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Non-linear acoustic transfer impedance of micro-perforated plates with circular orifices

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ABSTRACT

A practical description of the transitional behavior of micro-perforated plates (MPPs) is provided between the linear and strongly non-linear regimes. Micro-perforated plates are efficient sound absorbers whose application areas vary from room acoustics to duct acoustics. Although there are accurate models for the linear and strongly non-linear acoustic behavior of MPPs, the transition from one to another has not been a focus of interest so far. A series of measurements are performed with MPP samples for various excitation amplitudes. The deviation from the linear impedance is found to be a function of excitation amplitude and oscillating viscous boundary layer thickness, expressed in terms of the Strouhal number and the Shear number. Typical for MPPs is a Shear number of order unity, implying that the viscous boundary layer thickness is in the order of the perforation radius. Using the measurement data, expressions are proposed for calculating the non-linear acoustic resistance and reactance for circular perforations with sharp square edges. Some additional data is provided for the higher Shear number range. The behavior at low amplitudes for high Shear numbers deviates strongly from the typical MPP behavior. This is due to local vortex shedding at the sharp edges of the perforation.

1. Introduction

Maa [1] introduced the micro-perforated plates (MPPs) as promising sound absorbers in the presence of a supporting air cavity. MPPs are plates with small perforations whose diameter is in the order of a millimeter and low porosity, *i.e.* ~ 1 percent. Due to these features MPPs have high acoustic resistance and low reactance. Moreover, they can be produced from any material, so that their durability and weight can be adjusted according to the application. There are a large number of possible application fields such as room acoustics, duct acoustics and thermo-acoustics.

In many practical applications, even in case of moderate intensity of the incident sound, the acoustic particle velocity in the perforations can reach high values [2]. This results in flow separation and vortices at the sharp edges of the perforations. Vortex formation takes energy from the acoustic wave and as a result increases the acoustic resistance of the perforation.

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Sivian [3] was the first scientist to observe this phenomenon experimentally. Inspired by his findings, Ingard and Labate [4] have performed experiments to conclude that the mechanisms causing extra resistance are flow circulations and these vortices are visualized. Later on, Ingard and Ising [5] have measured quantitatively the non-linear acoustic resistance through an orifice. The orifice used in their experiments had sharp edges. Guess [6] proposes a design method for perforated liners with a backing cavity under high acoustic excitation and subjected to grazing flow. Nevertheless, non-linear effects are included only for the resistance in his method. Later, Disselhorst and van Wijngaarden [7] have measured and described theoretically the amount of dissipated energy due to vortex formation at an open pipe termination and have investigated the influence of rounding off the edges. Cummings and Eversman [8] have improved the quasi-steady model describing the behavior of perforations at high Shear numbers and very high amplitudes of the acoustic particle velocity. In their model, the acoustic flow separates at the sharp edges and forms a free jet with a cross-section smaller than the perforation area, this is called a *vena-contracta*. Testud et al. [9] report that the separated flow reattaches for thick orifices, whose thickness is larger than twice the diameter. Aurégan and Pachebat [10] have studied rigid porous materials both in the moderate and high intensity acoustic amplitudes. One of the most significant observations of this particular study is that in the moderate excitation case the relation between the resistance and Reynold's number is quadratic. Another contribution to the quasi-steady approach for high amplitude acoustic excitation has been provided by Hofmans et al. [11]. Instead of a circular perforation, they have investigated a slit geometry and a method is proposed for obtaining the *vena-contracta* factor as a function of geometry and Mach number of the acoustic jet. Shortly after the study of Hofmans et al., Jing and Sun [12] have proposed an empirical model for the non-linear acoustical behavior of the in-duct orifices. Their focus has been on very high excitation amplitudes. Leung et al. [13] have carried out some numerical experiments with an in-duct orifice with and without flow. They have observed that vortices are shed both upstream and downstream in the absence of main flow, but shedding can take place only in the downstream when there is a bias flow present. Buick et al. [14] have performed a quite comprehensive study including numerical, analytical and experimental results altogether for explaining the acoustic losses in the open termination of a tube. Although the models do not converge perfectly, all of them result in that there are two separate cases in non-linear acoustic absorption: one case in which vortices are formed locally and remain close to the edges; and the other case in which the vortices are shed far from the orifice. Their observations agree with those of Aurégan and Pachebat [10]. A more practical study has been carried out by Park [15]. A design method for MPPs is proposed including the non-linear effects for the impedance. The non-linear resistance term is updated in this study, however for the reactance, an expression from early works of Maa [2] is used. Ji and Zhao [16] have applied the Lattice Boltzmann Method for modelling the non-linear acoustic losses of an in-duct orifice. They have successfully reproduced the experimental results of Jing and Sun [12] and their method promises a less expensive computation compared to classical Navier–Stokes solvers. Nevertheless, none of these studies address MPPs directly. Also, they mainly focus on the regime where strong non-linear effects are observed.

With this study, we focus on non-linear acoustic behavior of MPPs with circular orifices with sharp square edges (90° angle). Besides, we extend our study to plates with perforations whose diameters are larger than those of MPPs. In this way, we link our results with previous studies on orifices whose diameter is larger than the MPP range. Furthermore, we limit the scope of this study to the transition between linear and non-linear regimes, to bridge the gap between these two regimes. Moreover, we investigate both the non-linear acoustic resistance and reactance.

Our results are obtained from open-end transfer impedance measurements. The dimensions of the samples used in these measurements cover both the typical MPP range and slightly beyond. We propose practical formulas forming a bridge between linear and non-linear regimes in MPPs. These formulas are expressed in terms of dimensionless parameters, introduced in the next section.

2. Theoretical background

In the linear regime the absorption of the acoustic energy takes place in the Stokes layers shown in Fig. 1a. These layers form due to the presence of the solid-walled plate [17]. The thickness of the oscillating Stokes layer is $\delta_v = \sqrt{\mu/\omega\rho_0}$ where $\omega = 2\pi f$ is the angular frequency, ρ_0 is the density of air (1.18 kg/m^3@25° C, 1 atm, dry air) and μ is the dynamic viscosity of air (1.85×10^{-5} kg/m s@25° C).

The Stokes layer thickness relative to the perforation diameter d_p is the main parameter that defines a micro-perforated plate (MPP) and is referred to as the *Shear number*,

$$Sh = \frac{d_p}{2\delta_v} = d_p\sqrt{\frac{\omega\rho_0}{4\mu}}. \quad (1)$$

In an MPP the Stokes layers cover almost completely the perforation, *i.e.* $Sh = \mathcal{O}(1)$. For low enough excitation amplitudes, the linear transfer impedance of an MPP is calculated as a function of perforation geometry and frequency only [18].

When the excitation amplitude is larger than a critical value, vortices start forming at the sharp corners of the perforation [5]. This is schematically shown in Fig. 1b. The formation of vortices is a non-linear mechanism. This takes up energy from the acoustic waves resulting in additional absorption. The criterion for these vortices to start forming is based