ESTIMATING SHEAR LOSS IN SMALL ACOUSTICAL CAVITIES

PACS REFERENCE: 43.38.Si

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ABSTRACT

In small cavities, acoustic losses cannot be predicted by the Helmholtz equation. The thermal loss can be taken into account by using complex impedance as it depends on the normal component of the pressure gradient, but the shear resistance depends on the tangential pressure gradient on the boundary. At first order, the shear loss is proportional to the integral of the square of the tangential velocity distribution over the surface.
Using the solution of Helmholtz equation obtained from BEM simulations, we calculate the expected shear loss in cavities. We apply the procedure to estimate frequency dependent lumped resistance of cavities.

INTRODUCTION

In mobile phones the resistive terms are important in order to predict its acoustics. Small cavities incur large boundary layers with respect to size of the cavity. Most of the acoustic design has traditionally been performed with lumped parameter equivalent circuits. However, in higher frequencies and in complicated cavities, the lumped parameter approximation is more complicated to apply, and finally ceases to give correct results as the wavelength of the sound is no more much larger than the size of the geometries involved.

With complicated cavities, the natural first step is to augment the lumped parameter impedances with more accurate acoustical components. One way to derive those is to use Finite Element methods to solve the Helmholtz equation in those cavities. This has been successfully applied [1]. However, a lossless Helmholtz equation is not able to predict the major resistive part of the impedance caused by the boundary shear. R.Bossart and allies developed an iterative approach to solve the problem [2]. We have a similar goal, but we try to circumvent the requirement for multiple solutions required in the method of paper [2]. Our approximation can be regarded as perturbation series of the lossy shear system developed around the solution of Helmholtz equation. The small perturbation parameter is the acoustical loss.

The structure of the paper is as follows. Firstly we will demonstrate our procedure for the lumped parameter equivalent circuit that corresponds our target system of two acoustical cavities. Secondly we will describe the Boundary element simulations used to solve Helmholtz equation. Finally we describe our measurements of the physical system and perform comparison of the system to the simulations.

SIMPLE LUMPED PARAMETER MODEL

The studied system includes two cavities and a narrow tube between them shown in Figure 1. It is very much like the Greenspan viscometer and thus it is obviously sensitive to the viscous losses at the tube.

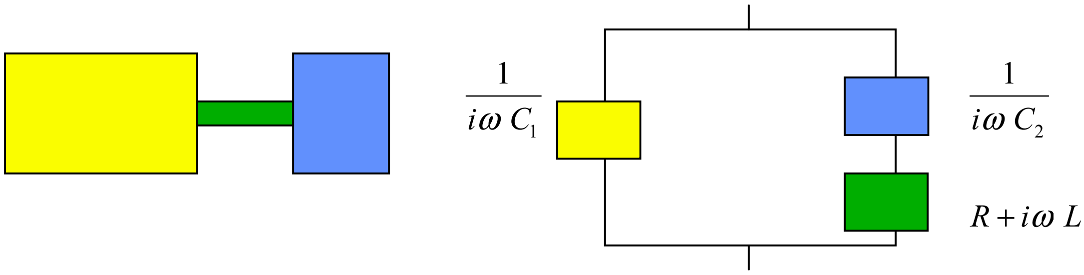


Figure 1 The schematic model of the acoustic cavity and the corresponding equivalent lumped parameter circuit.

According to the Lumped Parameter method the full impedance of the system at circular frequency ω is

$$Z = \frac{1}{i\omega C_1 + \dfrac{1}{\dfrac{1}{i\omega C_2} + i\omega L + R}},$$

where C_1 and C_2 are equivalent acoustical capacitances of the two cavities, L is the acoustical inductance of the tube and R its resistance. All these can be estimated from the geometry of the system in question:

$$C_1 = \frac{V_1}{\rho c^2},\ L = \frac{\rho \ell}{S}\ ,$$

where ρ is the air density, c is the speed of sound in air, V_1 is the volume of the cavity, S is the cross-sectional surface area and ℓ is the effective length of the tube [3,4].

The acoustic loss is significant only in a region at the boundary surface. The width of this boundary layer depends on frequency and the size of the cavity. Capillary effect occurs below the low frequency limit. In that case the boundary layer fills the tube and the resistance of the tube is constant. At higher frequencies, when the boundary layer is smaller than the tube radius, the resistance depends on frequency f

$$R_v = \rho c \sqrt{\frac{f}{f_v}}\frac{A}{S^2},$$

where $f_v \approx 2.7\times 10^9\, Hz$, and A is surface area of the walls.

RESISTANCE FROM FINITE ELEMENT SIMULATIONS

We will estimate the acoustic loss in cavities that arises from shear layer at the boundary layers. The loss that emerges from the thermal conduction is taken into account by using complex impedance at the rigid boundaries [3]

$$\frac{1}{Z} \approx \frac{1-i}{\rho c}\left[(\gamma-1)\sqrt{\frac{f}{f_h}}\right],$$

where $f_h \approx 1.9\times10^{9}\,Hz$ and $\gamma = 1.4$ is the ratio of specific heats. In order to get the shear resistance we use the fact that it depends on the tangential velocity distribution $u_{\tan}$ over the surface. The shear loss P_{shear} in a cavity is (for rms velocity and pressure)

$$P_{shear} = \rho c\sqrt{\frac{f}{f_v}}\int u_{\tan}{}^{2} dA = \frac{c}{4\pi^2 \rho f^2}\sqrt{\frac{f}{f_v}}\int \left|\nabla p\right|_t^{2} dA .$$

Figure 2 shows both the velocity distribution and the shear loss at the boundaries extracted from Boundary Element simulations.

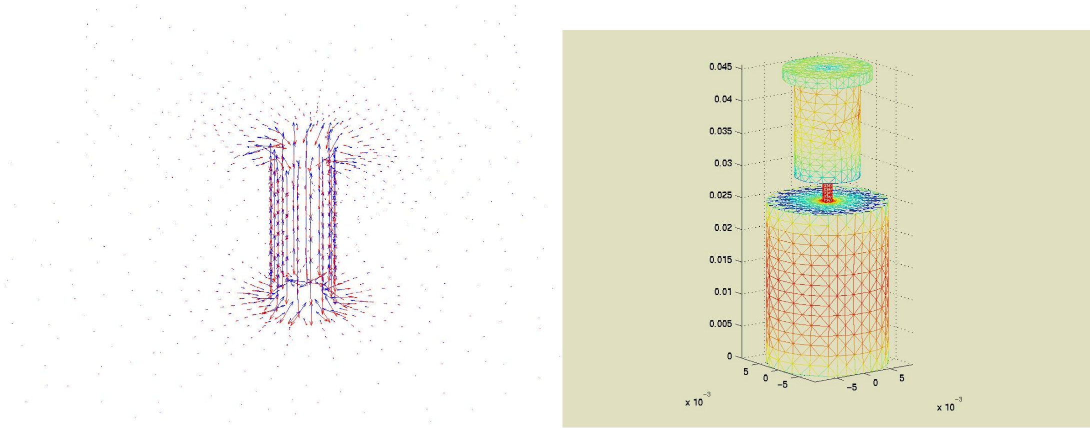


Figure 2 Figure shows the velocity distribution at the tube walls on the left and the logarithmic loss distribution at $f = 6816Hz$ on the right. The blue arrows correspond to real values (in phase with the excitation) and the red ones to imaginary values.

HYBRID METHOD

We express the lossy result in terms of the less loss one by combining Lumped Parameter Model and Boundary Element Method simulations. We assume that we have solved the Helmholtz equation with boundary conditions, which take into account the thermal conduction loss. Let the LPM impedance of this system be Z_0 and the thermal resistance $R = R_{th}$. If we assume that the change in resistance R_{sh} is small we can expand the LPM impedance Z as a perturbation series in terms of Z_0. This leads to equation for the impedance

$$Z \approx Z_0 + R_{sh}\left.\frac{dZ}{dR_{sh}}\right|_{R=R_{th}} = Z_0 + R_{sh}\left[\frac{I_2}{I}\right]^2 = Z_0 + \frac{P_{shear}}{I^2},$$

where I_2 is acoustical current i.e. the flux of the fluid that flows through the tube and I is the total current in the case with thermal conduction loss only. Within the BEM simulation we excite the system with constant volume velocity i.e. current and calculate the incurred power loss at the slit, using the less loss velocity. This procedure gives us the lossy impedance that was our aim.

MEASUREMENT OF ACOUSTIC IMPEDANCE

The acoustic impedance of the system can be determined through measurement. The basic method used determines the acoustic impedance at a point, with pressure measured using a probe microphone, plus a standard ½'' free field microphone acting as a constant volume velocity source [5]. The probe and source microphones are placed close together, positioned at the surface of a flat plate, and can be seen in cross-section in Figure 3.

The acoustic impedance of the test system is determined by:

$$Z_a = \frac{H_a}{H_{ref}} Z_{ref} \quad , \; H_a = \frac{p_a}{v_a} , \;\; H_{ref} = \frac{p_{ref}}{v_{ref}} ,$$

where H_a and H_{ref} are frequency response function measurements of the probe microphone pressure referenced to the source microphone input voltage. Href is measured with an attached volume of known acoustic impedance Zref. Response Ha is measured with the test system attached. Zref is simply the combined volume Veff of the reference cavity and the effective volume of the source microphone such that

$$Z_{ref} = \frac{\rho c^2}{i\omega V_{eff}} .$$

Using this expression limits the impedance measurement to frequencies below the first axial resonance of the reference cavity, which for the measurement system is approximately 8kHz.

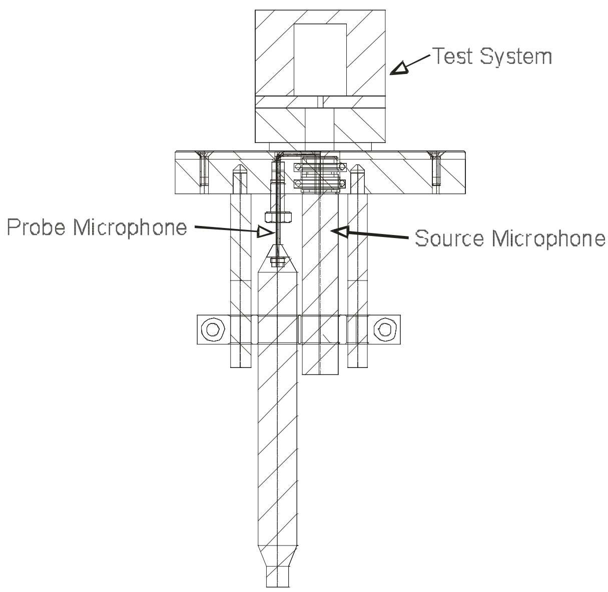


Figure 3 Impedance Probe Structure.

RESULTS

We have performed simulations of the system with I-Deas Vibro-acoustics Boundary Element Solver. Quadratic 8-node elements with few triangular 6-node elements were used in the mesh. The walls of the model were given the appropriate acoustic admittance that provides for the thermal conduction loss. The sizes of the elements were chosen to be small enough to provide good accuracy in the frequency range of interest. The simulation results, complex pressure values at each node, with the element geometry were exported as I-Deas universal files, and post-processed so that they could be imported into Matlab for final post processing.

Figure 4 shows the simulated pressure distribution at the boundary surface of the system. Figure 5 shows the improved estimation for the absolute value of the impedance as a function of frequency compared with the results of the effective Lumped Parameter Model and measurements. The LPM model is not valid at higher frequencies. The thermal and shear loss curves are shown in Figure 6. The estimated values of the shear loss are larger than the values of the thermal loss, which were initially taken into account as boundary condition in BEM simulations. Figure 6 also shows the enhanced impedance and the impedance, which is directly calculated from BEM simulations.

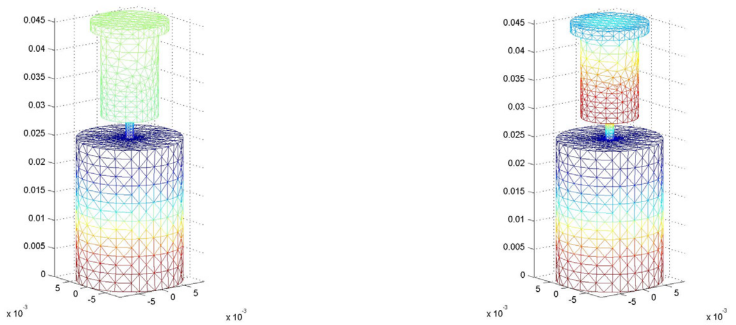


Figure 4 The left figure shows the real part of the simulated pressure at $f = 6816 Hz$. The right figure shows the imaginary part of the pressure.

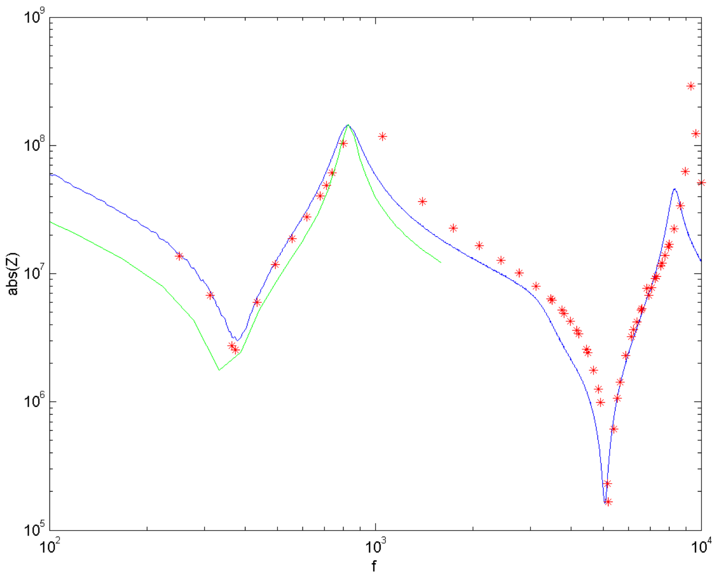
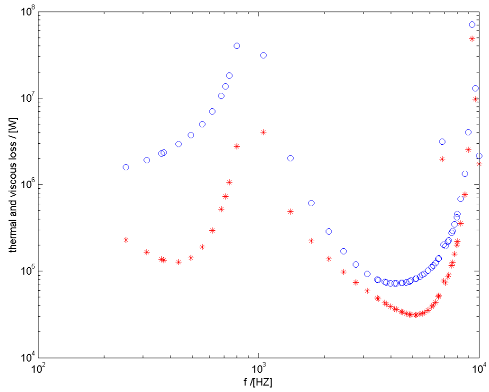


Figure 5 Comparison of the absolute values of acoustic impedances acquired by Lumped Parameter Model (continuous green curve), measurement result (blue curve) and enhanced BEM (red stars).



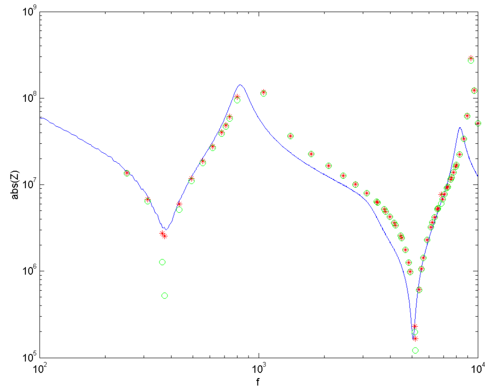


Figure 6 The blue dots above (higher curve) in the higher figure show the shear loss and the red stars (lower curve) show the thermal loss. The red stars in the lower figure show the impedance with our shear loss improvement, the green dots show the impedance calculated directly from the excitation surface of the BEM simulation. The continuous blue curve is the measurement result.

CONCLUSION

We have derived a method to estimate the increase in the input impedance due to shear loss for systems that have been calculated without taking it into account in the first place. The method provides a means to assess where in the system and how large the acoustic shear loss will be. For small shear losses, the perturbative scheme will give also a good quantitative result as shown by our measurements of the actual physical system. The accuracy reached here is sufficient even for advanced mobile phone acoustic design.

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