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Experimental investigation for determination of non-linear properties of perforated plates for tonal, multi tone and random excitation

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Perforated plates are used in numerous applications for noise reduction. Aircraft engines, automotive mufflers, combustion chambers, and gas turbines are examples of applications. An advantage of perforates is the acoustic losses that can be caused by air pumping through the small holes combined with their ability to withstand harsh environments. Many previous studies have shown that they become non-linear and show non-linear acoustic behavior when exposed to high level acoustic excitation. Therefore, it is important to understand their acoustic properties under such conditions. This paper presents a contribution to the ongoing research on non-linear properties of perforates mainly focused on the effect of combined tonal and broadband random excitation. Impedance tube measurements with the perforate sample placed at the open end of the duct has been used to experimentally investigate the nonlinear acoustic properties expressed as the transfer impedance of the perforate.

I. Introduction

Transportation is entering a new age where it faces many challenges i.e., mainly climate change but also noise pollution. EU has high level goals regarding environmental friendliness of air transport as expressed e.g., in the report FLIGHTPATH20250 [1]. Perforated plates and micro-perforated plates (MPP) with different design and material are part of the existing liners used to reduce aircraft engine noise but also part of more novel and innovative solutions to further improve noise reduction. The acoustic properties of perforated plates are known to depend on the environmental conditions they are exposed to such as mean flow and temperature gradients but also on the level of acoustic excitation [2-11][13-15].

The main purpose of this paper is to confirm or rebut some of the findings from the paper by Bodén and Fritzell [12] from 2017. In that paper an investigation of the combined nonlinear acoustic

effects on perforates by using broadband random excitation and tonal excitation was made. The study was made in an impedance tube with the sample placed at the end of the duct with an open end behind. The transfer impedance of the perforate was estimated by taking the difference of the normalized acoustic impedance at the sample surface cross section with and without the sample in place. The conclusions of that paper stated: “An experimental study of nonlinear acoustic interaction effects between pure tone and broadband random excitation of a perforate located at the end of an impedance tube has been made. The data has been presented in two different ways. First it was studied what happened if the pure tone excitation, in terms of voltage of the input signal to the loudspeaker, was kept constant and the level of broadband random excitation was increased. It was found that if the level of pure tone excitation was low the resulting impedance was determined by the level of broadband random excitation. The limited number of data points available indicated that the effect of nonlinear interaction between the tonal and broadband excitation could be detected if difference between the pure tone excitation level and broadband excitation level was around 0 to 10 dB. That is the sound pressure level at the frequency of pure tone excitation was 0 to 10 dB higher than the total broadband sound pressure level.

The second way to study the data was keeping the level of broadband random excitation constant and varying the level of pure tone excitation. The interest here was to see if the variation in tonal excitation changed the impedance measured at other frequencies where only random excitation was present. Nonlinear interaction effects could be found when the level of pure tone excitation was sufficiently high, of the same order of magnitude as the broadband excitation level. The result was an increase in resistance and decrease in reactance. This effect was found also if the broadband random was bandlimited to a maximum frequency lower than half the frequency of tonal excitation.” After the publication of this paper, it was put in question if the broadband change in impedance seen when the level of tonal excitation was increased could be caused by an increase also in broadband excitation associated with the higher tonal excitation. Unfortunately, the input signal to the loudspeaker was not monitored and retained in the 2017 study. So, the purpose of the present investigation is to repeat a similar study while keeping a strict control of the input signal to the loudspeaker.

II. Experimental methodology and setup

A small impedance tube with the sample mounted at the open end of the duct was used for this study, see Fig. 1.

Fig. 1: Impedance tube sketch and photo.

The normalized transfer impedance of the sample was obtained by performing ordinary plane wave decomposition, calculating the normalized impedance at the sample cross section and taking the difference between the impedances with and without the sample in place.

Three microphones were used, and so there are three different microphone separations to be used for the wave decomposition: between microphone 2 and 1 the distance is 0.03385 m, between microphone 2 and 3 0.19993 m, and between microphone 1 and 3 is 0.16608 m. The distance between microphone 2 and the center of the sample is 0.1697 m. The measurement is performed in a semi-anechoic chamber to minimize the effect of reflections and background noise.

To increase the level of excitation and monitor the input signal to the loudspeaker without overloading the data acquisition input a voltage splitter was mounted between the power amplifier and the loudspeaker.

The microphones used were three ¼ -inch GRAS 26CB microphones. The diameter of the test duct is 43 mm. The data acquisition system was a LabView based NI 9324 system controlled by a MATLAB code.

The perforate sample was placed in a holder at the end of the duct and measurements were made with and without the sample. The test sample has 1.2 mm hole diameter, 1.2 mm thickness and 2.45% open area. One of the important characteristics of perforate samples is the hole shape. Fig 2 shows photos of the holes obtained using a microscope.

Fig.2: Photos of the perforate test sample 1.2 diameter and 1.2 thickness 2.4 percentage of open area.

Measurements were made with tonal, multi-tone and random excitation plus combinations of tonal and random excitation for 15 different levels of excitation. For the tonal experiment the frequencies chosen were 210Hz, 320Hz, 630Hz, 960Hz, and for the multi-tone excitation with two frequencies, the combinations 210Hz and 320 Hz, 210Hz and 630Hz, 320 Hz and 960Hz were used. For the broadband random excitation, the experiment was performed for two cases, with and without combination with tonal excitation. The data analysis was made with Welch type averaging and using a Hanning window.

As stated in [12], when analyzing signals with a combination of pure tone and broadband random data it is not obvious how to compare the level of the tonal and broadband part. In a plot of the sound pressure level the broadband level will depend on the frequency resolution used for the spectral analysis. If the frequency resolution is made larger the broadband level in the plot will increase while the pure tone level will remain constant. It is however possible to sum the signal energy of the tone (three frequency components around the signal frequency because of the Hanning window) and the remaining signal when the tone is removed. In this way estimates of the sound pressure level, or particle velocity, of the pure tone and broadband random components can be obtained.

III. Results

A. Preliminary investigation

Figure 3 shows the normalized impedance measured using low level broadband excitation both with and without the perforate sample in place. These results are used for comparison and for calculating the transfer impedance.

Figure 3. Normalized impedance obtained using low level broadband random excitation black-real part, red - imaginary part.

B. Two tone investigation

For comparison with the outcome of the combined tonal and broadband excitation measurements some two-tone excitation results are also shown. The following set of experiments were made

- Pure tone excitation at 210Hz kept constant and level of pure ton excitation at 320 Hz varied
- Pure tone excitation at 210Hz kept constant and level of pure ton excitation at 630 Hz varied
- Pure tone excitation at 320Hz kept constant and level of pure ton excitation at 210 Hz varied
- Pure tone excitation at 630Hz kept constant and level of pure ton excitation at 320 Hz varied
- Pure tone excitation at 320Hz kept constant and level of pure ton excitation at 960 Hz varied
- Pure tone excitation at 960Hz kept constant and level of pure ton excitation at 320Hz varied

Figure 4 shows the result for the case when the excitation at 320 Hz is kept constant and the excitation at 210 Hz is varied and Figure 5 shows results for the case when the excitation at 210 Hz is kept constant and the excitation at 210 Hz is varied.

What can be concluded from these results is that by increasing the level of excitation at one frequency the resistance at the other frequency, where the excitation level in terms of voltage supplied to the loudspeaker is kept constant, is increased and the reactance is decreased. This is accompanied by an increase in sound pressure level at the sample and a decrease in particle velocity. The interpretation of this is that by changing the level of excitation at one frequency the boundary condition (impedance) as seen at the other frequency is also changed thereby changing the sound field in the duct. It is noticeable that increase in resistance at the frequency where the excitation level is kept constant comes with a decrease in the particle velocity. For single tone excitation the increase in resistance is assumed to be driven by an increase in particle velocity, which is also seen at the frequency where the level of excitation is increased.

a) Normalized transfer impedance as function of ratio between particle velocity at 210 and 320 Hz: black: 210 Hz, red: 320 Hz, solid line: real part, dashed line: imaginary part.

b) Normalized transfer impedance as function of particle velocity at 210 and 320 Hz: black – at 210 Hz, red – at 320 Hz, solid line – real part, dashed line – imaginary part.

c) Sound pressure level (Re.20 mPa) at sample surface as function of particle velocity at 210 Hz: black: 210 Hz, red: 320 Hz.

d) Particle velocity incident on sample surface at 320 Hz as function of the particle velocity at 210 Hz.

Figure 4. Results for experiment with tonal excitation at 210 Hz varied and tonal excitation at 320 Hz kept constant.

a) Normalized transfer impedance as function of ratio between particle velocity at 320 and 210 Hz: black – at 320 Hz, red – at 210 Hz, solid line – real part, dashed line – imaginary part.

b) Normalized transfer impedance as function of particle velocity at 210 and 320 Hz: black – at 320 Hz, red – at 210 Hz, solid line – real part, dashed line – imaginary part.

c) Sound pressure level (Re. 20 mPa) at sample surface as function of particle velocity at 320 Hz: black – at 320 Hz, red – at 210 Hz.

d) Particle velocity incident on sample surface at 210 Hz as function of the particle velocity at 320 Hz.

Figure 5. Results for experiment with tonal excitation at 320 Hz varied and tonal excitation at 210 Hz kept constant.

C. Tonal tone and Random investigation

For this case with tonal pure tone and random excitation different sets of measurement were taken:

- Pure tone excitation at 210Hz kept constant and level of broadband random excitation with bandwidth 2 kHz varied
- Pure tone excitation at 320Hz kept constant and level of broadband random excitation with bandwidth 2 kHz varied
- Pure tone excitation at 630Hz kept constant and level of broadband random excitation with bandwidth 2 kHz varied
- Pure tone excitation at 960Hz kept constant and level of broadband random excitation with bandwidth 2 kHz varied
- broadband random excitation with bandwidth 2 kHz kept constant and level of pure tone 210 Hz varied
- broadband random excitation with bandwidth 2 kHz kept constant and level of pure tone 320 Hz varied
- broadband random excitation with bandwidth 2 kHz kept constant and level of pure tone 630 Hz varied
- broadband random excitation with bandwidth 2 kHz kept constant and level of pure tone 960 Hz varied

Here only results for the cases where the broadband level is kept constant, and the tonal level is varied will be shown. The input level to the loudspeaker was checked carefully and it was confirmed that the broadband input level was unchanged as the level of tonal excitation was increased. All the changes seen in the curves with increased level of tonal excitation are therefore caused by nonlinear acoustic effects. Figure 6 to 9 shows the results obtained when the level of broadband excitation, in terms of the input signal to the loudspeaker, is kept constant and the level of tonal excitation at: 210, 320, 630 and 960 Hz is varied.

a) Real part of normalized transfer impedance

b) Imaginary part of normalized transfer impedance

c) Sound pressure level (Re. 210 mPa) at sample surface.

d) Particle velocity incident on sample surface.

Figure 6. Tonal excitation at 210 Hz varied and random excitation kept constant. Black solid line – $L_{p210\text{Hz}} = 125$ dB, $L_{p\text{Random}} = 104$ dB, blue line – $L_{p210\text{Hz}} = 139$ dB, $L_{p\text{Random}} = 105$ dB, magenta line – $L_{p210\text{Hz}} = 146$ dB, $L_{p\text{Random}} = 113$ dB, red line – $L_{p210\text{Hz}} = 150$ dB, $L_{p\text{Random}} = 119$ dB, black dotted line – random excitation only with: 110 dB. Stars pure tone excitation only with 123, 138, 144 and 148 dB.

a) Real part of normalized transfer impedance

b) Imaginary part of normalized transfer impedance

c) Sound pressure level (Re. 20 mPa) at sample surface

d) Particle velocity incident on sample surface.

Figure 7. Tonal excitation at 320 Hz varied and random excitation kept constant. Black solid line – $L_{p320\text{Hz}} = 125$ dB, $L_{p\text{Random}} = 104$ dB, blue line – $L_{p320\text{Hz}} = 140$ dB, $L_{p\text{Random}} = 105$ dB, magenta line – $L_{p320\text{Hz}} = 146$ dB, $L_{p\text{Random}} = 114$ dB, red line – $L_{p320\text{Hz}} = 150$ dB, $L_{p\text{Random}} = 119$ dB, black dotted line – random excitation only with: 110 dB. Stars pure tone excitation only with 124, 138, 144.5 and 148 dB.

a) Real part of normalized transfer impedance

b) Imaginary part of normalized transfer impedance

c) Sound pressure level (Re. 20 mPa) at sample surface

d) Particle velocity incident on sample surface.

Figure 8. Tonal excitation at 630 Hz varied and random excitation kept constant. Black solid line – $L_{p630\text{Hz}} = 106$ dB, $L_{p\text{Random}} = 104$ dB, blue line – $L_{p630\text{Hz}} = 120$ dB, $L_{p\text{Random}} = 103$ dB, magenta line – $L_{p630\text{Hz}} = 126$ dB, $L_{p\text{Random}} = 103$ dB, red line – $L_{p630\text{Hz}} = 130$ dB, $L_{p\text{Random}} = 103$ dB, black dotted line – random excitation only with: 110 dB. Stars pure tone excitation only with 105, 120, 126 and 128 dB.

a) Real part of normalized transfer impedance

b) Imaginary part of normalized transfer impedance

c) Sound pressure level (Re. 20 mPa) at sample surface

d) Particle velocity incident on sample surface.

Figure 9. Tonal excitation at 960 Hz varied and random excitation kept constant. Black solid line – $L_{p960\text{Hz}} = 105$ dB, $L_{p\text{Random}} = 104$ dB, blue line – $L_{p960\text{Hz}} = 119$ dB, $L_{p\text{Random}} = 98.5$ dB, magenta line – $L_{p960\text{Hz}} = 124$ dB, $L_{p\text{Random}} = 110$ dB, red line – $L_{p960\text{Hz}} = 128$ dB, $L_{p\text{Random}} = 116$ dB, black dotted line – random excitation only with: 110 dB. Stars pure tone excitation only with 103, 118, 122 and 126 dB.

It can be seen from these results that varying the level of the tonal excitation we can indeed see an increase in resistance in a frequency range around the frequency of the tonal excitation, especially at lower frequencies. This confirms the conclusions from [12] and it can for instance be seen in Fig. 9 a) that when the tonal excitation at 960 Hz is at 105 dB while the broadband excitation has

a sound pressure level of 104 dB the change in resistance is marginal, but when the tonal level is increased to 119 dB a large change in resistance is seen. The increased level of the tonal excitation is, similar to for the two-tone case, typically associated with a decrease in particle velocity while the sound pressure level at the sample can both increase or decrease. The interpretation is, similar to in the two-tone case, that the increased level of tonal excitation and associated nonlinear effect effectively changes the sample impedance as seen also from other frequencies, for instance increasing the resistance. This changes the boundary condition in the duct and thereby the sound field.

IV. Summary and conclusion

This study was made to confirm or rebut the findings of [12] regarding the effect of combined tonal and broadband random excitation. Especially the result of keeping the level of broadband random excitation constant while changing the level of tonal excitation was of interest since questions were raised regarding if the results seen in [12] could have been caused by an increased broadband excitation in the signal exciting the loudspeaker at the same time as the tonal level of excitation was increased. In the present study the input signal to the loudspeaker was monitored and it was possible to confirm the findings of [12]. An increasing level of tonal excitation gives an increase in resistance in a frequency range around the frequency of the tonal excitation, especially at lower frequencies. The effect seems to be detectable if the difference between the pure tone excitation level and broadband excitation level is around 0 to 10 dB.

The increased level of tonal excitation is, similar to for the two-tone case, typically associated with a decrease in particle velocity. The interpretation is that the increased level of tonal excitation and associated nonlinear effects effectively changes the sample impedance as seen also for other frequencies, for instance increasing the resistance. This changes the boundary condition in the duct and thereby the sound field.

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