale experiment and studying a number of physical quantities inside and on the surface of the sample, which can be used to refine the existing semi-empirical impedance models, as well as to correct the methods of experimental study of the acoustic characteristics of the liner.

Previously, the authors proposed a technique that, based on numerical simulation of processes in acoustic liner sample at normal incidence of waves, makes it possible to predict with good accuracy the acoustic characteristics of single-, double- and triple-layer honeycomb liners at high sound pressure levels [9-11]. In this case, the processing of the data obtained in the numerical simulation was carried out by the two-microphone transfer function method [12], which is easy to implement in a full-scale experiment and, accordingly, to verify the results of numerical simulation.

Another way to determine the acoustic characteristics of liner samples is Dean's method [13]. Its adaptation to numerical simulation was previously carried out by the authors for the case of normal [14] and grazing [15] incidence of waves.

The third way to determine impedance is the direct method. This method allows the impedance to be obtained directly from the ratio of acoustic pressure to normal acoustic velocity. The direct method is difficult to implement in a full-scale experiment, since it is required to measure the velocity variable in time and space inside the holes of the sample. However, this method can be relatively simple to implement in numerical simulation and thereby verify the existing computational and experimental methods for determining the impedance.

In the work [14], it was demonstrated that microphone measurements in the channel of a normal incidence impedance tube determine the impedance of the total front surface of the sample, and measurements by Dean's method determine the impedance of the resonator cell only. The present article is a continuation of the authors' work on determining the impedance of the samples of locally-reacting acoustic liners at a grazing incidence of a sound waves based on numerical simulation.

2. METHODS FOR DETERMINING THE IMPEDANCE OF ACOUSTIC LINER SAMPLE AT GRAZING INCIDENCE OF A SOUND WAVE

In ducts of the aircraft engines, sound propagates as grazing waves to the surface of the acoustic liners. To determine the impedance at the grazing incidence of sound waves, special installations are used – grazing incidence impedance tube (GIIT). These installations have a rather long narrow tube of the rectangular cross-section with flush-mounted microphones and liner sample. Acoustic drivers located outside the test section (distance between the first and last microphone) generate the sound waves. The transverse size of the duct is selected from the condition of single-mode sound propagation in the rigid-walled terminations of the test section. The use of a rectangular tube is dictated by the simplicity of the liner sample manufacture. In addition, GIIT allows the flow to be propagated in the duct, which is generated with compressors or fans (Fig. 1). It is also possible to supply the flow into the GIIT channel from the jet rig, as was done, for example, at the large-scale research facility "Anechoic Chamber with Flow AC-2" FSUE TsAGI [16].

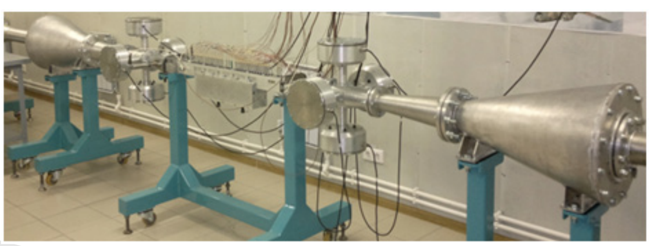


Fig. 1: Grazing incidence impedance tube with flow in PNRPU Acoustic Research Center

Various methods can be used to determine the impedance. Most of them are based on measurements of the acoustic pressure in the duct of GIIT [3, 6, 8]. Another method for determining the impedance of the acoustic liner samples is Dean's method. This method provides impedance determination on data obtained from microphones mounted into the acoustic liner sample. At the same time, when comparing the acoustic characteristics using different methods, a difference is observed. To better understand why it occurs, we can get useful information from computational experiments.

Determining the impedance by conducting a virtual experiment for a full-scale acoustic liner sample is extremely difficult, since such a sample consists of many honeycomb cells and holes in a perforated plate, which requires significant computational resources. In the work, we consider a model of a liner sample, which is a single honeycomb resonator with 5 holes. The parameters of the sample are presented in Table 1. Such a sample is too small to provide good absorption of sound energy in the duct, therefore, methods of impedance eduction based on minimizing the functional discrepancy between the calculated and measured acoustic pressure give large errors in impedance values. However, Dean's method and the direct method allow one to determine the impedance of a single resonator, so they are used to process the results of numerical simulations.

Parameter	Diameter of hole (mm)	Thickness of perforated plate (mm)	Height of honeycomb cell (mm)	Percent of open area (%)
Value	1.5	2	14	4.2

Tab. 1: Characteristics of honeycomb resonator

As is known, the normalized impedance is defined as the ratio of the acoustic pressure P at a point on the surface of the liner to the acoustic velocity Un at the same point, directed along the normal towards the liner surface:

$$\boldsymbol{Z = \frac{1}{\rho c}\frac{P}{U_n}} \tag{1}$$

where
ρ is a density of a medium; c is a velocity of sound. However, in practice, determining the impedance by formula (1) (hereinafter we call this the "direct method") is problematic due to the difficulties in simultaneous measurement of acoustic parameters at a point directly on the surface of the liner.

Dean proposed in [13] a method for determining the impedance, where the acoustic pressure on the front and rear wall of the resonator cell is measured. An important advantage of this method is that it can be used not only at the normal incidence of a sound wave but also at the grazing incidence. This allows one to determine the impedance of the acoustic liner directly on an aircraft engine [4]. The normalized impedance, in this case, is determined as:

$$\boldsymbol{Z = -i\frac{P_{face-sheet}}{P_{back-wall}}e^{i\varphi}sin^{-1}(kh)} \tag{2}$$

where
h is the liner depth and
φ is the phase angle between the two points of acoustic pressure measurement.

3. STATEMENT OF COMPUTATIONAL EXPERIMENT

Numerical simulation of acoustical processes at grazing incidence of waves is carried out using ANSYS Fluent software. It is used a system of nonlinear Navier-Stokes equations for a viscous heat-conducting gas. The computations are performed by under-resolved direct numerical simulation. The following features are used: Pressure Based Coupled Solver; implicit time-difference scheme of the second-order accuracy; second-order numerical schemes in spatial variables for approximation of convective terms in the equations.

The computational domain is the test section of the GIIT represented in Fig. 1 with liner sample. The test section of the GIIT has a cross section 0.04 x 0.04 m and length 0.76 m. The liner sample is a single honeycomb resonator with 5 holes (Fig. 2) located in the center of the GIIT's test section. The characteristics of the honeycomb resonator are given in Tab. 1.

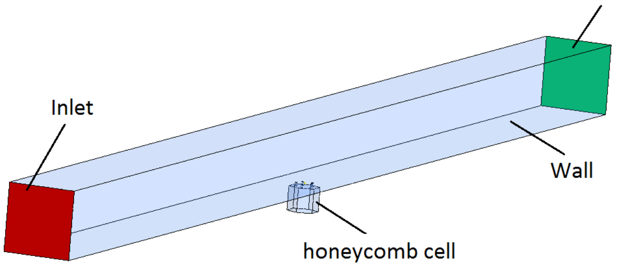


Fig. 2: Geometry of the computational domain

To reduce computational time, the CutCell meshing [17] was applied. The mesh was thickened in the orifices so that there were 12 cells along the orifice height. With distance from the orifice, the linear dimensions of the element increased until the average linear dimension was 4 mm. Additionally, it was used a thickening on the wall of 15 layers with a growth factor of 1.2. The size of the wall cell is 0.002 mm. As a result, a computational mesh of 541 019 elements was obtained. Examples of the computational mesh are shown in Fig. 3.

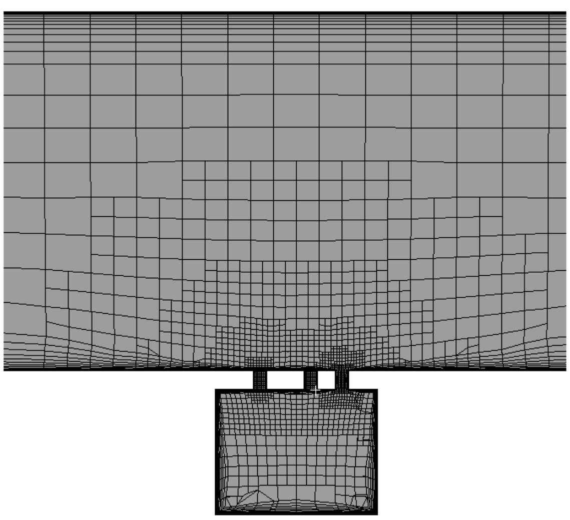


Fig. 3: View of the computational mesh near the honeycomb resonator

At the entrance to the computational domain, the "Inlet" boundary condition was used. The acoustic signal at this boundary was imported from the text file, in which instantaneous pressure values were recorded with a time step of 1/65536 s. This time signal is a time function with a flat frequency spectrum in the frequency range 500-3600 Hz with a total sound pressure level of 140 dB. During the computation, at each time step, the values at the inlet boundary were updated. As a result, a piston wave propagated inside the computational domain, similar in spectral composition to the text file. At the exit from the computational domain, the "Outlet" boundary condition was set with the non-reflecting boundary condition and zero excess pressure to exclude reflections of the acoustic wave from the output boundary. The "Wall" with adhesion boundary condition was used on the walls of the duct, perforated plate, and honeycomb. The computations were carried out under normal environmental conditions. The working medium was air, the properties of which changed according to the law of an ideal gas.

To record the pressure-time signal for Dean's method, one probe was set on the perforated plate and the other on the bottom of the resonator (Fig. 4). In the direct method, the probe for recording the pressure-time signal was set on the perforated plate, and the probes for recording the velocity-time signals were set on the orifices. The recorded signals were divided into segments and processed using the fast Fourier transform. The obtained spectra were averaged over the number of segments. The averaging was carried out taking into account the overlap of adjacent segments; when calculating the spectra, the Hanning window function was used. The computations were carried out with a time step of 1/65536 s for 32768 time steps.

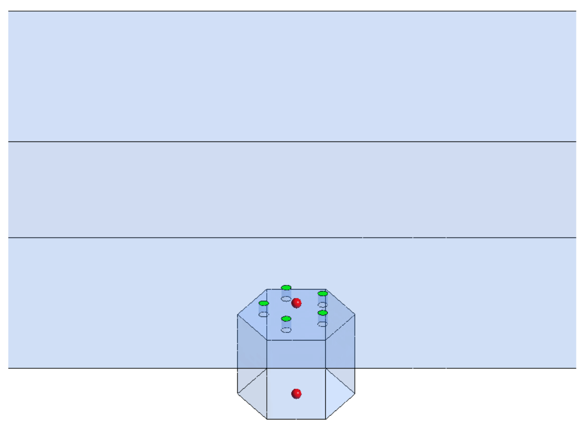


Fig. 4: Location of probes for recording pressure (red dots) and velocity (green dots) signals over time

To determine the impedance of the honeycomb resonator by Dean's method, the obtained pressure spectra can be substituted into the formula (2). However, in the direct method, the pressure and velocity spectra cannot be substituted directly into expression (1) for the following reasons. As the normal velocity on the face wall of the liner sample is zero, only the normal velocity in the orifices contributes to the velocity averaged over the face wall. The mass flow rate is a constant, therefore only porosity of the face wall is required to be taken into account for the correction of the velocity. The mass flow generated by the acoustic driver in GIIT propagates through the duct and then passes through the orifices of the liner sample. The flow that has passed through the orifices continues to propagate inside the cell of the honeycomb resonator. Therefore, it is possible to determine the porosity F through the ratio of the total area of the orifices $\boldsymbol{\Sigma S_{orifice}}$ to the total cross-sectional area of the honeycomb cavity $\boldsymbol{\Sigma S_i}$ in the sample. In this case, expression (1) is transformed to the form:

$$Z = \frac{P}{\rho c U_{aver} F} \tag{3}$$

The velocity at the orifice varies: it equals zero on the walls and then increases with the distance from the wall. The velocity profile across the orifice depends on the direction of the vortex movement and the stage of its formation or destruction. In this case, the velocity in each orifice is different, which is associated with a delay in the phase of the sound wave arriving at the every orifice. In this regard, in formula (3), we used the velocity averaged over all orifices of the honeycomb resonator at each moment of time:

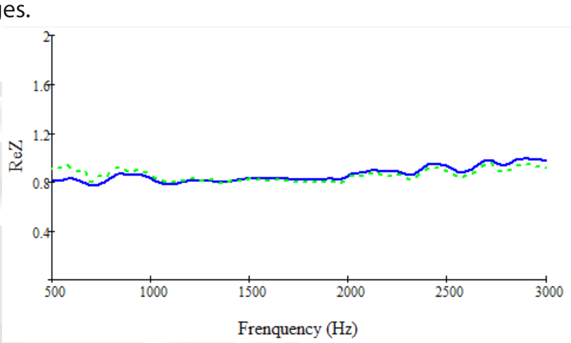
$$u_{aver} = \frac{1}{A}\int u\, dA \tag{4}$$

where

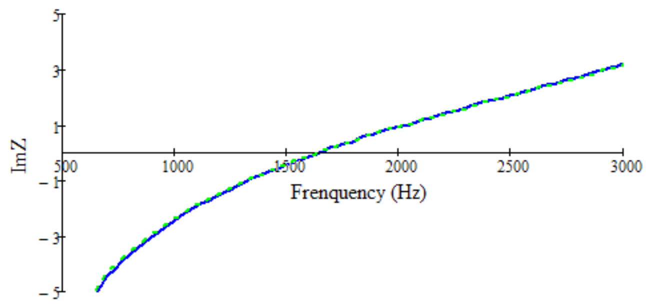
A is a total area of the orifices. In our computations, the average velocity varies within wide limits: from -24.55 m/s to 24.76 m/s. The modulus of the average velocity is 6.34 m/s, which corresponds to the Reynolds number 650.

4. RESULTS OF COMPUTATIONS

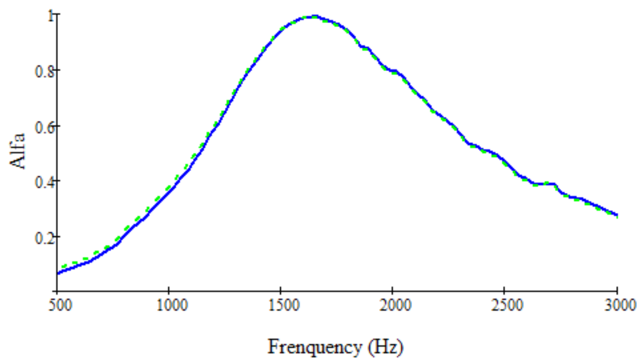
Fig. 5 shows the acoustic characteristics obtained by processing the results of numerical simulation by the direct method (3) and by Dean's method (2). As can be seen, the obtained acoustic characteristics are in good agreement with each other. Thus, Dean's method is well verified by the direct method and can be used in numerical simulation for sound propagation in GIIT with acoustic liner samples installed in it. This approach is relevant in the sense that the implementation of the full-scale determination of impedance based on Dean's method requires measurements at many points, since Dean's method determines the impedance of only one resonator, therefore, a full-scale experiment turns out to be very laborious. In addition, the mounting microphones in a sample is in itself a delicate work and takes a lot of time, and also violates the integrity of the sample, while the implementation of Dean's method in numerical simulation is free of the listed disadvantages.



(a)



(b)



(c)

Fig. 5: Comparison of the acoustic characteristics obtained by numerical simulation: green dot line is direct method; blue solid line is Dean's method; a) real part of impedance; b) imaginary part of impedance; c) sound absorption coefficient

5. CONCLUSION

The article presents the results of determining the acoustic characteristics of the liner sample based on the solution of the nonstationary gas-dynamic problem. The acoustic characteristics determined using Dean's method and the direct method agree well with each other. In this regard, it can be concluded that Dean's method allows one to qualitatively determine the acoustic characteristics of acoustic liner samples at a grazing incidence of a sound wave and can be successfully used both in a full-scale experiment and in computational methods.

ACKNOWLEDGEMENT

The work was funded by a grant from the President of the Russian Federation for young scientists - candidates of science MK-541.2021.1.2. The work was carried out on the basis of the large-scale research facility "Anechoic Chamber with Flow AC-2" FSUE TsAGI.

REFERENCES

[1] Khramtsov, I.V., Kustov, O.Yu., Palchikovskiy, V.V., Bulbovich, R.V.: Comparison of acoustic characteristics of resonant liner samples at normal incidence of waves based on semiempirical model, Natural Experiment and Numerical Simulation, AIP Conference Proceeding, Vol. 2351, No. 030036, 2021
[2] Motsinger, R.E., Kraft, R.E.: Design and performance of duct acoustic treatment, Aeroacoustics of flight vehicles. Theory and practice. Acoustical Society of America, New York, 1995
[3] Auregan, Y., Leroux, M., Pagneux, V.: Measurement of liner impedance with flow by an inverse method, AIAA Paper, No. 2838, 2004
[4] Gaeta, R.J., Mendoza, J.M., Jones, M.G.: Implementation of in-situ impedance techniques on a full scale aero-engine system, AIAA Paper, No. 2007-3441, 2007
[5] Schuster B.: A comparison of ensemble averaging methods using Dean's method for in-situ impedance measurements, AIAA Paper, No. 2012-2244, 2012
[6] Watson, W.R., Jones, M.G.: A comparative study of four impedance eduction methodologies using several test liners, AIAA Paper, No. 2274, 2013
[7] Bodén, H., Cordioli, J.A., Spillere, A., Serrano P.: Comparison of the effect of flow direction on liner impedance using different measurement methods, AIAA Paper, No. 2017-3184, 2017
[8] Sobolev, A.F., Ostrikov, N.N., Anoshkin, A.N., Palchikovskiy, V.V., Burdakov, R.V., Ipatov, M.S., Ostroumov, M.N., Yakovets, M.A.: Comparison of liner impedance derived from the results of measurements at two different setups using a small number of microphones, PNRPU Aerospace Engineering Bulletin, No. 45, p. 59-113, 2016
[9] Khramtsov, I.V., Kustov, O.Yu., Fedotov, E.S., Siner, A.A.: On numerical simulation of sound damping mechanisms in the cell of a sound-absorbing structure, Acoustical Physics, Vol. 64, No. 4, p. 511-517, 2018
[10] Khramtsov, I.V., Kustov, O.Yu., Palchikovskiy, V.V.: Determination of acoustic characteristics of full-scale sample of single-layered honeycomb liner based on numerical simulation, Akustika, Vol. 32, p. 182-188, 2019
[11] Khramtsov, I.V., Kustov, O.Yu., Palchikovskiy, V.V.: Determination of acoustic characteristics of the double-layer honeycomb liner based on numerical simulation, Akustika, Vol. 34, p. 32-36, 2019.
[12] Chung, J.Y., Blaser, D.A.: Transfer function method of measuring in-duct acoustic properties. I. Theory. II. Experiment, Journal of the Acoustical Society of America, Vol. 68, No. 3, p. 907-921, 1980
[13] Dean, P.D.: An in-situ method of wall acoustic impedance measurement in flow duct, Journal of Sound and Vibration, vol. 34, No. 1, p. 97-103, 1974
[14] Khramtsov, I.V., Kustov, O.Yu., Palchikovskiy, V.V.: Investigation of the reason for the difference in the acoustic liner impedance determined by the transfer function method and Dean´s method, Akustika, Vol. 39, p. 226-230, 2021
[15] Khramtsov, I.V., Kustov, O.Y., Palchikovskiy, V.V.: Technique for evaluating the acoustic properties of a liner at grazing incidence of wave based on numerical simulation, AIP Conference Proceedings, Vol. 2351, No. 030038, 2021
[16] Kopiev, V.F., Ostrikov, N.N., Yakovets, M.A., Ipatov, M.S., Kruglyaeva, A.E., Sidorov, S.Yu.: Radiation of sound from the open end of a duct simulating an air inlet under static conditions and in a flow, Acoustical Physics, Vol. 65, p. 76-89, 2019
[17] Ansys User's guide. Ansys Release 17.0. Ansys Inc., 2016

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