Experimental investigation of reflection and flow generated exhaust system tailpipe noise

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I. Abstract

This report concerns the sound generated in straight pipes. The task, formulated in cooperation with Scania, consisted in the investigation of the behaviour of the reflected sound at the outlet of a regular straight pipe and its relation with the total sound generated. The main objective was to find the location where this sound was generated in order to study it and thus reduce it.

In order to attain knowledge in the subject the KTH Sound and Vibration[1] book was taken as a reference. Furthermore, previously published articles and reports were read, for instance the J.Y.Chung and D.A.Blaser study of the Transfer function method of measuring in-duct acoustic properties[2] or the multiple microphone method for measuring in-duct acoustic properties in the presence of mean flow[3] of Seung-Ho Jang and Jeong-Guon. Furthermore, the 2015 report by Jonas Barskog, Kristina Bondemark and Viktor Wiese concerning the the flow generated noise in ducts[4] was studied and many of its conclusions are the basis of study of this work.

Additional facts regarding acoustic standards and behaviour of standing waves were compiled and studied. In order to carry out the measurements a test rig was used in the Marcus Wallenberg Laboratory, at KTH. The rig allowed measurements concerning the reflection coefficient and the sound power level with combinations of a straight pipe with and without outlet expansions, as well as with a variable flow velocity. Data from the different set of measurements was collected differently but all the post-processing was carried out in MatLab.

The results and the posterior investigation concerning the reflection phenomena indicated that extra sound radiation had to be produced on the outside of the tube and not inside, being the cause of this phenomena the interaction between the acoustic field and the flow flied.

II. Nomenclature

Variable	Name	Value	Unit
f_c	Center frequency	-	[Hz]
f_l	Lower frequency	-	[Hz]
f_u	Upper frequency	-	[Hz]
L_p	Pressure Level	-	[dB]
L_W	Sound Power Level	-	[dB]
L_{pr}	Pressure reference Level	-	[dB]
L_{Wr}	Sound Power reference Level	-	[dB]
p_{ref}	Reference sound pressure	$2 \cdot 10^{-5}$	[Pa]
$P(x, f)$	Frequency spectrum	-	[Pa]
P_+	Incidence pressure spectra	-	[Pa]
P_-	Reflected pressure spectra	-	[Pa]
Γ_+	Wavenumber in the flow direction	-	-
Γ_-	Wavenumber against the flow direction	-	-
k	Wave number	-	$[m^{-1}]$
c	Speed of sound	343	[m/s]
M	Mach number	-	-
R	Reflection coefficient	-	-
s	Microphone spacing	-	[m]
a	Pipe diameter	-	[m]
M_p	Mach number inside pipe	-	-
M_j	Mach number outside pipe	-	-
Z_p	Acoustic impedance	-	$[Pa \cdot s/m^3]$
S_p	Outlet pipe cross sectional area	-	$[m^2]$

III. Introduction

Nowadays, in our well developed and increasingly technological society the number of systems that emit sound and vibrations is regularly growing. For instance, machines, vehicles and processes of all kinds, are continually being increased even as simultaneous efforts are made to hold down weight and materials usage. This implies the need for an even more intensive research and development effort to identify and alleviate noise and vibration disturbances, and satisfy the needs of mankind for acceptable living and working environments.

Indubitably, SCANIA, the major Swedish automotive industry manufacturer of commercial vehicles is not going to be left behind in this regard. The intention with this report is then not other than the study of the sound generation in pipes focusing on the investigation of the extra radiated noise at low frequencies noticed in previous works for a conical outlet configuration. A very important aspect of this paper is then the research on the location where this extra sound is generated.

In order to sort out this inquiry some experiments concerning a straight pipe with different configurations of outlet and flow were performed in the Marcus Wallenberg Laboratory at KTH. The experiments basically were divided into two bigger groups. On the one hand it was essential to analyze the behavior of the sound waves inside the pipe, in order to do that the reflection coefficient both in the inlet and the outlet was analysed.

On the other hand, it was fundamental to know how much sound energy was emitted by the pipe. For that purpose the sound power level was evaluated. One again, the influence of the outlet shape and the flow velocity was taken into account for the study. All the materials and standards used to carry out all the experiments can be found in next sections.

When all the experimentation was done, data had to be correctly post processed. The software used to carry out this duty was Matlab. Final results are presented in graphical form for easy analysis and conclusions. In the following sections all this is treated in much greater detail, the final results are shown and final conclusions are drawn.

IV. Theory

This section deals with the 'why' and 'how' of all the methods used to carry out the study. First, the whole theory behind the calculation of the reflection coefficient is explained in detail. And finally the procedure to determine the sound power level is developed.

A. Reflection Coefficient

The reflection phenomena is a very interesting acoustic characteristic from which one can get an idea of how the sound behaves inside a pipe. It is the ratio of the reflected sound pressure wave over the incident one and it basically gives the information of how much of the sound energy goes out of the pipe and how much stays in.

In the past, the standing wave ratio (SWR) method using pure tone excitation was the classical acoustic measurement method in ducts with plane wave propagation. Indeed, it is a a reliable and accurate method but also time consuming. However, new technology has made possible much faster and still reliable measurement processes, the two-microphone method (TMM) is an example.

1. Two-Microphone Method

For this experimental study a similar two-microphone method to Blaser and Chung^2 was developed. Pressure measurements taken by the microphones were transformed into transfer functions with the aim to use them later to determine the acoustic reflection coefficient.

In every straight, cylindrical duct, the sound field in the presence of mean flow is considered as depicted in Fig. 1. At one end of the duct exists an acoustic source and a linear passive termination at the opposite end. The sound field for a plane wave propagating in the duct can be expressed as:

$$P(x,f) = P_+(f)exp(i\Gamma_+ x) + P_-(f)exp(i\Gamma_- x) \tag{1}$$

Here Γ_+ and Γ_- denote the incident and reflected plane wave propagation constants, respectively. For this study the attenuation is assumed to be zero so the plane waves are defined as follows.

$$\Gamma_+ = -k/(1+M) \qquad\qquad \Gamma_- = k/(1-M) \tag{2}$$

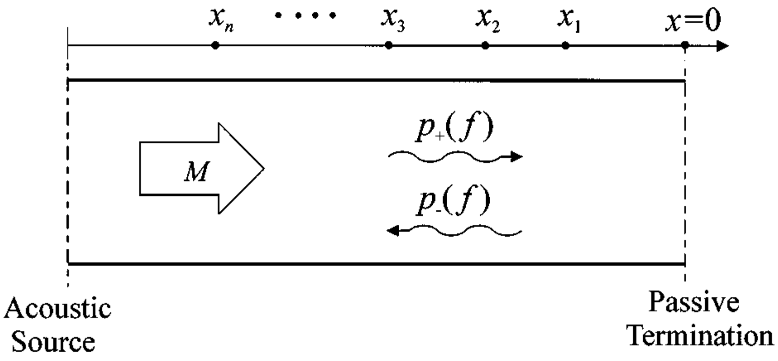

Figure 1 – Sound field in the acoustic duct with mean flow.

TMM requires the use of two microphones, then Eq. (1) can be rewritten in matrix form as follows:

$$Ax = b \tag{3}$$

$$A = \begin{bmatrix} exp(i\Gamma_+ x_1) & exp(i\Gamma_- x_1) \\ exp(i\Gamma_+ x_2) & exp(i\Gamma_- x_2) \end{bmatrix} \qquad x = \begin{Bmatrix} P_+(f) \\ P_-(f) \end{Bmatrix} \qquad b = \begin{Bmatrix} P_1(f) \\ P_2(f) \end{Bmatrix} \tag{4}$$

The problem then simplifies in a system of equations with two equations and two unknowns which can be easily solved for x. Furthermore, from the fact that Eq. (1) never changes by multiplying any complex constant to the reflection coefficient R, the transfer function $H_1(f)$ i.e., $P_1(f)/P_{ref}(f)$, can be used instead of $P_1(f)$ in Eq. (4). Same happens with $H_2(f)$. In this regard, the reference signal $P_{ref}(f)$ is the signal driving the source whichever is common to all measurements.

Finally solving Eq. (3) for x, the spectra of incident and reflected pressures $(P_-(f), P_+(f))$ are determined and can be used to get the final value of the acoustic reflection coefficient.

$$R(f) = \frac{P_-(f)}{P_+(f)} \tag{5}$$

2. Influence of errors

Other objective of this study was to get accurate results, thus, once explained the method by which the reflection coefficient is calculated is important to consider the possible errors that may appear and that were taken into account in order to achieve as much accuracy as possible.

The method used implies that the transfer function, the separation between the microphones (s), and the distance between one of the microphones and the end of the duct are known or can be measured experimentally. Then, the resulting errors in the calculated quantities depend on two things: errors in the input data and sensitivity of calculation formulas to errors in the input data.

From paper of Hans Boden and Matas Abom[5] an important conclusion drawn is that normally there is no problem to keep both the bias and random error in the transfer function estimation at 1% in magnitude and 0.6° in phase. However, error in the lengths has to be also taken into account, an it is at least $\pm 0.5mm$. Then it is necessary to use s $>$ 50mm to obtain error in less than 1%. This means that for microphone separations less than 50 mm, the influence of lenght errors might dominate.

The impact of these errors in the calculated quantities is of great importance and therefore the two-microphone method should only be used in the range where it has its lowest sensitivity to them, a region around $ks = \pi/2$. As a result, the TMM was only used when $0.1\pi < ks < 0.8\pi$ measuring with no flow and when $0.1\pi(1 - M^2) < ks < 0.8\pi(1 - M^2)$ if flow was included.

The frequency spectrum of interest in this study was between 100 Hz and 1000 Hz, however this range was at some point out of the minimum scope error established if the separation between the microphones remained constant. This is the reason of the use of three microphones, the two located further (higher s) were used for lower frequencies while the two closest (lower s) were used for the highest frequencies. Thus, for the entire frequency range of study the minimum error condition was respected.

B. Theoretical Model

In an experimental study is sometimes difficult to know whether the results are completely correct or not, for that reason the study was extended by a comparison with a theoretical model, through which final results could be compared and analyzed better.

1. *Davies Model of reflection coefficient for an unflanged pipe*

A prediction of the acoustic field within, or the acoustic radiation from, a freely discharging unflanged pipe is of interest in many practical situations and requires a quantitative description of the acoustic boundary conditions at the open end. A theoretical determination of both R and l was made by Levine and Schwinger, for M = 0 and their predictions are in good agreement with observation.

The expressions they developed describing the dependence of R and of l/a on the dimensionless wavenumber ka are tedious to evaluate, but a close empirical fit to their results is given by using the following values for the end correction:

$$l/a = 0.6133 - O.l168(ka)^2, \qquad ka < 0.5 \tag{6}$$

$$l/a = 0.6393 - O.l104(ka), \qquad 0.5 < ka < 2 \tag{7}$$

A good approximation to the dependence of R on ka can be obtained over the useful range 0 < ka < 1.5 with M = 0.

$$R = 1 + 0.01336ka - 059079(ka)^2 + 0.33576(ka)^3 - 0.06432(ka)^4 \tag{8}$$

C. Sound power level

The sound power level is a measure of the radiated sound power from a machine, and essentially independent of the acoustic environment, whereas the sound pressure level depends on both the distance and the direction to the machine, and the environment in which it is placed.

For this study, the sound power level was calculated following the standard ISO 3747. This standard describes a method based on relative measurements using a calibrated source. One of the reasons for using this standard lies in the fact that permits reflecting surfaces in the vicinity of the measurement object, condition that holds perfectly with the reverberation room used for the experiments.

It states that for a certain acoustic environment and a specific distance to the sound source the machine's power level L_W can be related to the resulting sound pressure level L_p at a point, using the so called room correction K[dB], in the formula:

$$L_p = L_W + K \tag{9}$$

Then the method is simplified to determine the room correction K. The sound pressure level from the measurement object is measured first, after which is replaced by the calibrated reference source, and the sound pressure level measured again at the same microphone positions. The sound power level L_W of the measurement object can then be determined from:

$$L_W = L_p + (L_{Wr} + L_{pr}) \tag{10}$$

This last formula was the one used to calculate the sound power level for all the different conditions of interest for the experimental study.

V. Experimental Methods

The experiments were performed in the Marcus Wallenberg Laboratory for Sound and Vibration Research (MWL), both the anechoic and reverberation room were used. The pipe employed was 1 meter long with a diameter of 6.5 centimeters. It was mounted in between the two rooms and to ensure its stability and minimize vibrations a support was used. Figure (2) shows an overview of how the general set up was mounted.

Figure 2 – Straight pipe mounted in the wall with the wooden support.

Figure (2) shows the pipe without any type of nozzle but as was mentioned in the Introduction, the effect of the shape of the output was also taken into account for the study. The nozzle used was a mountable conic shape piece which served as a diffuser. Figure (3) shows a model sketch where dimensions are described.

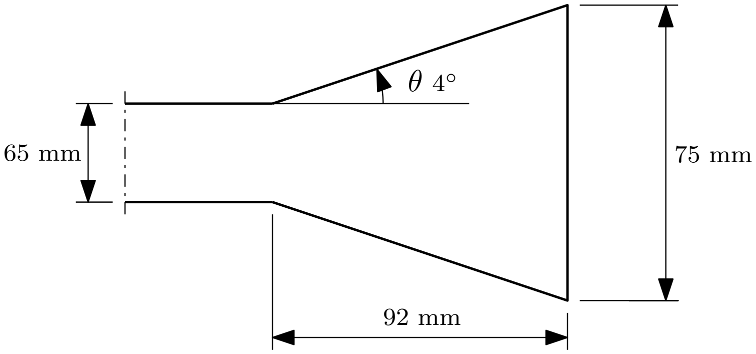

Figure 3 – Sketch of the conical outlet used in the esperiments.

Some of the experiments involved flow, which means that flow velocity had to be measured in advanced. The equipment used for that function was a Pitot tube. It is a simple and convenient instrument which determines fluid flow velocity by measuring the difference between static, total and dynamic pressure. At the beginning of each observation this device was mounted, velocity was measured and it was dismounted again to avoid the generation of undesired turbulence inside the pipe that could affect later measurements.

Apart from these general aspects, the two sets of experiments carried out required different measurement arrangement regarding equipment and data acquisition for instance. For that reason, now we will distinguish between experiments concerning the reflection phenomena and experiments concerning sound power level estimation.

A. Reflection coefficient

To calculate the reflection coefficient the sound inside the pipe had to be measured. The objective with these measurements was to determine how much sound was reflected at both sides of the pipe.

With that in mind the experimental set up was implemented as follows. A sound source, loadspeaker, was installed in each one of the rooms as can be seen in Figure (4). Then, when it was desired to analyse the behaviour of the sound at the outlet of the pipe the speaker located in the anechoic room was on. If on the contrary the inlet was the part to be analysed, the speaker on the reverberation room was the one on instead. Both experiences were executed for no flow and flow conditions.

Figure 4 – Speaker used in the Anechoic room for the sound excitation.

Undoubtedly, measurement instruments were needed to carry out these experiments and as the measures had to be taken inside the pipe, three microphones were installed flush the tube. The microphones chosen were Brüel & Kjær 4135 of condenser type given its precision in the acoustic measurements.

The three microphones were mounted with different angular positions around the circumference of the tube to minimize the impact on each other. The relative position of each one of the microphones is essential for the reflection calculation, two of them were quite close while the other one was further located. An sketch of this configuration can be seen in Figure (5).

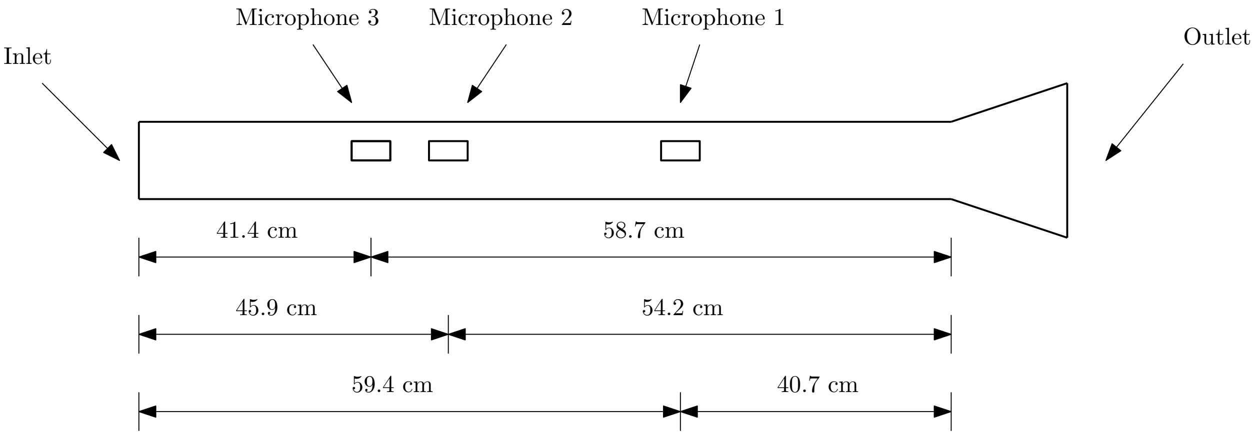

Figure 5 – Sketch of the pipe with the microphones and the conical outlet mounted.

Once all the set up was mounted and prepared it was essential to think about the best way to collect of the data. Being one of the key points of this study the accuracy in the measurements, the data acquisition was a very important point to consider. One of the recommendations of previous work was to use pure tones instead of measuring with a random signal. The coherence between sound generated by the speaker and the sound measured by the microphones was analysed using two types of excitation signals, random or sine.

In Figure (6) one can see the difference in the coherence of the measurements depending the type of signal used. As expected, the coherence of the sine signal at the determined frequency studied is the best possible (equal to 1). On the other hand, the random signal excites in all the broadband of frequencies but for an acceptable level of coherence the number of averages needed is really high, increasing considerably the measurement time.

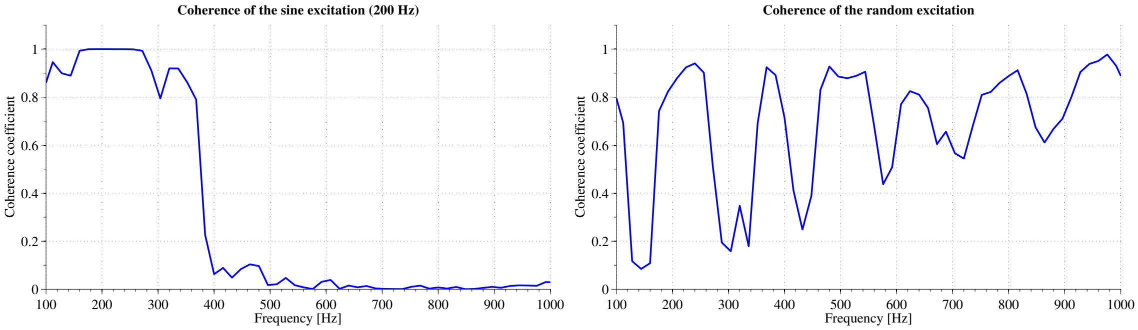

Figure 6 – Coherence comparison between both excitations at the Anechoic room (Averaging 1000)

The explanation is simple, when exciting with a sine signal with a determined frequency all the energy is concentrated on that frequency favoring that the signal produced by the sound source is correctly received by the measuring instrument, in this case the microphones. Thus, the procedure finally chosen to carry out the measures concerning the reflection coefficient was the one which gave the most accurate results, the sine excitation.

Then, a step frequency measurement with a sine signal was used. Later, the pressure signals from the microphones were converted to Transfer Functions, and exported to Matlab.

B. Sound Power Level

The second set of experiments performed concerned the sound power level estimation. Here, the set up and procedures carried out to execute the experiments was guided by the standard ISO 3747.

It specifies a method for determining the sound power level of a noise source by comparing measured sound pressure levels emitted by a noise source mounted in situ in a reverberant environment (the pipe), with those from a calibrated reference sound source.

Thus, a microphone was installed in the reverberation room. This type of room is designed to create a diffuse or random incidence sound field. In order to reduce the influence of defects of the reverberant field, a rotating microphone boom was used for these measurements. Its radius was approximately 1.5 meters and all measurements were taken at 1-2.5 meters above the floor. It can be seen in Figure (7)

Figure 7 – Microphone boom positioned in the reverberation room.

It took 64 seconds for the microphone boom rotating one turn and data was collected and averaged. Depending on the measurement carried out, it took a different number of averages and time to get reliable measurements. For this experiments, the analysis was controlled and recorded on a computer with the software PULSE Lab. With this method the entire frequency range was measured at the same time, unlike the method used for the reflection coefficient.

Finally, using those measurements the sound power level emitted by the pipe was calculated in third octave frequency bands. The frequency range of interest included the one-third-octave bands with mid-band frequencies from 100 Hz to 1000 Hz.

The post-processing of the data was entirely done in Matlab. For the calculation of the sound power level knowing the center frequencies of interest it was possible to find the width of the third octave bands as follows.

$$f_l = f_c/\sqrt{2} \tag{11}$$

$$f_u = \sqrt{2} f_c \tag{12}$$

$$B = f_u - f_l \tag{13}$$

VI. Results

This section shows and discuss the final results of all the experiments displaying comparative charts with the intention to analyze and discuss all data properly and efficiently.

As was mentioned in the introduction, the intention behind this study is to try to explain what happens to the sound generated in a pipe exhaust system at low frequency. Results of previous work showed a higher level in the sound power at the output of straight pipes when a nozzle acting as a diffuser was placed, which seems contrary to what one might expect.

For that reason new experiments of the same nature were carried out with the aim of ensuring if that conclusion was correct. Figure (8) displays the the sound power level over a frequency range going from 100 Hz to 1000 Hz for two different flow velocities distinguishing between the case when the nozzle is mounted and the case when is not.

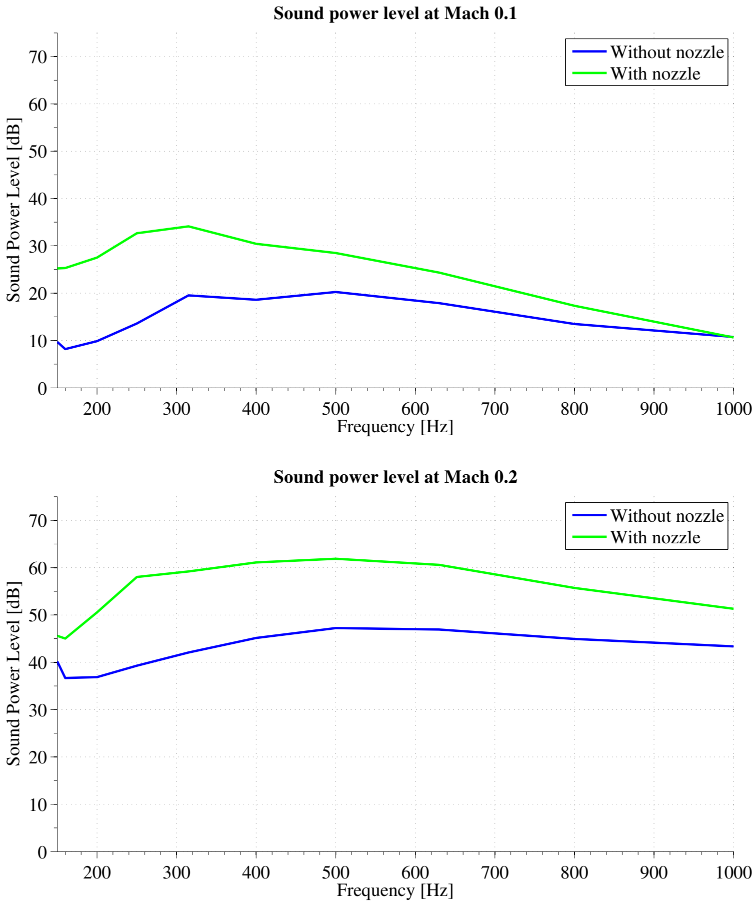

Figure 8 – Sound power level [dB] at the Reverberation room at Mach 0.1 and at Mach 0.2

As can be observed, the results obtained lead to the same conclusion as proposed by previous work. For some unknown reason yet the sound power level is considerable higher over the whole set of frequencies studied when a nozzle acting as a diffuser is used.

The main point then was to discover where the sound was generated to see if this could led to an idea that could explain this phenomenon. Two main possibilities were considered: jet noise and reflection phenomena. The first of the options considered concerned the jet noise which refers to the noise generation caused by high-velocity jets and the turbulent eddies generated by shearing flow at the end of the pipe. Although extremely high speeds have not been treated in this study, it may even be possible that the possibility that the use of a nozzle introduced more turbulence causing further expected sound generation from the pipe.

However, the nozzle used had a very smooth change between the largest and the lower area. So, by having this low opening angle (4 degrees) the flow is decelerated slowly and gradually over its length preventing boundary layer separation and thus notably reducing the turbulence of the flow. As the velocity of the flow decreases the dynamic pressure also reduces thereby diminishing the sudden pressure drop across the outlet.

This theoretical explanation was verified empirically during experiments. The air flow needed for some of the measurements of the study was created by the generation of a pressure difference between the anechoic and the reverberation room, thus, increasing the pressure in the anechoic chamber forced the air out through the pipe towards the room.

This procedure was controlled by a machine which simultaneously measured the power required to generate the pressure difference. In this way, it was observed that when the nozzle was placed in the pipe, the needed power to achieve the desired airflow velocity was less than the power needed to achieve the same velocity without the nozzle installed. Which means that the nozzle generated less pressure losses, resulting in a much smoother transition between the tube and the outside and thereby reducing turbulence and possible additional sound generated by them.

In light of this evidence it was quite clear that the jet noise was not the explanation of the extra radiation, in fact it predicted exactly the opposite. The research then focused on what happened inside the tube with the generated sound, by studying the reflection coefficient.

In order to get a whole idea of this phenomena the reflection coefficient was studied at the outlet and at the inlet of the pipe for different cases and outlet configurations. First, the result for the reflection coefficient at the outlet for no flow is shown.

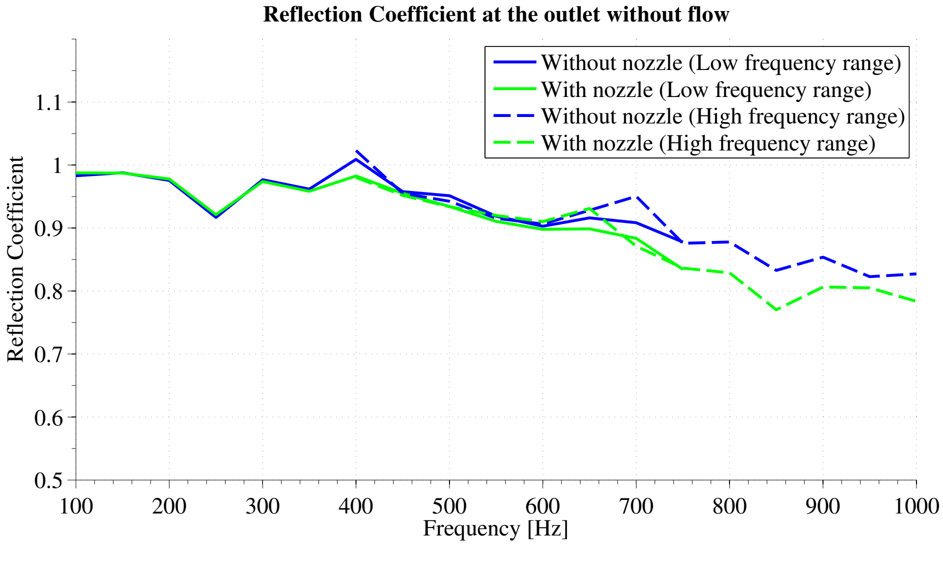

Figure 9 – Reflection coefficient at the outlet for no flow conditions.

Figure (9) shows a very interesting fact, at low frequencies the reflection coefficient has the same value for both configurations, however at high frequencies a reflection reduction occurs in the conical outlet. This was the same result obtained in previous works, and provides a possible explanation (for high frequencies) to the higher level of sound power produced by the pipe when the nozzle is installed . Reflection coefficient is lower at those frequencies, what means that more sound escapes from the pipe and spreads abroad causing the higher sound power level.

However, this hypothesis was only valid for the case of no flow since when studying the performance of the reflection coefficient for flow cases the behavior found was totally different. Figure (10) shows the reflection coefficient for the two different dispositions studied at a Mach number of 0.1 and 0.2.

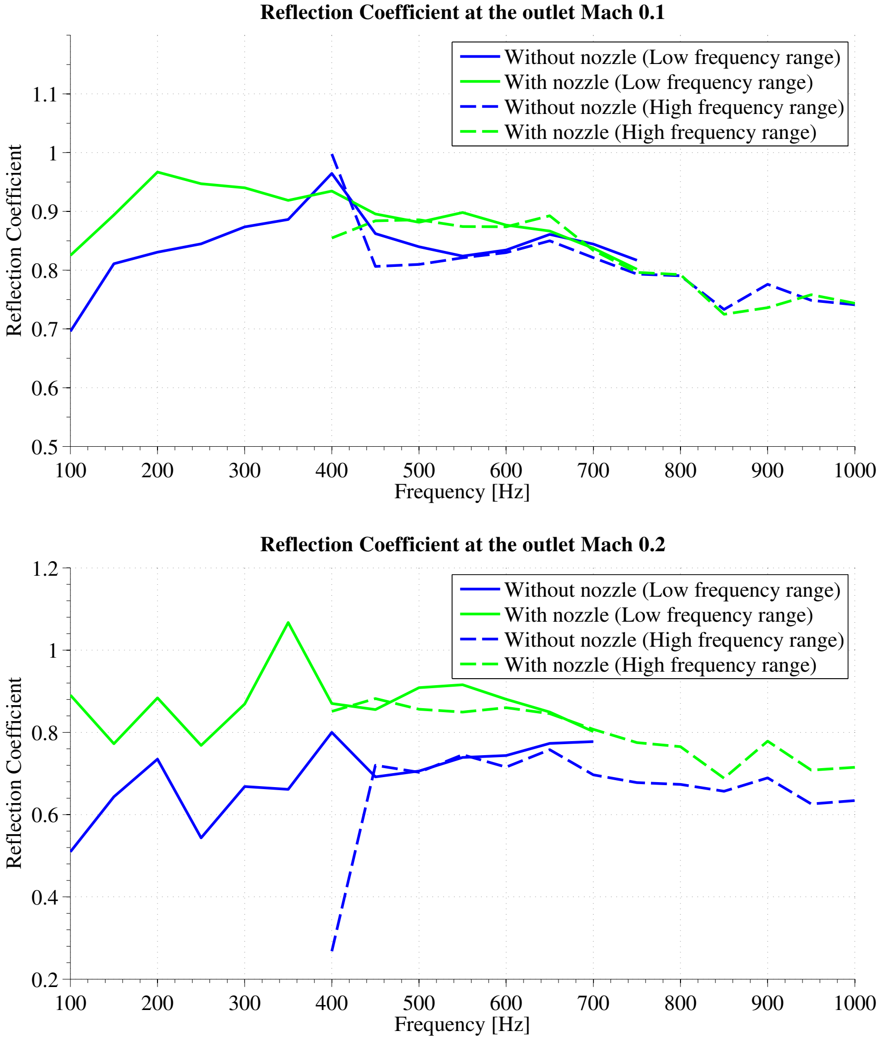

Figure 10 – Reflection coefficient at the outlet at Mach 0.1 and at Mach 0.2

Two conclusions can be drawn from these graphs. First we can see that the value of the reflection coefficient is slightly smaller with increasing air flow rate. And secondly and more importantly, it can be seen that the reflection coefficient is higher for the entire range of frequencies when the nozzle is installed in the pipe than when it is not. This behavior is the opposite to that one seen when there is no air flow present (at least for higher frequencies).

This implies that the conical outlet used on the exhaust generates higher levels of reflected sound in the pipe, or in other words less noise is leaking out, which should entail lower noise level produced in the exhaust. However is the opposite of what can be seen in Figure (8).

This fact shows that the behavior of the reflection coefficient at the pipe outlet does not explain the extra sound radiation for the conical outlet configuration but rather would indicate an opposite behavior.

In order to make sure no error was committed in the collection and post-processing of the data the theoretical model for no flow described before was implemented to compare with experimental results with the intention of seeing whether there are significant differences that may suggest a lack of precision that could have led to the conclusions drawn.

In Figure (11) Davies Model of reflection coefficient for an unflanged pipe in no flow conditions is compared with the experimental results in the outlet of the pipe for no flow case.

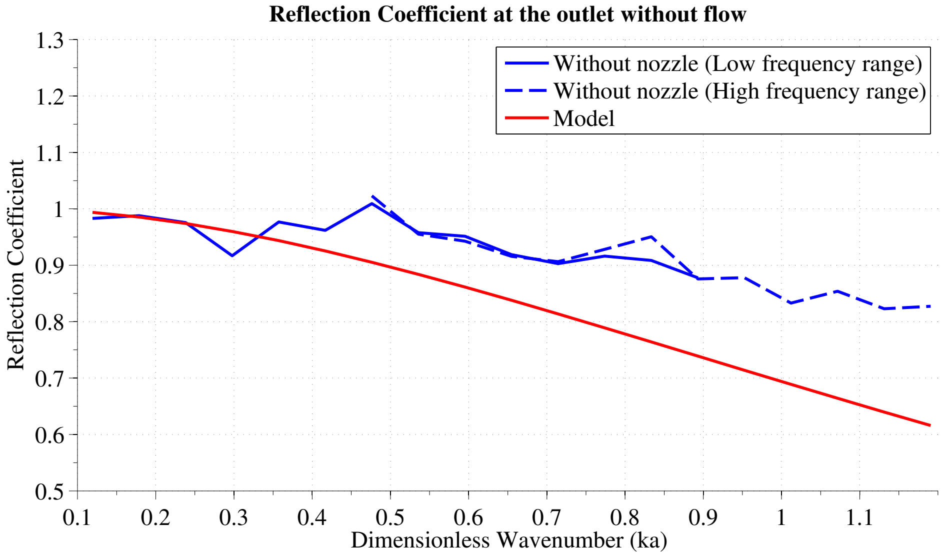

Figure 11 – Comparison between reflection coefficient at the outlet for no flow and the theoretical Model

One can see that for low frequencies both the curves of the model and the experimental result match quite good, however at high frequencies the theoretical model predicts a more pronounced decline in the value of the reflection coefficient, which does not correspond to the experimental results, where the reflection coefficient presents higher values. Nevertheless the difference is not very big so one could say that the results and the model match.

Then, it can be assumed that the results in the outlet are correct though they do not offer a direct explanation of the phenomenon under study. Therefore, the next step was to analyse what happened in the inlet with the intention of having a global vision of the sound behaviour inside the pipe. Figure (12) shows the reflection coefficient for the no flow condition and for Mach 0.1 taking into account the two different configurations of the outlet.

Clearly, it can be seen that the type of configuration used in the outlet pipe does not affect the value of the reflection coefficient at the inlet. Both for the case of flow and no flow both curves coincide for all the frequency range studied. As a consequence, this fact does not give any possible explanation or valuable information to find out the reason of the extra sound radiation of the conical outlet.

After studying the two possible explanations mentioned at the beginning of the section without finding a possible explanation, one might think that the extra noise is not generated inside the pipe and might appear outside the pipe, near the opening, and somehow adding an outlet makes something happen in that region that makes the sound power to considerably increase. The possible explanation then focuses on the interaction between the sound field and the flow field in that region.

As observed in the Figures, with the conical outlet installed in the pipe the reflection coefficient is larger at the outlet, meaning that more acoustic energy is trapped within the pipe so more sound waves are keep inside making the pressure within the tube much greater than with no outlet at all. As well as the amplitude of the pressure, the sound waves speed fluctuations increases too.

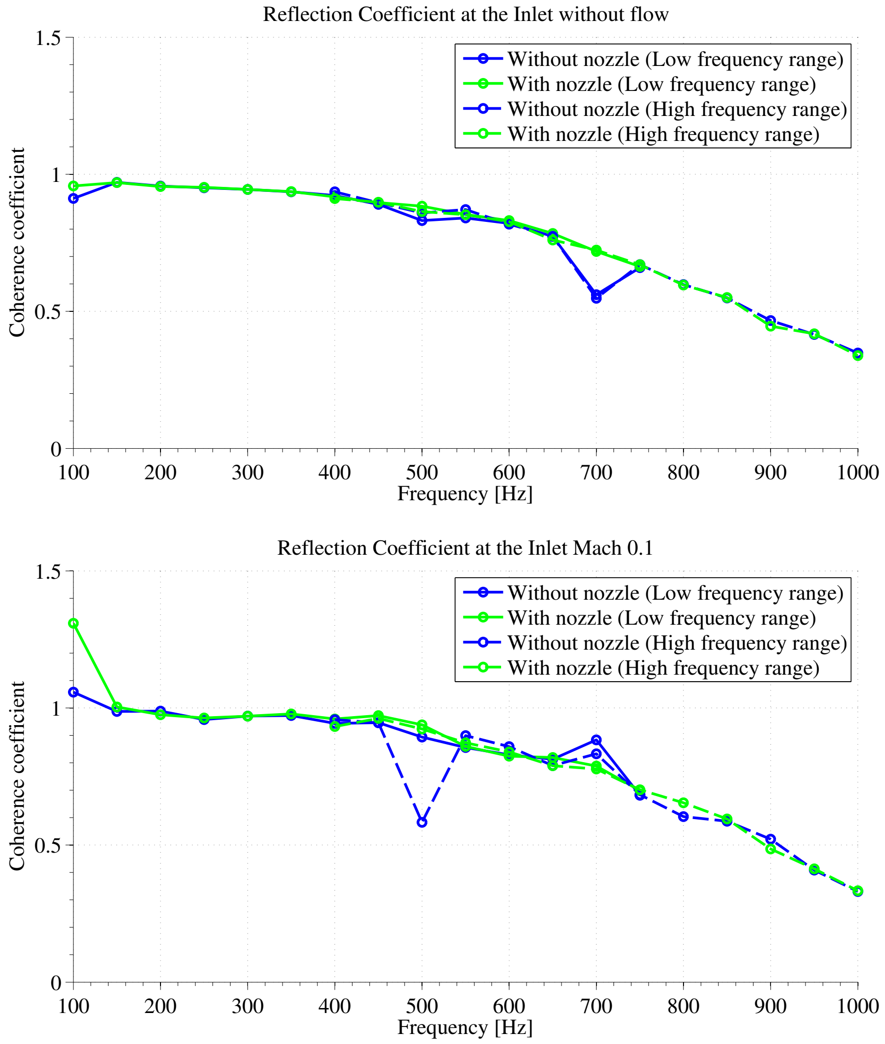

Figure 12 – Reflection coefficient at the Inlet for no flow and at Mach 0.1.

If one assumes according to Heckl[7] that the length of the tube does not affect the level of power sound generated, one can deduce that the power sound created inside the pipe is the same in both outlet configurations and on the other hand that this energy has to come out somehow to the outside.

Thus, although the reflection coefficient is high, the fluctuations velocity and pressure are also large inside. This velocity of the sound waves fluctuations is related to the sound generated near the outlet of the tube where it interacts with the flow vorticity. Hence, as this velocity is greater with the outlet configuration the sound generated by this interaction will be greater than with the configuration without outlet.

This can then be a possible explanation of why the sound power level is higher with the nozzle installed. The basic underlying physical phenomenon is that energy of fluctuating vorticity,which is shed from the nozzle edge, is converted into acoustic energy. However, the difference between the reflection coefficient for different output configurations is not large enough to generate a variation range of 20 dB as that shown in Figure (8). Then, some other phenomenon that influences the generation of sound should be missing or have not been taken into account.

VII. Conclusion

The reason for the extra radiation of noise from an exhaust pipe with a conical outlet has been investigated. Several laboratory experiments in the Marcus Wallenberg Laboratory at KTH including a tube and different configurations of output and flow were carried out for this work.

Two main possibilities were contemplated at first considering where the sound could be generated. The possibility that was produced because of the jet noise at the outlet was discarded soon. The conical outlet used had a low angle opening that prevented the separation of the boundary layer and thus the generation of additional turbulence, that may be the cause of the big difference in the sound power level.

The second possibility was that the sound was generated within the pipe, for that reason the reflection coefficient was studied. However, the results showed greater reflection coefficient when the outlet was mounted on the pipe, which suggested a totally opposite effect that the one registered for the power level. Sound was reflected and trapped inside the tube so that sound could not be the cause of the greater sound power level measured in reverberant room.

Finally, it was thought that the answer could be in the region near the tube outlet area. At that location the increased speed and pressure fluctuations of sound waves within the pipe, due to increased reflection coefficient, interact with the vorticity of the flow producing a considerably higher sound power level. The basic underlying physical phenomenon explaining it is that acoustic energy interacts with the energy of vorticity, which is created at the nozzle edge. However, further study will be need to prove this experimentally.

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