NONLINEAR ACOUSTIC PROPERTIES OF PERFORATED LINERS: NEW THEORY AND EXPERIMENT

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1. INTRODUCTION

Drastic noise reduction from modern high-bypass turbofan engines using acoustic liners is an important part of developing a novel environmentally- friendly aircraft engine technology. However, the development of new concepts for effective noise suppression needs more study. In fact, a number of techniques for determining the acoustic impedance of these liners have been developed over the last five decades. In addition, a number of models have been developed to predict the acoustic impedance of locally reacting liners [1-10].

However, the existing models still have some limitations to quantify the effects that are potential contributors to nonlinear impedance at high frequencies. In addition, they need more rigorous investigation in further understanding of diverse physical phenomena involved in the propagation through holes. These phenomena are becoming increasingly complex task because of the nonlinear assumptions due to high sound pressure levels (SPL) or liner material nonlinearities.

In order to circumvent these disadvantages, a new nonlinear impedance model of a micro-perforated panel (MPP) has been developed using an equivalent fluid [2] concept. This model is relatively easy to integrate into the Transfer Matrix Method (TMM) to predict performance of multiple MPP sound absorbers.

2. THEORY

There are a number of classical linear models for micro-perforated plates. Atalla and Sgard [2] give a review and show that a perforated plate or screen can be modeled as an equivalent fluid following the Johnson- Champoux-Allard approach [1] with an equivalent tortuosity:

$$Z_{perf-linear} = j\frac{\omega\tilde{\rho}_e\, t}{\phi} \qquad (1)$$

In this equation ϕ is the percentage of open area (porosity), t the plate's thickness and $\tilde{\rho}_e$ the effective density. The latter is linked to the air density ρ_0 and dynamic tortuosity $\tilde{\alpha}$, where $\tilde{\rho}_e = \rho_0\tilde{\alpha}$ with α_∞ denotes the geometrical tortuosity. To take into account the effects of mass on the pores, the following correction for the tortuosity is used $\alpha_\infty(\omega) = 1 + 2\varepsilon_e/t$. Here r represents the radius of the perforations and ε_e a correction length approximated by: $\varepsilon_e = 0.48\sqrt{\pi r^2}$. The end-correction is based on the low frequency limit of the radiation impedance of a piston in a rigid baffle. This can be implemented assuming that the velocity in the hole is uniform. However, this assumption is not valid at high SPL since this end correction doesn't predict the experimentally observed decrease in the mass reactance with increasing sound intensity. This is perhaps due to the fact that the piston radiation at the ends of the narrow tube is partly blown by the jet formed at high SPL. The classical model involves the effect of the array of holes, especially on the end correction of the hole impedance which needs further investigation. The main goal of this study was to extend the classical model to build a reliable nonlinear model to better describe the nonlinear effects. Therefore it is proposed to change the linear-end correction of the acoustic mass in terms of tortuosity [8, 9]. For this purpose, several schemes have been developed leading to:

$$\alpha_\infty = 1 + \varepsilon_{NL} \times \psi\left(\sqrt{\phi}\right) \times \delta_{lm} \times \frac{2\varepsilon_e}{t} \qquad (2)$$

The proposed nonlinear equivalent tortuosity is given by the following nonlinear end correction. The first term in equation 2 corrects for the non-linear effect on the correction length:

$$\varepsilon_{NL} = \frac{1}{1 + V_{ac}/\phi c_0} \qquad (3)$$

The second term in equation 2 accounts for the effect of adjacent holes on the end correction (Interaction effects) by the Fok function:

$$\psi\left(\sqrt{\phi}\right) = \left[\sum_{n=0}^{8} a_n \left(\sqrt{\phi}\right)^n\right]^{-1} \qquad (4)$$

Its effect is to decrease the end correction with increasing porosity. The nonlinear reactance end correction to account for sound amplitude effects. This is a fit to experimental data, was introduced by Elnady [10]: $\delta_{lm} = 0.5$. In addition, these corrections take into account the effect of vibration of air molecules vibrating tube in the viscous boundary layer [7, 8]. The effect of the vibration of the air particles on the baffle in the vicinity of the aperture increases the thermo-viscous frictions. To take this effect into account, Ingard and Labate [7] proposed an additional factor on the resistive part of the hole impedance. Denoting by R_s the surface resistance, the second resistive part of the viscous loss effect is:

$$\theta_{viscous} = \frac{4R_s}{\phi\rho_0 c}\frac{t}{d} = \frac{\sqrt{8\nu\omega}}{\phi c}\frac{t}{d}, \text{ with } R_s = \frac{1}{2}\sqrt{2\eta\omega\rho_0} \qquad (5)$$

Finally, to account for the effect of high SPL on the flow resistance of the system, including the perforation shape effect, the model of Melling [5] is used to correct the flow resistance of the system:

$$R_{NL} = R_{Melling} = \frac{\left(1-\phi^2\right)}{2c\left(\phi C_D\right)^2} V_{ac} \tag{6}$$

In this equation V_{ac} denotes the flow velocity inside the hole and C_D the perforation discharge coefficient. In consequence, the proposed impedance model takes the form:

$$Z_{perf-Nonlinear} = R_{NL} + \left(\frac{\sqrt{8\upsilon\omega t}}{cd} + j\omega\tilde{\tilde{\rho}}_e t\right) \Big/ \phi C_D\,, \tag{7}$$

with $\tilde{\tilde{\rho}}_e = \rho_0 \tilde{\alpha}_\infty \left(1 + \frac{\sigma\phi}{j\omega\rho_0\tilde{\alpha}_\infty} G_j\left(\omega\right)\right)$ (8)

3. EXPERIMENTAL VALIDATION

The measurements are made using in-house developed nonlinear impedance tube. The tube measurements are based on the classical two-microphone transfer function test method as described in ASTM E1050-98. In-house software was developed in Labview and Matlab to control the measurements and process the data. Reference velocity and pressure were calculated at the surface of the sample by transfer function method. As a first validation of the model, an experimental investigation of the linear and nonlinear impedance of single degree of freedom 1DOF and 2DOF MMP based liners are used with different type of geometric parameter. An equivalent fluid model for MPP was developed and implemented within the TMM methodology. For the experimental investigation, 1mm thick and 1mm diameter aluminum perforated plate samples were tested with different open areas from 4 to 15%. The test sample is a perforated plate backed by a 25mm air cavity. Fifteen perforate samples were tested in all. The impedance tests were performed using pure tones excitations at three SPLs (110, 130 and 150 dB) in the 500 Hz to 6500 Hz frequency range. Figure 1 and 2 show examples of the comparison between test and predictions for the resistance and reactance part at 150 dB SPL. The measured impedance are presented (red curve) and compared to theoretical models (blue curve). This shows that the tests are repeatable.

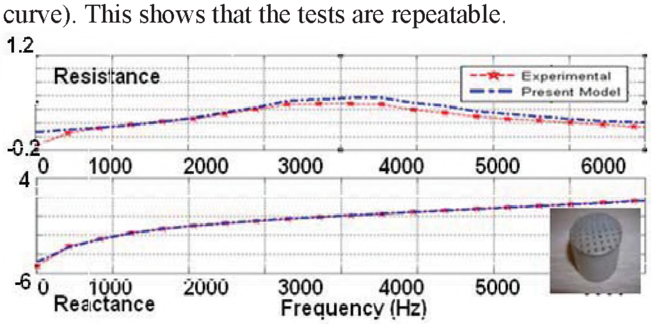

Figure1. Model vs. test: SDOF m with Pure tone 150 dB OASPL MPP A (POA =13.95%) - cavity 25mm

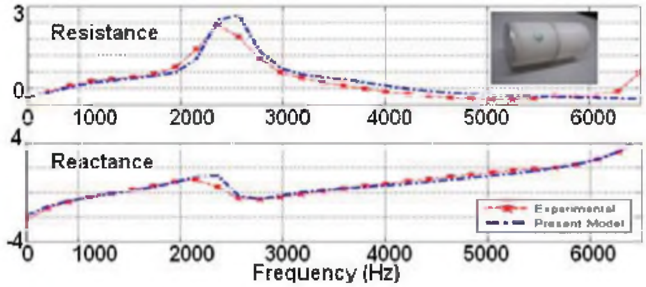

Figure2. Model vs. test: DDOF with Pure tone 150 dB OASPL MPPA (POA =13.95%) – top cavity 25mm - MPP B (POA =7.37%) – bottom cavity 25mm

We can see that there is a good agreement between the model and the experiments for the reactance part. This confirms the correction of the radiation part of the present model. Also, the new model has better prediction in linear and nonlinear regimes.

4. CONCLUSIONS

A fluid equivalent based model for MPP is presented and implemented within the TMM. It was validated in both linear and non-linear regimes using a set of 5 MPPS with various parameters in both SDOF and DDOF configurations. Excellent agreement has been found for the majority of tested configurations. However, more testing and complex configurations, such us combination with Honeycombs with embedded mesh caps, are necessary before the practical use of the model for design purposes.

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