AN EXPERIMENTAL STUDY OF THE EFFECT OF FLOW AND HIGH LEVEL ACOUSTIC EXCITATION ON THE ACOUSTIC PROPERTIES OF PERFORATES AND ORIFICES

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Perforates are for instance used in mufflers for automotive applications and in acoustic liners for aircraft engines. In these applications they are often exposed to high level acoustic excitation in combination with grazing or bias flow. The paper is based on an experimental study of the nonlinear properties of these types of samples without mean grazing or bias flow as well as on a study of an orifice with bias flow under medium and high sound level excitation. The effect of grazing flow is discussed based on data from the literature. It is known from previous studies that high level acoustic excitation at one frequency will change the acoustic impedance of perforates at other frequencies, thereby changing the boundary condition seen by the acoustic waves. This effect could be used to change the impedance boundary conditions and for instance increase the absorption. It could obviously also pose a problem for the correct modeling of sound transmission through ducts lined with such impedance surfaces. Experimental results are compared to a quasi-stationary model. The effect of the combination of frequency components and phase in the excitation signal is studied. The bias flow tests included different flow speeds for different frequencies. The level of acoustic excitation is varied from much smaller to larger than the mean flow velocity. It is shown that bias flow makes the acoustic properties more complex compared to the no bias flow case, especially when the velocity ratio between acoustic particle velocity and mean flow velocity is near unity.

1. Introduction

Orifice plates and perforates appear in many technical applications where they are exposed to a combination of high acoustic excitation levels and either grazing or bias flow or a combination. Examples are automotive mufflers and aircraft engine liners. Taken one by one the effect of high acoustic excitation levels, bias flow and grazing flow are reasonably well understood. The nonlinear effect of high level acoustic excitation has for instance been studied in[1-11]. It is well known from this literature that perforates can become non-linear at fairly low acoustic excitation levels. The non-linear losses are associated with vortex shedding at the outlet side of the orifice or perforate openings[9-10]. The effect of bias flow has for instance been studied in[12-19]. Losses are significantly increased in the presence of bias flow, since it sweeps away the shed vortices and transforms the kinetic energy into heat, without further interaction with the acoustic field. The combination of bias flow and high level acoustic excitation has been discussed and studied in[18] and some experimental investigations have been made in[19]. Luong[18] derived a simple Rayleigh conductivity model for cases when bias flow dominates and no flow reversal occurs.

If the acoustic excitation is random or periodic with multiple harmonics the impedance at a certain frequency will depend on the particle velocity at other frequencies[20-21]. The present paper discusses the effect of high level multi-tone acoustic excitation on the acoustic properties of perforates and liner samples. It is based on a large experimental study of the nonlinear properties of these types of samples without mean grazing or bias flow. It is known from previous studies that high level acoustic excitation at one frequency will change the acoustic impedance of perforates at other frequencies, thereby changing the boundary condition seen by the acoustic waves. This effect can pose a problem for the correct modelling of sound transmission through ducts lined with such impedance surfaces.

2. Semi-empirical impedance models

Starting for instance from[4] a number of semi-empirical models have been developed to include the effect of high level acoustic excitation, grazing flow and bias flow have been suggested. One example is the model presented in[8] which can be used to compare the magnitude of the terms related to high level nonlinear effects and bias flow, as well as grazing flow. It should be noted that these terms are based on studies of the effect of nonlinearity and flow separately and not simultaneously.

For an orifice with bias flow, a starting point is Cummings[6] empirical equation. It is based on the Bernoulli equation for unsteady flow, which in[18] is written as

$$l(t)\frac{dV(t)}{dt}+\frac{1}{2}\left(\frac{U+V(t)}{C_D}\right)\cdot\left|\frac{U+V(t)}{C_D}\right|+R_L V(t)=\frac{p_0+\Delta p(t)}{\rho_0}, \tag{1}$$

where $l(t)$ is an effective orifice thickness including end corrections which can be time varying, $V(t)$ is the fluctuating acoustic velocity in the orifice, U is the mean flow velocity in the orifice, C_D is a discharge coefficient to consider the vena contracta effect, p_0 is the steady pressure drop and $\Delta p(t)$ is the fluctuating pressure difference over the orifice. A term giving linear viscous losses has been added to Eq. (1).

In the article by Cummings[6] an empirical expression for the time varying effective orifice length was presented

$$l(t)=l_0+\frac{l_W+l_0}{1+\frac{\left(L_V(t)/d\right)^{1.585}}{3}}, \tag{2}$$

where l_0 is the end correction on one side of the orifice, l_W is the orifice length, $L_V(t)$ is a time varying jet length caused by the high level acoustic excitation and d is the orifice diameter. For irrotaional flow,the length is $l(t)$ 2 l_0 + l_W. Cummings suggested that the jet length should be estimated from

$$L_V(t) = \int_0^{\tau} |U + V(t)| dt \,, \tag{3}$$

where τ is the time from the beginning of the previous acoustic half cycle after U+$V(t)$ has changed sign. Here the result of using Eq. (3) has been compared to the assumption that L_V does not vary with time but only with the level of acoustic excitation such that

$$L_V = \int_0^{T/2} |U + V(t)| dt \,. \tag{4}$$

Using an effective hole thickness (l) which can vary between l_0 and $2l_0 + l_w$ we, for the case that there is no flow reversal, get a normalized impedance

$$Z = \frac{\Delta \hat{p}}{\rho_0 c \hat{V}} = ikl + \frac{U}{cC_D^2} + \frac{V}{2cC_D^2} \tag{5}$$

This gives a Rayleigh conductivity

$$K_R = \frac{ik\pi R^2}{Z} = \frac{\pi R^2}{l} \cdot \frac{(\omega l/U)}{(\omega l/U) + \frac{i}{C_D^2}\left(1 + \frac{\hat{V}}{2U}\right)} \tag{6}$$

If this is linearlized a Rayleigh conductivity model was in[18] developed as

$$K_R = \frac{K_0(\omega l/U)}{(\omega l/U) + j/C_D^2} \tag{7}$$

where $K_0 = \pi R^2 / l$ and $l = \pi R/2 + l_W$

3. Experimental setup

Most of the experimental data presented were obtained using an impedance tube with the perforate sample mounted at the end and an open termination behind the perforate sample. The sample was mounted using a holder causing a slight area reduction. The impedance change caused by the holder was measured separately and deducted from the perforate sample results. Three quarter inch condenser microphones were used with microphone separations 0.05 m and 0.3 m. The distance between the sample and the nearest microphone was 0.15 m. Some data was also used from a test setup according to Fig. 1 were a single orifice was mounted in a duct with two microphones on each side. The test object was an orifice plate with 3 mm thickness and 6 mm hole diameter. The orifice plate was mounted in a rigid tube with a diameter of 40 mm. On the left hand side, a high quality loudspeaker was mounted as the excitation source. The microphone separation was in this case 0.18 m. This test rig was used to study the combination of high acoustic excitation levels and bias flow. Tonal excitation was used either with single tone excitation or with a combination of tones with different frequencies.

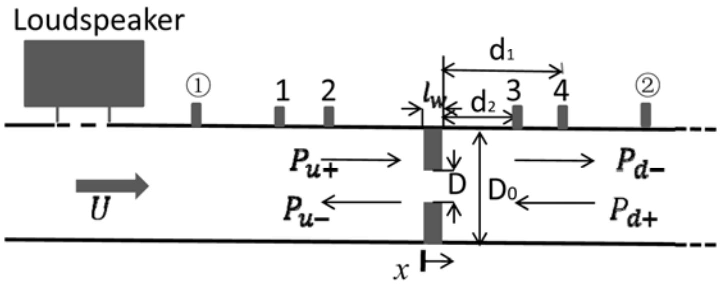
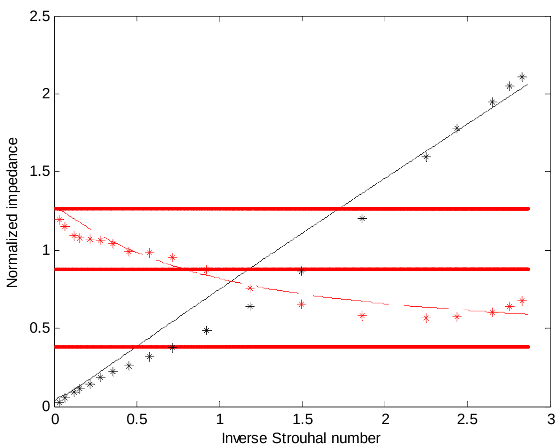


Figure 1. Test rig for measurement of orifice impedance.

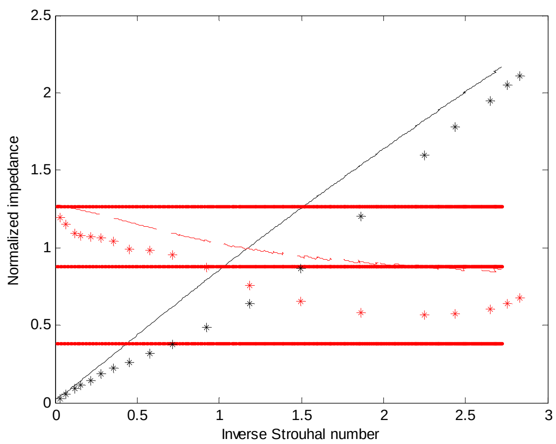
4. Results and discussion

Equation (1) was solved in the time domain using the assumptions regarding the jet length according to Eq. (3) and Eq. (4) for different levels of single tone excitation. The pressure difference was assumed to be sinusoidal and the equation was solved to obtain *V(t)*. The impedance at the frequency of excitation was then obtained by taking the FFT of Δp and V and then dividing the two. These results were then compared to measured impedances. Figure 2 shows results at 200 Hz for the single orifice with 2.25% porosity. It can be seen that the best agreement is obtained using the jet length according to Eq. (4) while the assumption according to Eq. (3) gives an under prediction of the drop in effective orifice length caused by the high level acoustic excitation. The model can give reasonable results when compared to experimental data and will therefore be used to complement experimental results in the subsequent sections.

Figure 3 shows the variation of measured impedance, for a 2% porosity perforate, at 330 Hz and 110 Hz when the excitation at the other frequency is varied. For comparison the impedance obtained using single tone excitation is also included. The resistance increases as the level of secondary tone excitation increases while the reactance decreases. For very high secondary tone excitation levels the impedance will go to minus the impedance seen from the sample back towards the impedance tube[21], so the resistance will have a maximum and then drop down and become negative.



a)



b)

Figure 2. Normalized impedance for single orifice with 2.25 % porosity, plotted against inverse Strouhal number: black stars – measured real part, red stars – measured imaginary part, black solid line – simulated real part, red dashed line – simulated imaginary part, red thick lines – imaginary parts obtained assuming: $l = l_0$, $l = l_0 + l_W$ and $l = 2l_0 + l_W$. a) Jet length according to Eq. (4), b) jet length according to Eq. (3).

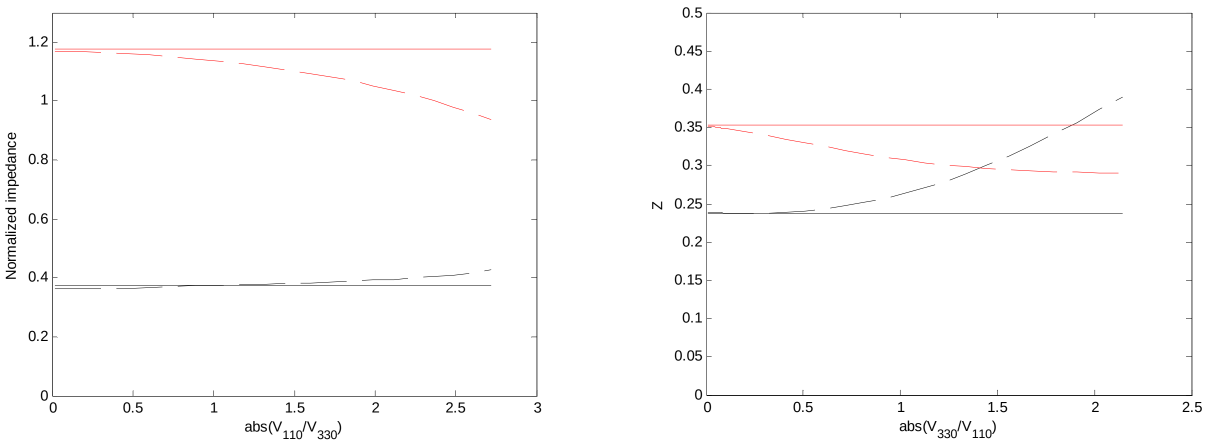
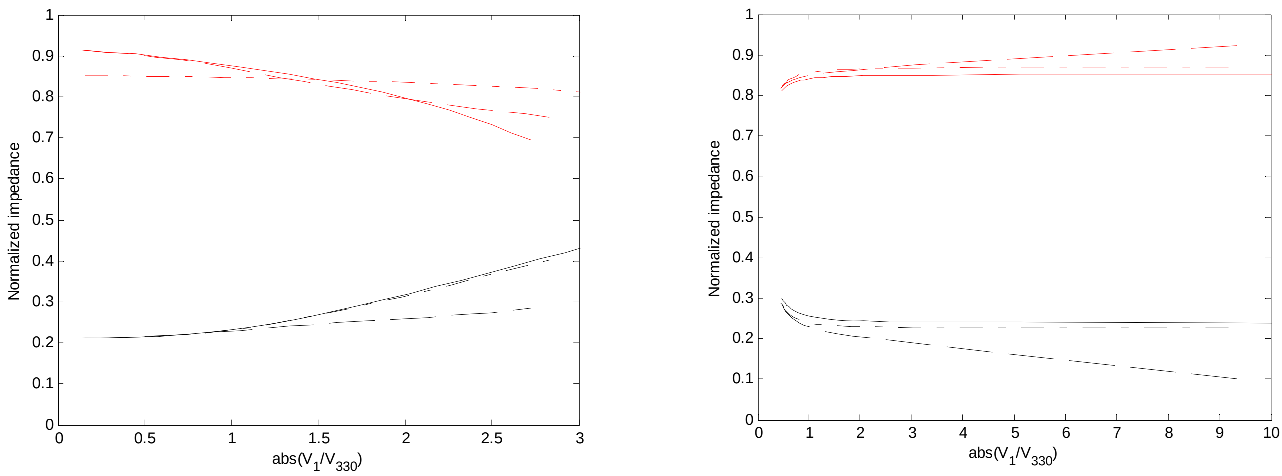


Figure 3. Measured normalized impedance for a perforate with 2 % porosity, plotted against the ratio between velocities at 110 Hz and 330 Hz: a) impedance at 330 Hz: black solid line – real part excitation only at 330 Hz, red solid line – imaginary part excitation only at 330 Hz, black dashed line – real part excitation at 110 Hz and 330 Hz, red dashed line – imaginary part excitation at 110 Hz and 330 Hz, b) impedance at 110 Hz: black solid line – real part excitation only at 110 Hz, red solid line – imaginary part excitation only at 110 Hz, black dashed line – real part excitation at 330 Hz and 110 Hz, red dashed line – imaginary part excitation at 330 Hz and 110 Hz.

Figure 4 presents the results of another experiment where it was studied if it makes a difference for the results obtained using two-tone excitation if the frequencies used are exact harmonics or not. It can be seen that the largest variation is obtained when excitation at 110 Hz interacts with the result at 330 Hz. This again shows that the combination of frequencies does make a difference and that excitation at harmonics have a larger effect compared to excitation at other frequencies.



a) b)

Figure 4. Normalized impedance for perforate with 2 % porosity at 330 Hz plotted against velocity ratio: Black – real part, red – imaginary part, solid line – $V_1 = V_{100}$, dashed line – $V_1 = V_{110}$, dashed-dotted line - $V_1 = V_{120}$. a) Excitation at 330 Hz varied and excitation at the other frequencies kept constant, b) excitation at 100 Hz, 110 Hz and 120 Hz varied and excitation at 330 Hz kept constant.

In order to test if changing the phase of the higher harmonics has an influence on the result a standard impedance tube tests have been made with excitation at 110 Hz and 330 Hz. The level of excitation was varied either by changing the excitation level at 110 Hz or 330 Hz. At each excitation level the phase at 330 Hz was shifted 180 degrees. Figure 5 shows a comparison of experimental results and simulation results for the normalized impedance at 110 Hz obtained when the level of excitation at 110 Hz was varied. In the measurements the phase at 330 Hz was shifted by 180 degrees while a few additional results are shown in the simulation results. When comparing the experimental and simulated results it should be noticed that the reference case shown as solid lines do not have exactly the same phase in the experiments and simulations. What should be compared is the magnitude of the difference caused by a phase shift. It can be seen that this variation is predicted well by the simulation. The phase relation between the tones is of importance at least at higher ratios between the velocities.

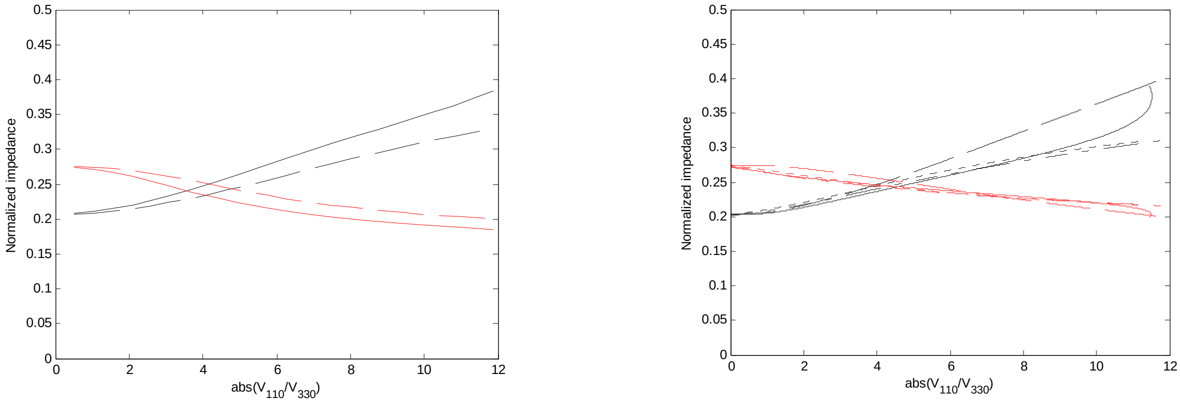


Figure 5. Real and imaginary parts of normalised impedance at 110 Hz for a perforate sample with 2% porosity plotted against velocity ratio for excitation at 110 Hz varied and excitation at 330 Hz kept constant: black – real part, red – imaginary part, solid line – phase at 330 Hz not shifted, dashed – phase at 330 Hz shifted 180 degrees, dashed-dotted – phase at 330 Hz shifted 60 degrees, dotted – phase at 330 Hz shifted 90 degrees. a) Measured, b) simulation.

When there is a bias flow through the orifice the acoustic properties become more complex. Figure 6 shows the normalized impedance as a function of the ratio of oscillating velocity to flow velocity. We divide the results into three parts according to the value of the velocity ratio: much less than unity (I), near unity (II) and much larger than unity (III). The resistance reduces as the velocity ratio increases in region I, has a minimum in region II and then increases in region III where the acoustic particle velocity dominates the behaviour. The reactance has a more complex behaviour and can either initially increase or decrease with increasing velocity ratio in region I. It then has a minimum in region II and the increases in region III to finally approach a constant value.

Figure 7 compares the measured result with Elnady[8] and Cummings model. Neither resistance nor reactance is consistent with experimental data, especially near the ratio of unity. It seems the physics is much more complex and further works should focus on the interaction of frequency, acoustic particle velocities and mean flow velocity.

In the conclusions of[18] it was mentioned that the Rayleigh conductivity for the case without flow reversal ($\left|\hat{V}\right| \leq U$) should approach the result in Eq. (7). In order to check this experimental results for the Rayleigh conductivity has been compared to the model results. Figure 8 shows the Rayleigh conductivity plotted against flow Strouhal number ($\omega R/U$). This means that at each Strouhal number there are a number of experimental data points representing different acoustic particle velocity levels. It can be seen that the Rayleigh conductivity does not exhibit a linear behaviour since the results vary with acoustic excitation level at each flow Strouhal number point. The agreement with the model result is also not very good. It can be seen that by varying the effective hole thickness results of the right order of magnitude can be obtained but it seems that the Rayleigh conductivity has a more complicated dependence on both mean flow velocity and acoustic excitation level than indicated by Eq. (7).

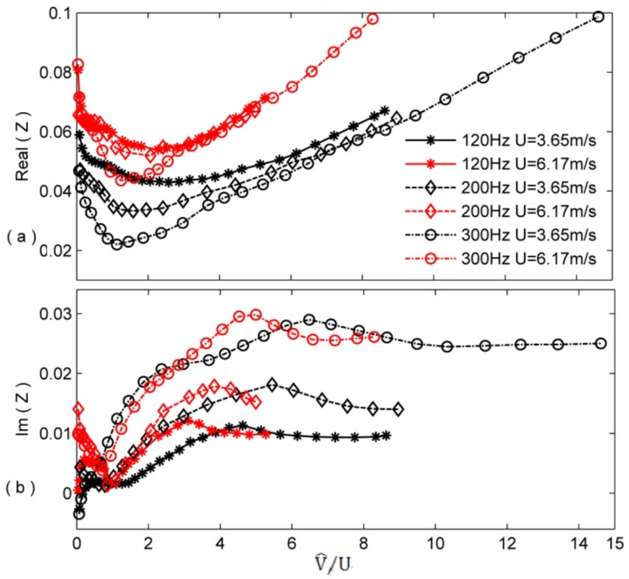


Figure 6. Measured normalized impedance in the orifice as a function of ratio between an acoustic particle velocity and mean flow velocity.

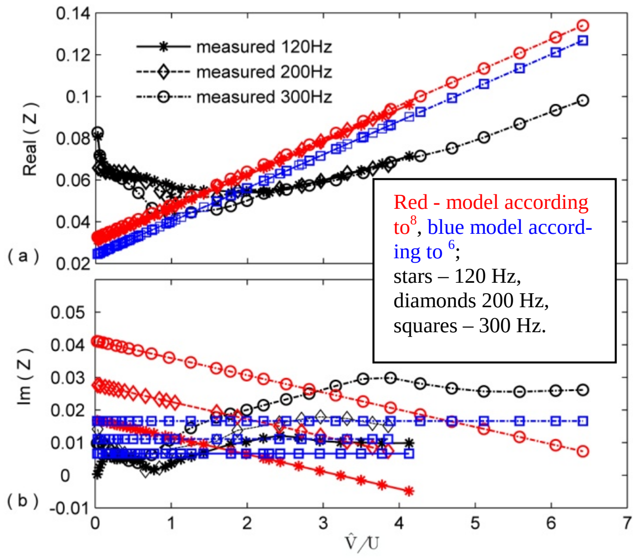


Figure 7. Normalized impedance in the orifice as a function of ratio between an acoustic particle velocity and mean flow velocity (U=6.17 m/s).

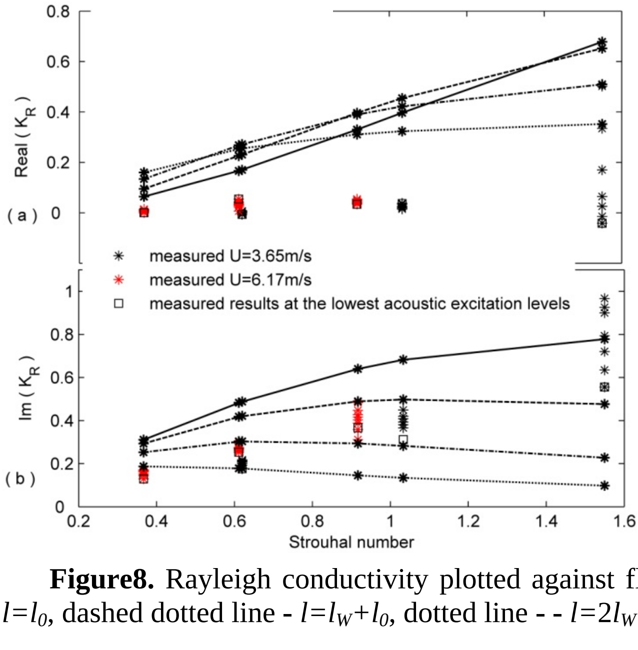


Figure8. Rayleigh conductivity plotted against flow Strouhal number: solid line – $l=l_W$, dashed line – $l=l_0$, dashed dotted line - $l=l_W+l_0$, dotted line - - $l=2l_W+l_0$,

5. Conclusions

The result of high level acoustic multi-tone excitation on the acoustic properties of perforates has been investigated experimentally and using a model. It was shown that a modified version of the Cummings model[6] gives sufficiently good results when compared to experimental data to use the model for parameter variation studies. It was concluded that the combination of frequencies is of importance for multi tone excitation and that harmonically related tones have a stronger influence on the nonlinear interaction results compared to other combinations of frequencies. The phase of the tones used also makes a difference for the result. It was concluded that no single parameter which controls the obtained impedance results for an arbitrary combination of tones could be found.

An experimentally study was also made of the acoustic properties for an orifice plate under high acoustic excitation levels and bias flow conditions. Three regions were identified in terms of the ratio between acoustic particle velocity and mean flow velocity being: (I) smaller than unity, (II) around unity and (III) larger than unity. For region I there was a decrease in resistance and a variation in reactance with velocity ratio. In region II both parts of the impedance had a minimum. In region III resistance increases while the reactance first has an increase and the approaches a constant value. Compared with experimental data, it seems neither the Elnady nor the Cummings model gives a good prediction result since the nonliear acoustic machanism with bias flow is much more comlex than that without. In[8] it was predicted that the Rayleigh conductivity would go to the linearized value according to Eq. (7) for cases when the acoustic particle velocity is smaller than the mean flow velocity in the orifice so that no flow reversal occurs. Comparisons with experimental results shows that this is not the case there is still nonlinear variation In Rayleigh conductivity even when the velocity ratio is small.

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