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STUDY ON VARIOUS METHODS ON DESIGNING THE MICRO PERFORATED PANEL

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Abstract:
The subject of this paper is about the Micro perforated panels (MPP) with low percent of opened area (POA) having various methods to make it. The proposed calculation methods are based on the Maa, Beranek, Transfer Matrix Method and Finite Element Method. In FEM software the acoustic impedance of a MPP can be calculated using a simplified method that uses Maa equations and "Distance-Based Linearized Navier-Stokes-Fourier" (DBLNSF) method, that calculates the acoustic propagation in micro perforations taking into account the visco-thermal losses effects.

Keywords **—Matrix Method(TMM),Distance-Based Linearized Navier-Stokes-Fourier"(DBLNSF) , Finite Element Method (FEM)**

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I. INTRODUCTION

Micro perforated panel (MPP) is represented by a reactive structure used at noise control and noise reduction solution. They are thin panels perforated with a lot of submillimeter holes, to increase the viscous and thermal losses inside the perforations. They provide high acoustic resistance and low acoustic mass reactance to tune the sound absorption peak frequency. MPP sound absorbers were first proposed by Maa, who established the approximate theory and general theory to predict the acoustic properties of MPP absorbers.The resulted impedance is assigned only to a surface of the CAD model without meshing the fluid from perforations and the back-air cavity.

II. THE PRINCIPLES AND MATHEMATICAL MODELS

A micro perforate panel with a thickness t, perforation diameter d, holes step b and air cavity length D is presented in Fig 1. Only the plane wave at normal incidence on the perforated panel is considered in this study. The numerical methods described by the Maa, Beranek, Transfer Matrix Method TMM and two FEM methods are proposed in this paper.The transfer impedance of a multi-perforated panel is expressed in relation to the porosity of the plate (also called open area) σ, which is defined as the ratio of open area by the total surface of the plate.

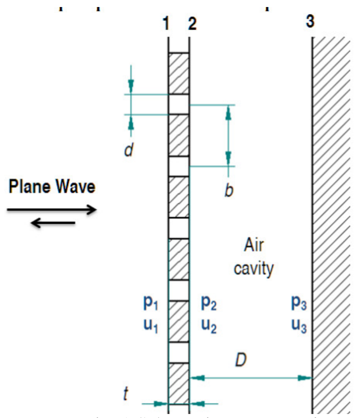

Fig. 1 Schematic representation of a MPP

Considering that the solid has no motion, only the acoustic transfer across the sheet is considered. The impedance Zp of a single perforation can be written as:

$$Z_p = \frac{\partial p}{\overline{u}} = R_p + jX_p \quad (1)$$

where ∂p = p2 − p1 is the pressure drop across the panel and considering u1 = u2 the u is the average normal particle velocity across the perforation, Rp is the acoustic resistance, Xp is the acoustic reactance. From the above assumptions, the normalized specific acoustic impedance is:

$$z_p = \frac{Z_p}{\rho_0 c_0} = r_p + jx_p \quad (2)$$

where ρ0 is the density of the medium at rest (1.225 kg/m3 for the air at ambient conditions) and c0 the speed of sound at rest (340 m/s for the air at ambient conditions). The transfer impedance of a multi-perforated panel is expressed in relation to the porosity of the plate (also called open area) σ, which is defined as the ratio of open area by the total surface of the plate. For a square grid, POA is defined as $\sigma = \pi\frac{a^2}{b^2}$and for triangular grid, the POA is $\sigma = \frac{2\pi a^2}{\sqrt{3}d^2}$.

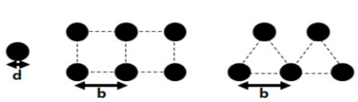

Fig. 2Square and triangular perforation grid

The transfer impedance and dimensionless transfer impedance of the whole plate are:

$$\overline{Z}_p = \frac{Z_p}{\sigma} = \frac{1}{\sigma}\left(R_p + jX_p\right) \quad (3)$$

$$\overline{z}_p = \frac{1}{\sigma}\left(r_p + jx_p\right) \quad (4)$$

2.1 MAA MODELS.

First studies related by the impedance of short tube and sound propagation through thin cylindrical perforation in a panel were performed by Crandall after Rayleigh. The acoustic impedance of a tube was approximated by Maa after Crandall's solution for the wave equation. The exact formula for the specific acoustic impedance of an MPP proposed by Maa , which includes the impedance of the tube, given by Crandall and the end correction, is:

$$Z_{Maa\_exact} = \frac{\sqrt{2}\mu s}{\sigma d} + \frac{j\omega\rho_0}{\sigma}\left\{0.85d + t\left[1 - \frac{2}{s\sqrt{-j}}\frac{J_1\left(s\sqrt{-j}\right)}{J_0\left(s\sqrt{-j}\right)}\right]^{-1}\right\} \quad (5)$$

The second approach that will be analysed is the approximate formula proposed by Maa, which includes the impedance of the tube and the end corrections:

$$Z_{Maa\_approximate} = \frac{32\mu t}{\sigma d^2}\left(\sqrt{1 + \frac{s^2}{32}} + \frac{\sqrt{2}sd}{32t}\right) + \frac{j\omega t\rho_0}{\sigma}\left(1 + \frac{1}{\sqrt{3^2 + \frac{s}{2}}} + 0.85\frac{d}{t}\right) \quad (6)$$

After the impedance of the micro perforation is calculated, the total impedance must be determined taking into account the impedance of the back-air cavity from which results the total impedance of the structure:

$$Z_{back\_air} = -i\rho_0 c_0 \cot(kD)$$
$$Z_{total} = Z_{M(MPP)} + Z_{back\_air} \quad (7)$$

where k is the wave number and D is the cavity length. From the total impedance of the system, the acoustic reflection coefficient and acoustic absorption coefficient at normal incidence are determined according to following equations:

$$R = \frac{(Z_{total} - \rho_0 c_0)}{(Z_{total} + \rho_0 c_0)} \quad (8)$$

$$\alpha = 1 - |R|^2 \quad (9)$$

2.2 *BERANEK MODEL.*

In their study, Beranek and Ver [8] used an empirical model for calculating the acoustic resistance and reactance of a perforated panel.

$$R_{pB} = \frac{8.076 \times 10^{-5}\sqrt{f}}{\sigma}\left(1 + \frac{t}{d}\right)$$
$$X_{pB} = 0.0185\,\frac{f}{\sigma}\left[\frac{0.0044}{\sqrt{f}}\left(1 + \frac{t}{d}\right) + t + \delta\right] \quad (10)$$

where RpB and XpB is the resistance and reactance part, δ = 0.85dφ(σ) is a function of the porosity and φ(σ) =1−1.47 $\sqrt{\sigma}$+ 0.47 $\sqrt{\sigma^3}$.

The end correction term is represented by the 0.85 constant from the reactance. To determine the absorption, the impedance of the back air cavity is added from eq.7 and the absorption is determined according eq. 9.

2.3 *TRANSFER MATRIX METHOD (TMM) :*

It is a practical way in finding the acoustic impedance of different structures. In addition, this method is a very practical way to determine the acoustic impedance of a complex structure. The TMM consist in modelling the panel as a four-pole matrix, which includes the sound pressure and particle velocity on each side of the MPP. In fig. 1 at the top face of the perforated panel, we have the pressure and velocity p1 and u1 where at the other surface we have the pressure p2 and velocity u2. The transfer matrix can be expressed as:

$$\begin{bmatrix} p_1 \\ u_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} p_2 \\ u_2 \end{bmatrix} \quad (11)$$

in which the A, B, C, D are the four-pole parameter of the acoustical element. Considering the third element, a hard-reflecting wall, the particle velocity u3 at surface is zero.

The total impedance of the acoustic structure presented in Fig 1 is resulted from the multiplication of the matrix of the panel with the matrix of the back air cavity:

$$T = T_{MPP} * T_{aer} = \begin{bmatrix} 1 & Z_T \\ 0 & 1 \end{bmatrix} * \begin{bmatrix} \cos(kD) & j\rho_0 c \sin(kD) \\ j\frac{\sin(kD)}{\rho_0 c} & \cos(kD) \end{bmatrix} \quad (12)$$

ZT is the acoustic impedance of the perforated panel calculated from the eq. 6, D is the cavity length and k is the wavenumber. The input impedance of a MPP system is obtained from the relation:

$$Z_{TMM} = \frac{T(1,1)}{T(2,1)} \quad (13)$$

in which T(1,1) and T(2,1) represents the first and second element of the total impedance matrix. The acoustic reflection coefficient is obtained by introducing Z_{TMM} in eq.8, from which the acoustic absorption coefficient is determined from the eq.9.

III. THE FINITE ELEMENT METHODS

The MPP can be computed using FEM to determine the impedance at normal incidence, using MSC Actran software. In the FEM software, the MPP can be modelled in two ways. The first way is to use a built-in module of the software, which uses the exact solution according to Maa. This module reduces the model dimensions by pre-calculating the total impedance of the perforated panel both with the back-air cavity. The resulted impedance is assigned only to a surface of the CAD model without meshing the fluid from perforations and the back-air cavity. The second method to determine the acoustic impedance of an MPP is to model and mesh the fluid inside the perforation as a visco-thermal component using a DBLNSF model "Distance-Based Linearized Navier-Stokes-Fourier". In this paper, the both methods are considered and compared. For the first FEM method with Maa equations (5), the model consists only in the air from the impedance tube as is presented in Fig 3. A reduced CAD model was used to reduce the computational time, where the diameter of the impedance tube was 5mm with the length of 60mm. The red surface represents the surface for which the impedance was computed using the Maa equation. The blue region represents the boundary condition of the acoustic radiating surface with plane waves, for which an intensity of 1W in the sample direction was defined. Also, on the same surface, a free field condition in the opposite direction was imposed in order to compute the reflected wave, which is reflected by the sample. The remaining non-defined surfaces are considered by the software as hard walls with total reflection. The air properties from the all domain were ρ0=1.225 kg/m3, c=340m/s and air dynamic viscosity 18.2e+06 Pa.s. The parameters of the perforated panel studied in the FEM analysis were: perforation diameter d=5e-04m, thickness t=5e-04 m, holes step b=1.5e-03 m from which results a porosity of σ=8.73%. Two different back air cavity lengths were modelled and studied: D1,2=0.02 and 0.04 m. It is important that in FEM analyses the motion of the solid part was not considered, only the acoustic transfer across the sheet being considered. The analysis was defined in the 50-7000Hz frequency domain with a frequency step of 10Hz. As a rule, in mesh definition, when quadrilateral elements are used in acoustic analysis, four elements per wavelength must be created for the highest studied frequency. In our case, considering the small dimensions of the virtual impedance tube, sub-millimeter elements were used.

To determine the acoustic absorption coefficient at normal incidence, the radiated power of the noise source surface in the direction of the sample and the power of the reflected wave were used in the next equation:

$$\alpha = \frac{\left(P_{incident} - P_{reflected}\right)}{P_{incident}} \tag{14}$$

3.1 IN THE SECOND FEM METHOD:

a DBLNSF method was used, where the mesh needs to be sufficiently refined close to the wall to capture accurately the boundary layer effects. A major drawback of the proposed model is the mesh refinement conditions, which can drastically increase the computational time. Therefore, only one perforation was chosen together with the air volume from the cavity that corresponds to it, according to the Fig. 4. The hexagonal volume represents the back air cavity, the cylindrical shape represents the fluid from the impedance tube and the red surface represents the boundary condition of plane wave. As it is presented in detail of Fig. 4, the element size in the perforation area was limited at 5.04e-05 m and in FEM analysis, this volume was defined as viscothermal component, to model the acoustic propagation in narrow channels, which computes the visco-thermal losses. The elements length from other fluid domains was set in order to respect the rule of eight tetrahedral elements per the minimum wavelength. As in the first FEM model, the motion of the solid part was not considered, the solid being subtracted from the model.

The air properties from the all domain were: ρ0=1.225 kg/m3, c=340m/s, air dynamic viscosity 18.2e+06 Pa. s, and the same plane wave condition was applied as in the first model case.

IV. IMPEDANCE TUBE MEASUREMENTS

The measurements of acoustic absorption coefficient at normal incidence were made by using a 28mm diameter impedance tube and two microphones.

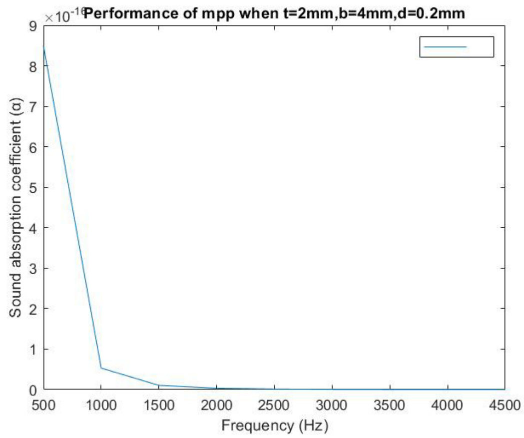

Fig. 3Characteristics of MPP at d=0.2mm

The method uses transfer function between the both signals according to the ISO 10534-2.The sample is represented by a stainless-steel sheet with diameter of 28mm, with perforations diameter d=5e-04m, sheet thickness t=5e-04 m, distance between perforations b=1.5e-03 m, resulting a porosity of σ=8.73%. Two different back air cavity lengths were measured D1,2=0.02 and 0.04 m. The tested sample and the impedance tube.

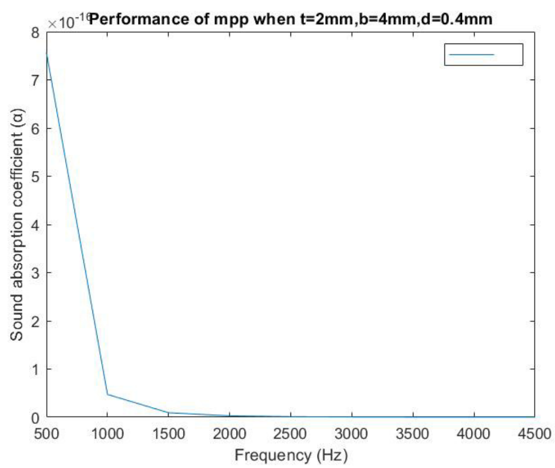

Fig. 4Characteristics of MPP at d=0.4mm

According to the ISO 10534-2, the acoustic absorption coefficient is obtained by using two microphones (M1, M2) positioned at a distance from the sample. The standard position is with microphone M1 in position A and M2 in position B, from which the uncorrected transfer function between them H I 12 is measured.

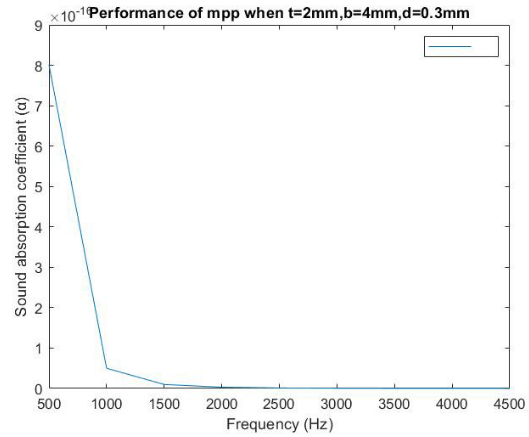

Fig. 5Characteristics of MPP at d=0.3mm

In order to increase the precision of the measurements, the standard provides phase and amplitude calibration, technique that consists in microphones interchange.

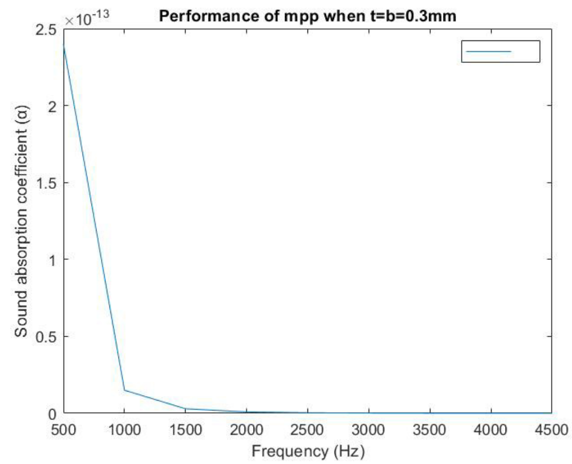

Fig. 6Characteristics between sound absorption coefficient and Frequency at t=b=0.3mm

The second uncorrected transfer function is measured by placing microphone M1 in position B and the microphone M2 is placed in position A.

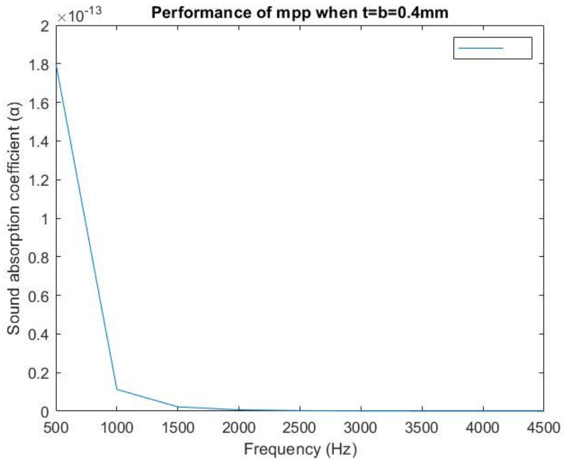

Fig. 7Performance characteristics between sound absorption coefficient and Frequency at t=b=0.4mm

Using the two transfer functions, the corrected transfer function is obtained:

$$H_{12}(\omega) = \sqrt{H_{12}^{I}(\omega) * H_{12}^{II}(\omega)} \quad (15)$$

The acoustic reflection coefficient R(ω) is determined by using the corrected transfer function:

$$R(\omega) = \frac{e^{-jk_0 s} - H_{12}(\omega)}{H_{12}(\omega) - e^{jk_0 s}} e^{2jk_0 x_1} \quad (16)$$

in which s represents the distance between the microphones, x1 the distance from the sample to the M1 in standard position and k0 is the wavenumber.

$$\alpha = 1 - |R(\omega)|^2 \quad (17)$$

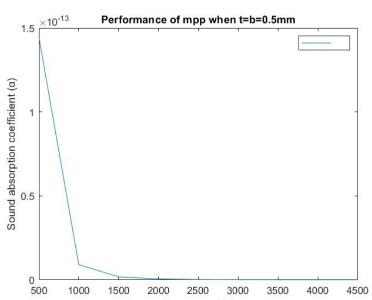

Fig. Performance characteristics between sound absorption coefficient and Frequency at t=b=0.5mm

The acoustic absorption coefficient at normal incidence is determined from the reflection coefficient.

V. CONCLUSION

Many studies were made on micro perforated panel with porosity lower than 3%, which provides sufficient resistance to dissipate the acoustic energy in heat. Finding on market MPP with low porosity can be a problem but a solution is to use existing MPP with high POA. The aim of this study was to compare several models from the literature, to see which one provide the closest results to the impedance tube measurement. The FEM DBLNSF model results can be declared the most precise method. The main advantage is given by the possibility to determine the impedance even for complex perforation shapes or non-uniformly distributed perforations, but the major disadvantage is represented by the long computing time. Small elements must be used in the area of the viscous and thermal boundary layer, to observe better the visco-thermal effects and to increase the precission of the computation. Comparing the results of TMM with the Beranek model, from the point of view of absorption maxima and their frequencies, the second model can be considered more precisely. Taking into account the simplicity of the Beranek model, this can be chosen as the optimum model in impedance calculation of the MPP with high POA. In the next researches, it is intended to raise the acoustic resistance of high POA MPP by using metallic micromesh and to study the influence on the acoustic impedance by decreasing the air density from the cavity, which can be conducted by creating a semi vacuum condition.

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