In-situ measurements of the complex acoustic impedance of materials in vehicle interiors

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ABSTRACT
Over the years, several methods of measuring the complex acoustic impedance of materials have been presented, but none of them is well-established for practical in-situ measurements. The more stable and confident method to obtain such data (ISO 10534), requires ideal sound field conditions such as the propagation of plane waves inside of a tube; this condition is certainly not fulfilled inside of an automobile. In this context, the behaviour of the Microflown p-u intensity probe is of interest, and it is analyzed in the free-field method. The small size of this transducer makes it possible to achieve measurements of the sound pressure and particle velocity very close to the surface, and could constitute an advantage for the measurement of acoustic impedance.

Two main methods have been tested in this context: a portable standing wave tube and the free field method. The results show that the portable tube provides relatively good results for stiff materials. On the contrary, the free field method is more suitable for soft materials.

INTRODUCTION
This project has been carried out by the Technical University of Denmark in collaboration with Volkswagen AG – Germany. The accurate characterization of materials inside of vehicles in terms of surface acoustic impedance is of interest. Concerning this matter, the impedance tube is the most commonly used means of measuring the normal surface impedance of materials [1]. However, the fact that test samples need to be mounted inside of the tube in order to achieve measurements reveals a clear difficulty if complicated surfaces, with several materials, one on top of the other, are under analysis. As a response to this difficulty, several methods have been presented over the years, but none of them has been well-established for practical in-situ measurements.

There have been a number of studies into the accuracy of the transfer function method, concerning mainly with the effect of the mounting conditions on the measured values of the acoustic impedance. An interesting result was reported by Cummings, whom studied the effects of air-gaps around the sample on the measurement of the acoustic impedance [2]. He reported that the effects of air-gaps increase as the frequency falls, and media of high flow resistivity tend to be more susceptible to measurement errors incurred by air-gaps than those with low flow resistivity.

On the other hand, Round-Robin tests have been carried out by several authors across Europe [3]. The same samples of material were analyzed in different laboratories using the transfer function method. Considerable variations in the measured spectra for the acoustic absorption coefficient have been observed both in results between individual samples and individual laboratories. The variations are attributed to inhomogeneity of
the provided material samples, methods of sample preparation, mounting and structural conditions during test, diameter of the standing wave tube, and signal processing method.

Regarding the materials inside of an automobile, one could imagine that most of them are not porous materials; on the contrary, the materials are rather stiff and they would not be represented properly by, for instance, the Delany&Bazley model [4]. Pointed out the complicated task, two main methods have been analyzed and results will be presented throughout this document. Firstly, a portable impedance tube is analyzed in detail and results for different conditions of mounting are shown. Secondly, the free-field method, attributed to Allard and Sieben [5], is analyzed. Variations of this method, by using the microflown intensity probe, which allows measuring the particle velocity and the sound pressure at the same point, have been attempted.

PORTABLE IMPEDANCE TUBE

Few papers have been found regarding portable standing wave tubes for in-situ applications. In the early 60’s, Berendt and Schmidt presented a portable impedance which had a narrow operational frequency range - 400 to 900 Hz.[6]. The open end of the tube was terminated with an annular gasket of soft neoprene rubber, in order to provide an airtight seal against and prevent marring of the acoustical material under test. The measurements of the maximum-minimum sound pressure ratio for a given sample were repeatable within ± 0.10 dB.

A portable impedance tube has been built and installed in a tripod as this instrument helps to locate the termination of the tube in any direction (See figure 1). The response of the tube is analyzed schematically and comparisons with a standard impedance tube are presented as a reference in all the results.

Figure 1: Portable impedance tube in a handy tripod.

The tube has a circular cross-section, and according to the ISO recommendations, the working frequency range is approximately from 500 Hz to 5 kHz.

As a first step, two extreme cases are analyzed: open tube, where no resistance to movements of air at the termination of the tube is presented, and rigid surface, where
the particle velocity at the termination should be close to zero. The results will be presented in two different figures. One figure includes the reflection and absorption properties: on the upper part, the real and imaginary part, as well as the amplitude and phase of the reflection coefficient are presented, whereas the absorption coefficient is presented in the bottom. The other figure shows the real and imaginary part, as well as the amplitude and phase of the normalized acoustic impedance. The results with the portable tube are always presented in dashed line. Some of the results are not shown here due to formatting requirements.

Figure 2 shows the result for the open tube case. As it can be seen, the real part of the reflection factor is -1 as it should for both tubes. The response with the portable tube presents -1 even in a broader band of frequency, which is basically an effect of the geometry difference. Both curves present a fairly good agreement in the whole frequency range.

![Figure 2: Reflection and Absorption properties - Open tube case.](image-url)
It is important to remember that the radiation impedance of an *open tube* increases with the frequency; this is definitely revealed in all the sub-figures. Still in the open tube case, the comparison for the normalized acoustic impedance is shown in figure 3. The normalized acoustic impedance on the termination of the tubes should be close to zero since the air does not represent any resistance; good agreement is again observed for both curves in a broad range of frequency.

On the other hand, figure 4 shows the result for the *rigid surface*. In this case, the real part of the reflection coefficient is giving 1 as it should, while the imaginary part keeps constantly close to 0 in the whole frequency range. The absorption offered by the surface is minima since most of the sound field is reflected backwards into the tube. The normalized acoustic impedance is introduced in figure 5.
In theory, the impedance of a rigid surface should go to infinity. However, there will always be small movements of air in the surface and thus, the measurement gives usually a fairly high value but still finite. Figure 5 shows an amplitude of around 20 [\] for low frequencies in the portable tube, which means 20 times the acoustic impedance of the air, a fairly high value. In general, it is always difficult to measure zero or infinite; thermal losses produce always a small absorption and that could be concerned in this cases. Nevertheless, the portable tube is given reasonable results, which are comparable with the reference in both extreme analyzed cases.

Following with the analysis, samples of porous materials have been cut and introduced in the portable tube, as well as in the standard reference tube. The comparison is shown as follow:

Figure 6: Normalized Acoustic Impedance - porous material placed in the tubes.
Figure 6 shows the normalized acoustic impedance of the material. Since the separation of microphones in the standard tube is larger than in the portable tube, theoretically the results given by the standard tube should be more accurate at low frequencies. Following this way of thinking, the new portable tube over-estimates the absorption coefficient at low frequencies. However, the results are in quite good agreement above 200 Hz. In the case of the reflection and absorption properties (not shown here), the differences are again presented mainly at low frequencies, below say, 200 Hz. This could be improved doing measurements with a larger separation between microphones. The behaviour of the portable tube is analyzed for in-situ measurements. The samples have not been mounted inside of the tube from now on in all the results; instead the samples are in-situ. For the interface, a rubber ring is been included in the termination, as an attempt to provide an airtight seal (See figure 1-right).

If the measurement is done keeping the tube at 1 cm above the surface, the behaviour is similar to an open tube. Special attention should be taken in the real part of the reflection coefficient, which is close to minus one in a considerable range of frequency (See figure 7). Regarding the absorption, the curve drops down as expected, since only air is found at the termination. For the normalized acoustic impedance, the result is completely similar to the result in the open tube case; basically almost 0 in the whole frequency range.

![Figure 7: Reflection and Absorption properties - tube 1 cm. above the surface under test.](image)

If the measurement is done with the tube on the surface (See figure 8), not pressing at all the material, the real part of the reflection factor increases a bit but still is close to minus one at low frequencies, which indicates leaking and therefore similar to the open tube. The absorption, surprisingly, increases in the whole frequency range. About the normalized acoustic impedance, it seems to improve and get closer to the curve in the old tube for high frequencies; however, for low frequencies still keeps close to 0 which also indicates similarities with the open tube.
Now if the measurement is done with the tube on the surface, pressing the material, and therefore changing the properties of the material, the real part of the reflection factor becomes positive but still at a difference larger than 0.5 comparing with the measurement given in the old tube. Above 600 Hz the result seems quite in agreement with the measurement in the standard tube. However, an over-estimation of the absorption coefficient is observed, without any physical explanation. Regarding the normalized acoustic impedance (see Figure 9), the real part can be well-estimated above 200 Hz; a shift towards low frequencies is recognized in the portable tube curve. For the imaginary part, the comparison with the old tube is showing similar results above 700 Hz. However, the phase is not comparable in the whole frequency range.

Figure 9: Normalized Acoustic Impedance - tube pressed against porous material.
Hence, it can be concluded that leaking constitutes a big problem in the measurement of the normalized acoustic impedance; the measurements with the tube on the surface, not pressing the material, are comparable with the open tube since the real part of the reflection factor is negative, meaning a release. Once the material is deformed by pressing the surface, as an attempt to avoid leaking, strange phenomena occur and the absorption coefficient gets close to 1. The normalized acoustic impedance, although it seems similar to the result given by the standard tube at high frequencies, is definitely erroneous.

A shift towards low frequencies in the results of the normalized acoustic impedance can be noticed in figure 9. This is been studied following a simulation study which shows the effect of small holes on the seal. The four-pole method has been used in a *matlab*-code, in order to find out the effect of a small leak on the interface tube-material. The hole on the seal is represented by the radiation impedance of a circular piston of radius $a$ [7].

The simulation shows that the bigger the hole, the more shifted the curve is towards low frequencies. This has been noticed in the previous results and clearly confirms the importance of the interface tube-material and the method to seal the junction.

On the other hand, propagation of waves in the material could constitute an important factor. In order to see whether the release is due to waves propagating in the medium or due to leaking, the result given with a small sample is been compared with the result given with a big sample of the same material. The same height and pressure over the material is attempted. According to the results (not shown here), the differences are not considerable. The small sample presents a higher release compared with the big sample, which might be due to the size of the sample. Nevertheless, propagation of waves in the medium does not seem to be the main reason why the results are given a release, and on the contrary the leaking seems a more important issue.

If the material would not be affected by the pressure of the tube as an attempt to avoid leaking, one would expect good results; the measurement with the rigid surface presented before demonstrates that. The sealing method constitutes the breaking point of the portable tube. Therefore, one could argue that the portable tube could be used for stiff or hard materials, rather than for soft materials. Figure 11 shows the results for a relatively stiff surface.
This proves that the portable tube could be used to study stiff materials, following a schematic analysis.

**FREE FIELD METHOD**

The free field method applied by Allard in the 80’s has been tested but, instead of pressure microphones, a microflown probe has been used and, thus, the sound pressure and particle velocity have been obtained at the same position. Calibration of the microflown probe has been applied according to Jacobsen [8]. The small size of the microflown transducer makes it possible to measure close to the surface. This can constitute an advantage mainly for the analysis of soft materials. In the case of stiff materials, the particle velocity component on the surface is small and problems in the measurement might occur.

A sound source which behaves as a monopole is been used. Since the material is exposed to a spherical sound field, simple solutions to the problem of measuring the acoustic impedance on the surface as in the case of plane wave sound field are not suitable. However, approximations to calculate the acoustic impedance on the surface out of a measurement somewhere above the material have to be applied. Three main approximations have been tested. The simplest one assumes plane wave sound field and the calculation of the acoustic impedance on the surface is performed as simple as in the standing wave tube. A slightly more complicated model makes use of the image source model and a plane wave reflection coefficient that is independent of the position of the receiver. This model, therefore, takes into account the spherical sound field, but assumes that these waves are reflected in the same way as in the plane wave sound field. A third approach, which is by far more complicated, includes the calculation of the spherical reflection coefficient $Q$. There have been numerous studies into the calculation of the spherical reflection coefficient. This has been solved and it is presented by several authors, but, the calculation is a function of the geometry of the problem and the actual acoustic impedance on the surface. Hence, in order to calculate the spherical reflection coefficient $Q$, the acoustic impedance on the surface, strictly impossible to
measure, is needed. Therefore, some assumptions should be taken in order to calculate a $Q$ factor and then analyze the behaviour and try to apply corrections.

One particular set-up is been analyzed. The source is located 1 meter above a porous material (Rockwool 50mm A-batt) and the microflown transducer is located on the surface, which means that the actual measurement is taken approximately 5 mm. above the surface. A sample of the same material has been cut and analyzed in the impedance tube; the result is used for comparison. Figure 12 shows the normalized acoustic impedance obtained in the tube ($Z_{a \text{ tube}}$), on the surface as the direct ratio of sound pressure and particle velocity ($Z_{a \text{ measured}}$), using the plane wave sound field approximation ($Z_{a \text{ plane wave sound field}}$), and using the image source model approximation ($Z_{a \text{ image source model}}$). The direct measurement of the ratio of sound pressure and particle velocity on the surface (5 mm. above), is in good agreement with the result given by the tube above, say, 200 Hz. The approximations, since the input is the direct measurement of the acoustic impedance 5mm. above and the direct path is almost the same as the reflected path, are quite close to the direct measurement. This wouldn’t be the case if the measurement would be done farther. Problems at frequencies below 200 Hz are noticed, and they were also pointed out by Allard. This is attributed to the finite size of the sample, which produces reflections on the boundaries.

The result indicates that the direct measurement of the ratio of sound pressure and particle velocity on the surface it is already a good estimation of the acoustic impedance of the material, and the procedure is simplified, since no approximation is needed. However, the more complicated model, which includes the calculation of $Q$, is been analyzed as follow.

![Figure 12: Normalized Acoustic Impedance – 50mm Rockwool A-Batt.](image)

Since the actual acoustic impedance of the surface is needed to calculate $Q$, we assume that the result given by the image source model is a good approximation and, therefore, it is used for the calculation. Figure 13 presents the reflection coefficients for all three approximations, including the comparison with the tube result.
Figure 13: Reflection and Absorption properties – 50mm Rockwool A-Batt. Comparison of three approximation models and the impedance tube result,

Differences between the plane wave sound field model and the image source model are noticed specially at low frequencies. The spherical reflection coefficient is quite close to the image source model throughout the whole spectrum.

A more detailed analysis of the spherical reflection factor is presented in Figures 14 and 15. The position of the source is kept constant, whereas the receiver position is changed and calculations of $Q$ are achieved.

Figure 14: Spherical reflection coefficient $Q$. 
Figure 15: Spherical reflection factor for specific frequencies and variance with respect to the receiver position.

For this specific case, the variance of $Q$ with respect to the receiver position is almost negligible in all the frequency range. Since the spherical reflection coefficient is known, as well as the differential of $Q$ with respect to the height, it is possible to calculate the sound pressure and the particle velocity everywhere in the space. Therefore, one is able to compare the measured sound field with the predicted sound field (Figure 16). The differences are, of course, attributed to the assumption when calculating $Q$; the image source model, which contains the plane wave reflection coefficient, is different to the actual acoustic impedance on the surface, and the difference seems to be enhanced through the calculation of $Q$.

Figure 16: Normalized Acoustic impedance. Measured and predicted sound field.
An iterative procedure is been attempted, by changing the input \( Z \) of \( Q \), in order to minimize the differences between the measured and predicted sound field. However, no success has been found since infinite solutions have been obtained.

**CONCLUSIONS**

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**REFERENCES**


