Nonlinear Properties of Acoustic Liners Under High Level Random Excitation in Combination with Single-Tone Excitation

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Stockholm 2017-05-22
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Abstract

With the increase in air travels the last decades the number of airplanes have increased dramatically. The sound generated by the engines have become a significant problem. The last 60 years a lot has been made trying to reduce the noise levels. Modern jet-engines generates a combination of broadband random noise and tonal components. Acoustic liners are commonly used sound attenuators in jet-engines. Research has shown that acoustic liners can behave both linearly and nonlinearly depending on the sound pressure level.

Many studies on the nonlinear effects of acoustic liners have been made and in this report the effect of high level broadband excitation in combination with tonal excitation is evaluated. If nonlinear effect occur it can be of importance for future construction of sound attenuators for jet-engines.

The result from this study indicates that at high levels of excitation there is a nonlinear relationship between the random excitation and the tonal excitation. High levels of tonal excitation can increase the level of the random excitation over the full frequency range. For high levels of random excitation the level at the excited tone decreased. Even random excitation at lower frequencies than of the tone can have an effect at the tonal frequency.

Sammanfattning


Mycket forskning har gjorts kring de ickelinjära effekterna hos akustiska liners och i detta arbete undersöks om bredbandigt brus i kombination med toner ger upphov till ickelinjära effekter. Om ickelinjära effekter förekommer kan det vara av intresse vid konstruktionen av ljuddämpning för jetmotorer.

Acknowledgements

First of all I want to thank my supervisor Professor Hans Bodén for introducing me to the subject of acoustic liners. During the whole process of this work Bodén has helped me with everything from introducing me to his own work in the area, the setup of the test, introduction to new equipment and discussions about the results.

I also want to thank Ph.D. student Luck Peerlings for helping me to solve a problem with the test setup and for being very kind and helpful, Research Technician Danilo Prelevic and Researcher Ulf Erik Carlsson for helping me with the access to the laboratory.
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I. Introduction

With the increase of international travels the last decades the number of airplanes have increased dramatically [1]. The last 60 years a lot has been done to reduce the noise generated by the airplanes and especially to reduce the engine noise where most of the sound is produced [2]. Today there are strict noise emission regulations and to be able to meet future regulations continuous research in noise reduction is necessary [3]. With the evolution of jet-engines also the sources of noise in the engines have changed from the 1960 until today. Before the most significant noise was produced by the jet itself resulting in a broadband random noise. Today noise generated by fans inside the engine has become an equally important part of the generated noise [1]. A fan has important tonal components at the blade passing frequency and its multiples [4]. Therefore modern sound absorbents needs to be able to attenuate both random and pure tone components.

One commonly used acoustic absorbent placed inside jet-engines is acoustic liners which has shown desirable acoustic attenuation [5]. The liners can be placed at different places inside the engine and cover the inner walls and are usually placed both upstream and downstream the fans [5]. The single degree-of-freedom (SDOF) liner typically consists of a perforated face-sheet enclosing a cellular structure with cavities mounted on a solid back-sheet [1], see figure 1.

![Figure 1. Picture of an acoustic liner with different perforated plates, a square shaped core and a back-sheet.](image)

This type of liner can be described as an array of Helmholtz resonators which can be said to correspond to a mechanical mass-spring system [1]. The air in the orifices of the perforated plate acts as the mass and the air in the cavities of the cellular structure acts as the spring [6]. The dissipation of acoustic energy which results in the attenuation of the sound is due to friction losses when air is pushed back and forth through the orifices [6].

It has been shown that an acoustic liner can behave both linearly and nonlinearly depending on the sound pressure level [7]. When the sound pressure level is low the acoustic impedance of the liner is independent of the sound field but when the sound pressure level is high it will depend on the particle velocity in the orifices [8]. Normally semi-empirical methods have to
be used to calculate the acoustic properties of liners because of the nonlinearity [7]. Many studies on the nonlinear effects of acoustic liners have been carried out where different aspects such as; flow, pure tone excitation, multi-tone excitation and random excitation etc. have been investigated.

In 1935 L. J. Sivian discovered that the resistance of small orifices in plates depends on the level of the incident sound wave. In his report *Acoustic Impedance of Small Orifices* he writes that his results indicate that the nonlinear effects mostly depends on the velocity rather than amplitude or acceleration [9].

U. Ingård and S. Labate investigated the effect of change in particle velocity and the effect of circulation around the orifices. In their report *Acoustic Circulation Effects and the Nonlinear Impedance of Orifices* from 1950 they describe a strong relationship between the nonlinear acoustic losses and the circulation effect. They found that when the circulation around the orifices started an increase of resistance followed. Their explanation of the nonlinear acoustic losses is that energy is required to drive the circulation currents that occurs at higher velocities [10].

In the report *Experimental Investigation of Nonlinear Acoustic Properties for Perforates* from 2006 by H. Bodén, Y. Guo and H. B. Tözün multiple pure tone and random noise excitation was tested and the impedance calculated. The results showed that when the excitation at one frequency is changed it can effect both the resistance and reactance at other frequencies giving a nonlinear dependency. For both multi-tone excitation and random excitation different impedance results was measured compared to only single-tone excitation [11].

In 2012 H. Bodén investigated the effect of combination of frequency components that was harmonically related to each other. In the report *The effect of high level multi-tone excitation on the acoustic properties of perforates and liner samples* tones that are multiples of each other was tested where the excitation at one frequency was kept constant while the excitation at another frequency was changed. The results showed that when tones that are harmonically related to each other are combined there is a stronger nonlinear influence compared to tones that are not harmonically related [12].

In a following report from 2013 *Acoustic properties of perforates under high level multi-tone excitation* the focus was on combinations of more than two tones at a time. The excitation at one frequency was kept constant while the excitation at other frequencies was varied. The results showed that in addition to tones that are harmonically related also tones that are close in the frequency plane have a stronger influence on each other [13].

In this report the effects of single-tone excitation in combination with broadband random excitation will be investigated. Since jet-engine noise consists of a combination of random and pure-tone components the results from this study can be of importance for future construction of sound attenuators for jet-engines.
II. Two-Microphone Method

The Two-Microphone Method is a frequently used method to calculate a test samples acoustic properties such as reflection coefficient, impedance and absorption factor. The method uses two microphones mounted in a test tube lengthwise separated by a distance \( s \) as seen in figure 2. The distance \( s \) gives a lower frequency limit for the model [14].

![Figure 2. Impedance tube with an acoustic source mounted at the left and the test sample mounted at the right. The incident soundwave propagating to the right and the reflectedsoundwave propagating to the left. The two microphones mounted on the top of the impedance tube separated by a distance \( s \).](image)

By mounting an acoustic source in one end of the tube and the test sample in the other end the sound field in the tube will be determined by the incident and the reflected wave components [15]. The formula can be written as

\[
p(x, f) = \hat{p}_+ (f) e^{-jks} + \hat{p}_- (f) e^{jks}
\]

where ^ denotes the Fourier transform, \( \hat{p}_+ \) and \( \hat{p}_- \) the incident and reflected waves respectively, \( f \) the frequency, \( x \) the position in the tube and \( k \) the wave number. With no flow in the tube the wave number is calculated as

\[
k = \frac{2\pi f}{c}
\]

where \( c \) is the speed of sound in air. This model of the sound field assumes that only plane waves propagate in the duct giving an upper frequency limit for the model [14]. Following from equation (1) the pressure spectra at microphone one can be written as

\[
p_1(f) = \hat{p}_+ (f) + \hat{p}_- (f)
\]

and for microphone two with a length difference of \( s \) as

\[
p_2(f) = \hat{p}_+ (f) e^{-jks} + \hat{p}_- (f) e^{jks}
\]

The reflection coefficient is determined by the ratio between the incident and reflected wave components as

\[
R(f) = \frac{\hat{p}_- (f)}{\hat{p}_+ (f)}
\]

By introducing the transfer function

\[
H_{12} = \frac{p_2}{p_1}
\]

the reflection coefficient can be calculated as
\[
R(f) = \frac{H_{12} - e^{-jk_s}}{e^{jk_s} - H_{12}}
\]

using equation (1)-(6). From the reflection coefficient the acoustic impedance can be calculated as

\[
Z = \rho c \frac{1 + R}{1 - R}
\]

where \( \rho \) is the density of air [16]. The normalized acoustic impedance is calculated as

\[
Z = \frac{1 + R}{1 - R}
\]

When all the parameters are calculated the pressure at all positions in the impedance tube can be calculated using equation (1) where the pressure at the test sample can be of importance. To calculate the sound pressure level the formula

\[
L_p = 10 \cdot \log \left( \frac{\bar{p}^2}{p_{ref}^2} \right) = 20 \cdot \log \left( \frac{\bar{p}}{p_{ref}} \right)
\]

was used where \( \bar{p} \) is the rms value of the sound pressure and the \( p_{ref} \) is a reference value here equal to \( 2 \cdot 10^{-5} \). From the pressure also the particle velocity can be calculated as

\[
u = \frac{p}{\rho c}
\]

In this study this method was used to calculate the reflection coefficient, acoustic impedance, sound pressure level and particle velocity from the measured sound pressures at the two microphone positions.

III. Experimental Setup and Procedure

The test was carried out at the Marcus Wallenberg Laboratory MWL at the Royal Institute of Technology KTH.

A. First test

In the first test an acoustic liner optimized for a frequency of 3000 Hz was used with a perforated face-sheet, square structured core and a solid back-sheet. The liner was mounted in the end of the impedance tube so that the tube was closed. To analyse the signals a SigLab data acquisition system was used from where the results was further processed in Matlab. For conditioning and amplification of the signal a B&K Nexus Conditioning Amplifier and a Stereo Power Amplifier was connected. To generate the sound field a loudspeaker was mounted to the impedance tube. The two microphones was of model 1/4-tum B&K 4338 with B&K 2670 preamplifiers.

To generate the pure tone SigLab’s sinusoidal function was used and to generate the random signal SigLabs random function was used. Three different frequencies for the sinusoid signal was tested; 2700, 3000 and 3300 Hz respectively. For each frequency the excitation was set to three different levels. The random signal was either set to span over the full bandwidth or only over 0-2000 Hz to see if random noise at lower frequencies than the tone still could have an
effect on the tone. For the two types of random signal the excitation was set to five different levels.

All variations of the tonal component was tested to all variations of the random component one at a time. Also the effect of only tonal or only random signal was tested separately for all frequencies and all levels of excitation. The acquisition and averaging was set to stop after as much as 200 averages were completed not to miss the unpredictability in the random signal. Before and after the measurements the microphones was calibrated against each other by mounting them in a closed tube at the same distance from the wall where the sound pressure should be the same. Also one microphone was calibrated against a known sound pressure level to be able to recalculate the measurements from the test to actual sound pressure levels.

The results of this test did not show any significant non-linear effects. One problem might have been that the Stereo Power Amplifier got overheated when the level of excitation was set to high. If the level could have been higher non-linear results might have occurred. Therefore a new test was carried out where the Stereo Power Amplifier was changed and also the impedance tube and the perforated plate.

B. Second test

In the second test the same test setup was used except for the change of Stereo Power Amplifier and impedance tube with a connected perforated plate. For this test the perforated plate used was mounted to the end of the tube without cellular structure and back-sheet so that the termination behind the perforated plate was open, see figure 3.

![Figure 3. The perforated plate used in test two with an open termination.](image)

Also three microphones was used instead of two to be able to cover a wider frequency range with two different microphone separations $s_1$ and $s_2$. For the lowest frequency interval, 0-274 Hz, the longer distance $s_2$ was used. It could be seen from the measurements that the two different microphone separations overlapped each other under a frequency range and between 275-364 Hz the average of the two was used. Above 364 Hz the results from the shorter microphone separation was used. The impedance tube that was used can be seen in figure 4.
This test was carried out at two different frequencies for the sinusoidal signal, 280 Hz and 660 Hz. Each of them was tested at three different levels of excitation. The random signal was both set to span over the full bandwidth, in this test 0-2000 Hz, and to be limited to frequencies lower than the tonal excitation. For the 280 Hz tone the bandwidth was set to 0-100 Hz for the limited case and for the 660 Hz tone to 0-200 Hz for the limited case. All types of random noise was evaluated at four different levels of excitation. Each tone and level of excitation was tested to the two types of random noise at all excitation levels. Also in this test only tonal or only random excitation was tested separately. The acquisition and averaging was set to stop after 200 averages were completed. The calibration was completed in a similar way as for the first test but this time all the three microphones was calibrated at the same time in the closed tube.

IV. Results and Discussion

The results presented here is from the second test where the termination behind the perforated plate was open. To be able to analyse the effect of a combination of single-tone and broadband noise first the effect of them separately needs to be evaluated.
A. Single-tone and random noise evaluated separately

In figure 5 the sound pressure level at the sample calculated using equation (1)-(10) is presented for the three levels of pure tone excitation at the two different frequencies, 280 and 660 Hz respectively.

From figure 5 it can be seen that the difference in sound pressure level is less between the two higher levels of excitation than for the two lower levels. The two higher levels are almost similar regarding maximum value. For the two higher levels of excitation the top value is around 125 dB for the 280 Hz tone and 120 dB for the 660 Hz tone. The lowest level of excitation reaches a maximum value of around 105 dB for the 280 Hz tone and 100 dB for the 660 Hz tone.

Also the different levels of excitation for the three types of random excitation was tested separately. Figure 6 shows the sound pressure level and particle velocity at the sample for the 0-100 Hz random excitation at its four different levels of excitation. It was calculated using equation (1)-(11).
It can be seen from figure 6 that there is a reduction in sound pressure level above 100 Hz even though there is still a high increase in sound pressure level also at higher frequencies. For the highest level of excitation the maximum value is around 115 dB and for the lowest around 80 dB. It can be seen that the difference in sound pressure level between the two higher levels is not very big between 0-100 Hz but larger at higher frequencies. The reduction of the particle velocity is faster above 100 Hz compared to sound pressure level. At 200 Hz the particle velocity is reduced a least four times compared to the maximum value for all levels of excitation and above 600 Hz the particle velocity is almost zero for all levels of excitation. Figure 7 and figure 8 shows the same results for the 0-200 Hz and 0-2000 Hz random excitation.

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**Figure 6.** All four levels of excitation for the random noise with bandwidth 0-100 Hz evaluated separately: blue line – 1st level, red line – 2nd level, yellow line – 3rd level, pink line – 4th level. a) Sound pressure level at sample, b) Particle velocity at sample

**Figure 7.** All four levels of excitation for the random noise with bandwidth 0-200 Hz evaluated separately: blue line – 1st level, red line – 2nd level, yellow line – 3rd level, pink line – 4th level. a) Sound pressure level at sample, b) Particle velocity at sample
The results presented in figure 7 is similar to the results for the 0-100 Hz random excitation. There is a reduction in sound pressure level and particle velocity above 200 Hz even though the level is still increased at higher frequencies as well.

![Graph showing sound pressure level and particle velocity](image)

**Figure 8.** All four levels of excitation for the random noise with bandwidth 0-2000 Hz evaluated separately: blue line – 1st level, red line – 2nd level, yellow line – 3rd level, pink line – 4th level. a) Sound pressure level at sample, b) Particle velocity at sample

The results from the 0-2000 Hz random excitation shows that the sound pressure level at the sample is not constant over the full frequency range. A slow reduction can be seen after 600 Hz at it can also be seen that the sound pressure level oscillates depending on the frequency. The two higher levels of excitation is almost the same over the full frequency range measured both for sound pressure level and particle velocity at the sample. The highest level of excitation reaches a maximum sound pressure level of around 100 dB and the lowest a maximum sound pressure level of around 80 dB.

**B. Level of random excitation constant and tonal excitation varied**

Figure 9 shows the sound pressure level at the sample for the two lowest levels of random 0-2000 Hz excitation when it is kept constant and the level of excitation at 280 Hz is varied from zero excitation at 280 Hz up to the third level of excitation.
Figure 9. Sound pressure level at the sample when 0-2000 Hz random excitation is constant and the level of 280 Hz excitation is varied: blue line – no excitation at 280 Hz, red line – 1st level of excitation at 280 Hz, yellow line – 2nd level, pink line – 3rd level. a) 1st level of random excitation, b) 2nd level of random excitation.

The results from figure 9 shows that the two higher levels of tonal excitation effects the sound pressure level over the full frequency range and not only at 280 Hz and its multiples. The two high levels of tonal excitation leads to an increased sound pressure level that follows the variation in the random excitation. For the lowest level of tonal excitation no significant change in sound pressure level at other frequencies than 280 Hz is observed and the blue and red line is overlapping each other in a high degree. This indicates nonlinear effects above a certain level of tonal excitation that effects the random excitation.

When the random excitation is increased to the third level the difference in sound pressure level at other frequencies than 280 Hz and its multiples is reduced as can be seen in figure 10. This indicates that the random excitation in this situation is so high that it dominates over the tonal excitation and the effects seen in figure 9 is eliminated.
Figure 10. Sound pressure level at the sample when 0-2000 Hz random excitation is constant at the 3rd level and the level of 280 Hz excitation is varied: blue line – no excitation at 280 Hz, red line – 1st level of excitation at 280 Hz, yellow line – 2nd level, pink line – 3rd level.

In figure 11 the results at the excited frequency, 280 Hz, is evaluated in detail for the same levels of excitation as in figure 10. Sound pressure level at the sample when the third level of random excitation was kept constant and the tonal excitation was varied. For comparison the sound pressure level measured at 280 Hz with only tonal excitation is plotted in the same figure.

Figure 11. Sound pressure level at the sample when 0-2000 Hz random excitation is constant at the 3rd level and the level of 280 Hz excitation is varied: blue line – no excitation at 280 Hz, red line – 1st level of excitation at 280 Hz, yellow line – 2nd level, pink line – 3rd level, red circle – 1st level of tonal excitation evaluated separately, yellow dot – 2nd level evaluated separately, pink plus – 3rd level evaluated separately.
The results in figure 11 shows that the broadband noise reduces the tonal excitation at 280 Hz. For the first level of tonal excitation, red line, no peak at 280 Hz can be seen and the level is approximately the same as for no excitation at 280 Hz, blue line. For the first level of tonal excitation there is a reduction in sound pressure level of around 7 dB compared to the same tonal excitation evaluated separately. For the second level of tonal excitation, yellow line, only a small peak at 280 Hz can be seen and the reduction compared to when tonal excitation is tested separately is around 18 dB. For the third level of tonal excitation, pink, there is a reduction of around 4 dB compared to the same level of tonal excitation evaluated separately. The result that high level broadband noise instead of increasing the sound pressure level at the excited tone reduces it, indicates a nonlinear relationship.

For comparison the same evaluation but with the lowest level of random excitation can be seen in figure 12. At this lower level of random excitation no significant reduction in sound pressure level at the excited tone can be seen. For all three levels of tonal excitation the random noise have no important effect on the sound pressure level at 280 Hz. This result indicates that the nonlinear effects depends on the level of random excitation.

![Figure 12. Sound pressure level at the sample when 0-2000 Hz random excitation is constant at the 1st level and the level of 280 Hz excitation is varied: blue line – no excitation at 280 Hz, red line – 1st level of excitation at 280 Hz, yellow line – 2nd level, pink line – 3rd level, red circle – 1st level of tonal excitation evaluated separately, yellow dot – 2nd level evaluated separately, pink plus – 3rd level evaluated separately.](image)

When the same evaluation that has been made for tonal excitation at 280 Hz in figure 9-11 is evaluated for the 660 Hz tonal excitation similar results are found. This results can be seen in appendix A. For the two lower levels of random excitation the higher levels of tonal excitation effects the sound pressure level at all frequencies and not only at 660 Hz and its multiples. When the effects at 660 Hz is studied in detail it can be seen that high levels of random excitation reduces the sound pressure level of the tonal excitation at 660 Hz.
In figure 13 the absolute value of the reflection coefficient calculated using equation (1)-(7) is evaluated when the random 0-2000 Hz excitation is constant and the tonal excitation is varied at 280 Hz. The results are presented for all four levels of random excitation.

The results from figure 13 shows that for the two lowest levels of random excitation the tonal excitation effects the reflection coefficient at all frequencies and not only at 280 Hz and its multiples. This effect occurs for the two higher levels of tonal excitation. For the lowest level of tonal excitation there is no significant difference compared to no tonal excitation except below 300 Hz. For the two higher levels of random excitation there is no significant effect on the reflection coefficient when the tonal excitation is varied. This result indicates that high
levels of tonal excitation effects the reflection coefficient at all frequencies but when the random excitation is high the effect of the random excitation is dominating over the tonal excitation. This effect could also be seen when sound pressure level was evaluated in figure 9 and figure 10.

In figure 14 the absolute value of the reflection coefficient when the tonal excitation at 660 Hz is varied is presented. The results are evaluated for all four levels of random excitation at 0-2000 Hz.

Figure 14. Absolute value of the reflection coefficient when 0-2000 Hz random excitation is constant and the level of 660 Hz excitation is varied: blue line – no excitation at 660 Hz, red line – 1st level of 660 Hz excitation, yellow line – 2nd level, pink line – 3rd level. a) 1st level of random excitation, b) 2nd level of random excitation, c) 3rd level of random excitation, d) 4th level of random excitation.
In figure 14 similar results can be seen as in figure 13 when excitation at 280 Hz was evaluated. For the two lower levels of random excitation high levels of tonal excitation effects the reflection coefficient at all frequencies but the effect is less compared to 280 Hz excitation. One difference between excitation at 280 Hz and 660 Hz is that for the 280 Hz excitation peaks in the reflection coefficient can be seen at 280 Hz and its multiples. For the 660 Hz excitation no peak at 660 Hz and multiples of 660 Hz is present.

The real part of the normalized acoustic impedance calculated using equation (1)-(9) is evaluated in figure 15. All levels of 0-2000 Hz random excitation is evaluated for all levels of tonal excitation at 280 Hz.

![Figure 15. Normalized real part of the acoustic impedance when 0-2000 Hz random excitation is constant and the level of 280 Hz excitation is varied: blue line – no excitation at 280 Hz, red line – 1st level of 280 Hz excitation, yellow line – 2nd level, pink line – 3rd level. a) 1st level of random excitation, b) 2nd level of random excitation, c) 3rd level of random excitation, d) 4th level of random excitation.](image-url)
The results presented in figure 15 shows that for the two lower levels of random excitation high level single tone excitation at 280 Hz effects the acoustic impedance. For the lowest level of tonal excitation the impedance is almost the same as for the no tonal excitation case. The effect of the high tone excitation is less significant at the second level of random excitation but follows the same pattern as for the first level. For the two higher levels of random excitation the real part of the acoustic impedance is almost the same for all levels of tonal excitation.

In figure 16 the same evaluation but for excitation at 660 Hz is shown as for 280 Hz in figure 15. The real part of the acoustic impedance is evaluated when the tonal excitation is varied.

Figure 16. Normalized real part of the acoustic impedance when 0-2000 Hz random excitation is constant and the level of 660 Hz excitation is varied: blue line – no excitation at 660 Hz, red line – 1st level of 660 Hz excitation, yellow line – 2nd level, pink line – 3rd level. a) 1st level of random excitation, b) 2nd level of random excitation, c) 3rd level of random excitation, d) 4th level of random excitation.
The result in figure 16 shows that a variation in tonal excitation at 660 Hz did not have any major impact on the real part of the acoustic impedance. Some smaller differences occurs above 1100 Hz but compared to the differences noticed for the 280 Hz excitation the effect is small. This indicates that the nonlinear relationship between random and tonal excitation that has been noticed in this study also might depend on other factors such as the shape of the perforated plate.

When the imaginary part of the acoustic impedance is studied and the same comparison as for the real part is evaluated similar results are found. The results can be seen in appendix B. High levels of tonal excitation at 280 Hz effects the imaginary part of the impedance when the random excitation is low. For the tonal excitation at 660 Hz no significant differences in the impedance was calculated when the excitation at 660 Hz was varied.

C. Level of tonal excitation constant and random excitation varied

When the tonal excitation at 280 Hz is kept constant and the random 0-2000 Hz excitation is varied the results for sound pressure level can be seen in figure 17. The result focuses on what happens at 280 Hz and for comparison the same level of tonal excitation without random excitation is plotted as a black circle.
Figure 17. Sound pressure level at the sample when tonal excitation at 280 Hz is constant and the level of 0-2000 Hz random excitation is varied: blue line – 1st level of random excitation, red line – 2nd level of random excitation, yellow line – 3rd level of random excitation, pink line – 4th level of random excitation, black circle – tonal excitation at 280 Hz without random excitation. a) 1st level of tonal excitation, b) 2nd level of tonal excitation, c) 3rd level of tonal excitation.

In figure 17 it can be seen that when the random 0-2000 Hz excitation is increased the sound pressure level at the tonal excitation is reduced. For the lowest level of tonal excitation the two lowest levels of random excitation do not have any noticeable effect on the sound pressure level at 280 Hz. For the two higher levels of random excitation however there is a reduction in sound pressure at 280 Hz and a peak at the excited tone can no longer be seen. For the second level of tonal excitation there is a reduction in sound pressure level at 280 Hz for the three higher levels of random excitation. For the two higher levels of random excitation the reduction at 280 Hz is almost 25 dB and for the highest level no peak at 280 Hz can be seen. When the highest level of tonal excitation is studied similar results follows, there
is an increasing reduction at 280 Hz when the random excitation is increased but a peak at 280 Hz can still be seen at the highest level of random excitation. The results presented in figure 17 indicates that at a certain relationship between tonal and random excitation the sound pressure at the excited tone starts to decrease when the random excitation is increased. The sound pressure level can decrease until no peak at the excited tone can be seen.

The same evaluation but for the 660 Hz tone can be seen in figure 18. The results obtained when excitation at 660 Hz is studied is similar to the results obtained when 280 Hz excitation is evaluated.

![Figure 18. Sound pressure level at the sample when tonal excitation at 660 Hz is constant and the level of 0-2000 Hz random excitation is varied: blue line – 1st level of random excitation, red line – 2nd level of random excitation, yellow line – 3rd level of random excitation, pink line – 4th level of random excitation, black circle – tonal excitation at 660 Hz without random excitation. a) 1st level of tonal excitation, b) 2nd level of tonal excitation, c) 3rd level of tonal excitation.](image-url)
The result in figure 18 shows that also when excitation at 660 Hz is studied an increased level of random 0-2000 Hz excitation reduces the sound pressure level at the excited tone. The highest reduction in sound pressure level can be seen for the second level of tonal excitation where the two highest levels of random excitation give a reduction of almost 25 dB.

When the random excitation is limited to frequencies lower than the frequency of the excited tone a reduction of sound pressure level at the excited tone can still be seen. In figure 19 the sound pressure level is evaluated at 280 Hz for the 280 Hz tone when the 0-100 Hz excitation is varied. For comparison, the sound pressure level at the same level of tonal excitation but without random noise is plotted as a black circle.

![Figure 19](image.png)

**Figure 19.** Sound pressure level at the sample when tonal excitation at 280 Hz is constant and the level of 0-100 Hz random excitation is varied: blue line – 1st level of random excitation, red line – 2nd level of random excitation, yellow line – 3rd level of random excitation, pink line – 4th level of random excitation, black circle – tonal excitation at 280 Hz without random excitation. a) 1st level of tonal excitation, b) 2nd level of tonal excitation, c) 3rd level of tonal excitation.
In figure 19 it can be seen that when the 0-100 Hz random excitation is increased it leads to a reduction in sound pressure level at 280 Hz. What must be taken into account is that even if the random excitation is set to span over 0-100 Hz there is still an increased sound pressure level also at higher frequencies as was discussed in section IV A. Therefore, it can’t be determined if the reduction seen at 280 Hz depends on the higher excitation below 280 Hz, the increased sound pressure level at 280 Hz or a combination of the two. If the result in figure 19 is compared with the result in figure 17 and the sound pressure level above and below 280 Hz is compared for different levels of random excitation the tendency is that the excitation below 280 Hz can have an effect on the reduction at 280 Hz.

In appendix C the limited 0-200 Hz random excitation in combination with the 660 Hz tonal excitation is evaluated for sound pressure level. The result can be compared with the results found in figure 19. An increase in random 0-200 Hz excitation led to a decrease in sound pressure level at the excited 660 Hz tone.

As was discussed in section IV A for the two cases with limited random excitation the reduction above the upper limit was faster for particle velocity than for sound pressure level. In figure 20 the particle velocity at the sample when the tonal excitation at 280 Hz is constant and the level of random 0-100 Hz excitation is varied is evaluated. The black circle indicates the particle velocity at the sample with only tonal excitation at 280 Hz and no random excitation.
Figure 20. Particle velocity at the sample when tonal excitation at 280 Hz is constant and the level of 0-100 Hz random excitation is varied: blue line – 1st level of random excitation, red line – 2nd level of random excitation, yellow line – 3rd level of random excitation, pink line – 4th level of random excitation, black circle – tonal excitation at 280 Hz without random excitation. a) 1st level of tonal excitation, b) 2nd level of tonal excitation, c) 3rd level of tonal excitation.

The result in figure 20 shows that the particle velocity at 280 Hz is reduced when the random 0-100 Hz excitation is increased. It can be seen for the two higher levels of tonal excitation that even though the particle velocity below and above 280 Hz is almost zero the higher levels of 0-100 Hz random excitation generates a significant reduction in particle velocity at 280 Hz. This indicates that an increased particle velocity at lower frequencies than the excited tone can have a significant effect on the particle velocity at the tonal frequency.
The same evaluation of particle velocity at the sample but for the 660 Hz tone and limited random excitation at 0-200 Hz can be seen in figure 21.

![Graph 1](image1)

**Figure 21.** Particle velocity at the sample when tonal excitation at 660 Hz is constant and the level of 0-200 Hz random excitation is varied: blue line – 1st level of random excitation, red line – 2nd level of random excitation, yellow line – 3rd level of random excitation, pink line – 4th level of random excitation, black circle – tonal excitation at 660 Hz without random excitation. a) 1st level of tonal excitation, b) 2nd level of tonal excitation, c) 3rd level of tonal excitation.

The result from the study of the limited random excitation indicates that random excitation at 0-200 Hz have a small effect on the particle velocity below and above 660 Hz. For the second level of tonal excitation the particle velocity at 660 Hz is reduced multiple times. The result from the study of the limited random excitation indicates that random excitation at
lower frequencies than the exited tone still can effect both sound pressure level and particle velocity at the excited tone which also effects the acoustic impedance.

V. Conclusions

The results presented in this study indicates that there is a nonlinear relationship between random excitation and tonal excitation at high levels of excitation. At lower levels of random excitation high levels of tonal excitation effects the acoustic properties at all frequencies and not only at the tonal frequency and its multiples. The high levels of tonal excitation increased the sound pressure level, reduced the reflection coefficient and effected the acoustic impedance. It could also be seen that the effect on the reflection coefficient and acoustic impedance was stronger for the 280 Hz tone than for the 660 Hz tone indicating that the shape of the perforated plate influences the nonlinear relationship.

The results also showed that high levels of random excitation can reduce the sound pressure level and particle velocity. Low levels of random excitation did not effect the sound pressure or particle velocity at the excited tone. When the random excitation was increased the level at the excited tone started to decrease which indicates a nonlinear relationship. The measured level at the tone can decrease until no peak at the excited tone can be seen. The maximum reduction in sound pressure measured in this test was as much as 25 dB which can make a significant difference for the human hearing.

When the random excitation was set to span over a frequency range lower than the excited tone a reduction in sound pressure level and particle velocity at the tonal frequency could still be seen. Even though the limited random excitation had an effect on the background level also above its upper limit and at the tonal excitation, that effect ought to be smaller than the measured reduction. That indicates that an increased level of random excitation also below the excited tone can have an influence on the measured level at the tonal frequency.

The result of this study indicates that there are certain levels of excitation where the nonlinearity starts to appear. The level seems to depend on both the random excitation and tonal excitation and it could be seen that at certain levels one starts to dominate over the other. At other levels there is a strong interaction between them, and small changes in one of them effects the other.
VI. References


Appendix A – Sound pressure level for 660 Hz tone

a) Sound pressure level at the sample when 0-2000 Hz random excitation is constant and the level of 660 Hz excitation is varied: blue line – no excitation at 660 Hz, red line – 1st level of 660 Hz excitation, yellow line – 2nd level, pink line – 3rd level. a) 1st level of random excitation, b) 2nd level of random excitation.

Sound pressure level at the sample when 0-2000 Hz random excitation is constant at the 3rd level and the level of 660 Hz excitation is varied: blue line – no excitation at 660 Hz, red line – 1st level of 660 Hz excitation, yellow line – 2nd level, pink line – 3rd level.
Sound pressure level at the sample when 0-2000 Hz random excitation is constant at the 3rd level and the level of 660 Hz excitation is varied: blue line – no excitation at 660 Hz, red line – 1st level of 660 Hz excitation, yellow line – 2nd level, pink line – 3rd level, red circle – 1st level of tonal excitation evaluated separately, yellow dot – 2nd level evaluated separately, pink plus – 3rd level evaluated separately.

Sound pressure level at the sample when 0-2000 Hz random excitation is constant at the 1st level and the level of 660 Hz excitation is varied: blue line – no excitation at 660 Hz, red line – 1st level of 660 Hz excitation, yellow line – 2nd level, pink line – 3rd level, red circle – 1st level of tonal excitation evaluated separately, yellow dot – 2nd level evaluated separately, pink plus – 3rd level evaluated separately.
Appendix B – Imaginary part of acoustic impedance

Normalized imaginary part of the acoustic impedance when 0-2000 Hz random excitation is constant and the level of 280 Hz excitation is varied: blue line – no excitation at 280 Hz, red line – 1st level of 280 Hz excitation, yellow line – 2nd level, pink line – 3rd level. a) 1st level of random excitation, b) 2nd level of random excitation, c) 3rd level of random excitation, d) 4th level of random excitation.
Normalized imaginary part of the acoustic impedance when 0-2000 Hz random excitation is constant and the level of 660 Hz excitation is varied: blue line – no excitation at 660 Hz, red line – 1st level of 660 Hz excitation, yellow line – 2nd level, pink line – 3rd level. a) 1st level of random excitation, b) 2nd level of random excitation, c) 3rd level of random excitation, d) 4th level of random excitation.
Appendix C – Sound pressure level for 660 Hz tone and limited random excitation

Sound pressure level at the sample when tonal excitation at 660 Hz is constant and the level of 0-200 Hz random excitation is varied: blue line – 1st level of random excitation, red line – 2nd level of random excitation, yellow line – 3rd level of random excitation, pink line – 4th level of random excitation, black circle – tonal excitation at 660 Hz without random excitation. a) 1st level of tonal excitation, b) 2nd level of tonal excitation, c) 3rd level of tonal excitation.
Appendix D – Time schedule and work process

Planering i form av ett Gantt-schema