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Broadband acoustical characterization in a horn shaped impedance tube

J.-M. Coulon^a, F. Chevillotte^b, F.-X. Bécot^b and L. Jaouen^b

^aL&L Products, 1 rue Lindberg ZA Activeum, Altorf, 67129 Molsheim, France

^bMATELYS, 1 rue Baumer, 69120 Vaulx-En-Velin, France

jm.coulon@llproducts.eu

Impedance tube is widely used to characterize acoustical materials, but it is restricted to frequencies corresponding to plane wave mode propagation. Broadband measurements require testing samples within tubes of different cross-sections: the smaller the diameter the higher the maximum frequency allowed. This is a critical issue for materials or multilayers samples (i) with elastic frames for which shape and size affect vibrations (ii) which cannot be considered as homogeneous for small diameters. In order to cope with the paradox of testing large samples with a small tube section, an impedance adaptation is necessary. A horn above its cut-off frequency can be a good coupling element. A horn shape portion has been designed using 1D and 3D modeling for the 1.6 kHz-6.4 kHz frequency range. This approach has been validated based on comparisons against “standard” impedance tube measurements for various materials. Selected materials represent a large range of weak to important structural behavior and single to multi-layers arrangements. This opens interesting perspectives for the design of broadband frequency impedance tube apparatus.

1. Introduction

Impedance tube is a quick and reliable method for characterizing small components noise attenuation and absorption. It has been standardized through ISO 105534, ASTM E1050 and ASTM E2611 [1, 2, 3]. The transmission and reflection coefficients at both sides of the sample can be computed by measuring the transfer function between microphones and dissociating forward and backward travelling waves inside the tube. This decomposition is valid below the cut-off frequency with plane wave's conditions ($f_{\text{cut-off}} \propto 1/\text{sample size}$). So the method high frequency limit is given by the tube diameter. To make broadband absorption measurements, a kit of tubes is generally used with different diameters and their associated frequency band. This approach supposes that samples of different size have the same behavior. This is not valid for closed cell or highly resistive foams, multilayers or rigid parts where structural behavior cannot be neglected. With multimodal decomposition methods [5, 6], it is possible to extend the frequency range (up to four times cut-off frequency), but they involve heavy set-ups with a lot of microphones. Another alternative is to use a small test section with a larger sample and connect both with an impedance adapter. It has been experimented by Northwood [4] using an exponential horn as a coupling element and results were promising. The objective of this work is to examine this approach experimentally, numerically in order to define a procedure for absorption and transmission loss measurements.

This paper starts with a brief presentation of the existing method and its limits. Transmission loss has been firstly investigated. If the type of coupling can influence test results, it can be corrected using a 1D analytical model of the horn. Different types of components have been tested using an exponential horn and the comparison with FEA modeling shows the potential of this method. The same set-up has been used for absorption measurements and the same type of correction has been applied. Experimental results show that in some cases the extension of the frequency domain is more limited.

2. Current test method description and limits

Figure 1 shows set-ups used for absorption and transmission loss measurements with an impedance tube. The standard set-up used for industrial applications is made of a 100mm diameter tube for 50Hz-1.6 kHz range and a 29mm diameter tube for 200Hz-6.4 kHz range.

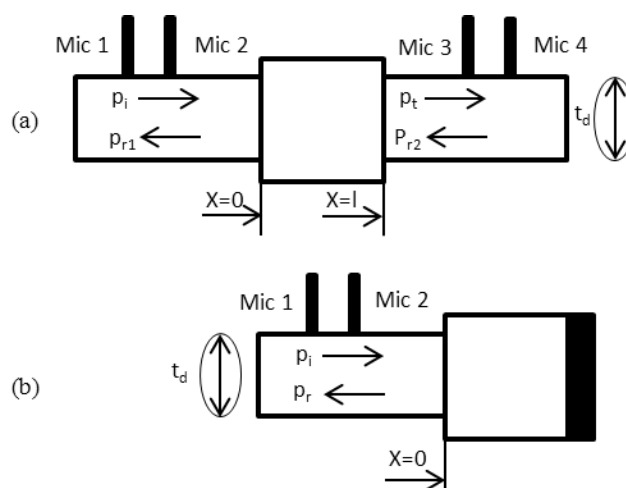


Figure 1: Impedance tube transmission loss (a) and absorption (b) test set-up

For absorption measurements, noise is generated on one side and the sample is backed by a rigid wall on the other side. Normal impedance at $x=0$ and normal incidence sound absorption coefficient are measured from the transfer function between two microphones H_{12} . For transmission loss experiments, noise is generated at one or both sides of the sample, measurements are made on each side. We measure transfer function between four microphones and two configurations (A and B) H_{13}^A , H_{23}^A , H_{43}^A and H_{13}^B , H_{23}^B , H_{43}^B . Ways to generate two configurations are: two load method (open end, closed end) or two sources method (activating sources separately at both sides) [7].

Computations suppose standing wave conditions inside the tube made of incoming (p_i) and reflected (p_r) travelling plane waves. In reality, there is a quasi-plane mode inside a tube below its first cut-off frequency f_c which is a function

of the tube cross section. For a circular pipe (diameter t_d), f_c is given by:

$$f_c = \frac{0.586 c}{t_d},$$

where c is the speed of sound.

For a 100mm diameter sample, the upper cut-off frequency is 1600 Hz 1/3 octave band. This is too restrictive for most of noise engineering applications, where we need to go up to 6.4 kHz or 10 kHz. The most common alternative is to test two sample sizes: 100mm diameter up to 1.6 kHz and 29mm diameter up to 6.4 kHz (figure 2).

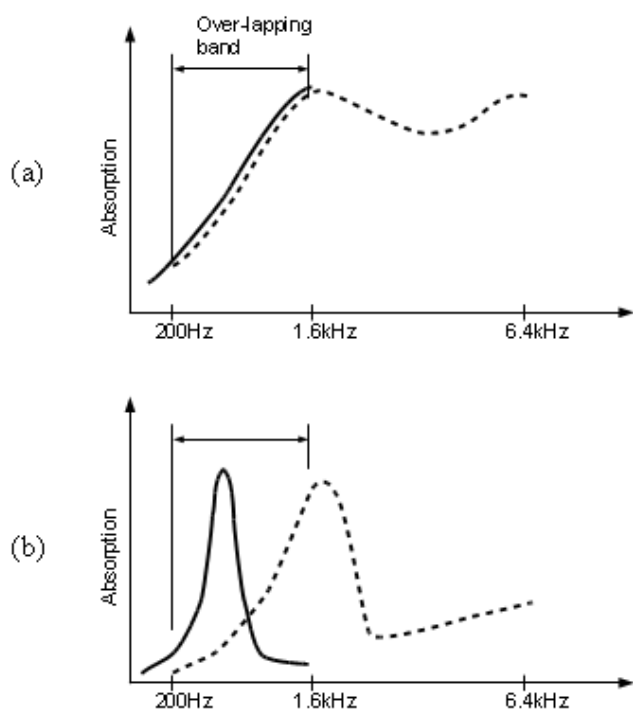


Figure 2: Typical absorption curves from 29mm (---) and 100 mm samples (—). (a) When curves overlap (b) When curves don't overlap

This approach supposes that the behavior of the component is not a function of its shape factor. Agreement between both curves in the over lapping band is a good indicator of the validity of this hypothesis. This is true for a limited number of cases (rigid foams, felts ...). For materials with high structural behavior, like non porous materials or mass-spring systems, where size matters, curves don't overlap. It's even more problematic if we have to characterize the insulation and the absorption of inserts for automotive body in white. These inserts are made of non-porous or highly resistive foams and rigid plastics with dimensions that don't authorize measurements above 1.6 kHz. Set-ups using multimodal approach or diffuse field are too complex or too large for these kinds of components. A standard test procedure has been defined [8] using Insertion Loss, but it doesn't include absorption and does not give intrinsic performance of the component. The challenge is to

define a test set-up with an extended frequency range which is able to measure absorption and transmission loss.

3 Extended frequency range test method definition

3.1 Transmission Loss

The goal is to define a coupling between a 29mm test section and a 100mm sample in order to test it up to 6.4 kHz. Shape and length of the coupling element are the dimensioning parameters. This can be firstly evaluated by simulating TL measurements with a 1D transfer matrix code (figure 3). "Reference" represents the performance of a component with plane wave conditions. Below 1600Hz results are very distorted but for this frequency range coupling element can be removed analytically by inverting their transfer matrix. Above 1600Hz we observe oscillations but if we use a horn they are limited below 1dB. Increasing horn length and curvature tends to reduce these fluctuations.

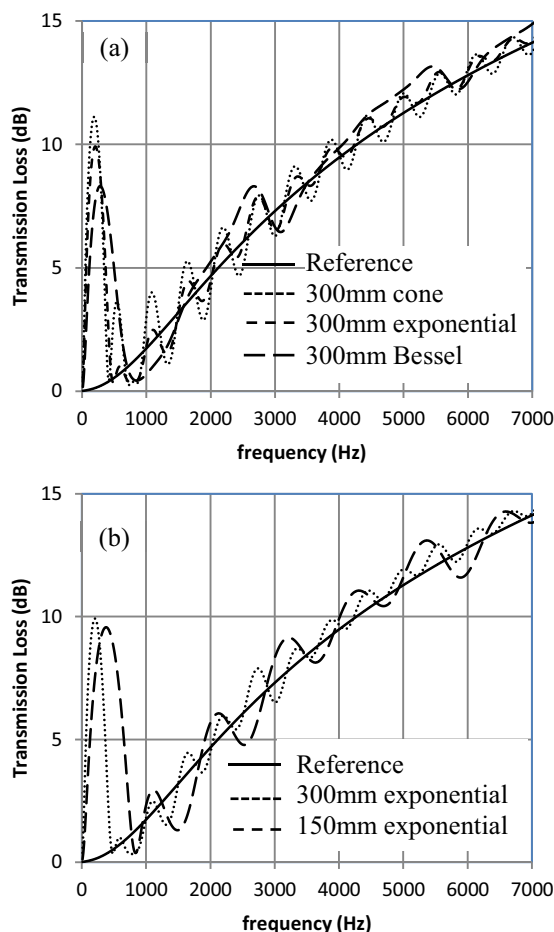


Figure 3: Transmission Loss simulations using (a) different shapes and (b) different lengths of coupling element between a 100mm sample and a 29mm test section

One way to test the method experimentally is to use the property of materials with a very weak structural behavior. In this case two samples of the same thickness but different

diameters must have the same transmission loss curve. (Figure 4-a) Tests done on two 50mm thick PU foam samples (29mm and 100mm diameter) using 300 mm long exponential horns confirms issues observed in computations in low and mid frequencies. Once horns removed numerically, results from both samples are very similar (figure 4-a). We can also compare test results with 3D FEA modeling. A round clamped plate made of polyamide 6 is straightforward to test and model. (Figure 4-b) Again results are similar in the whole frequency band.

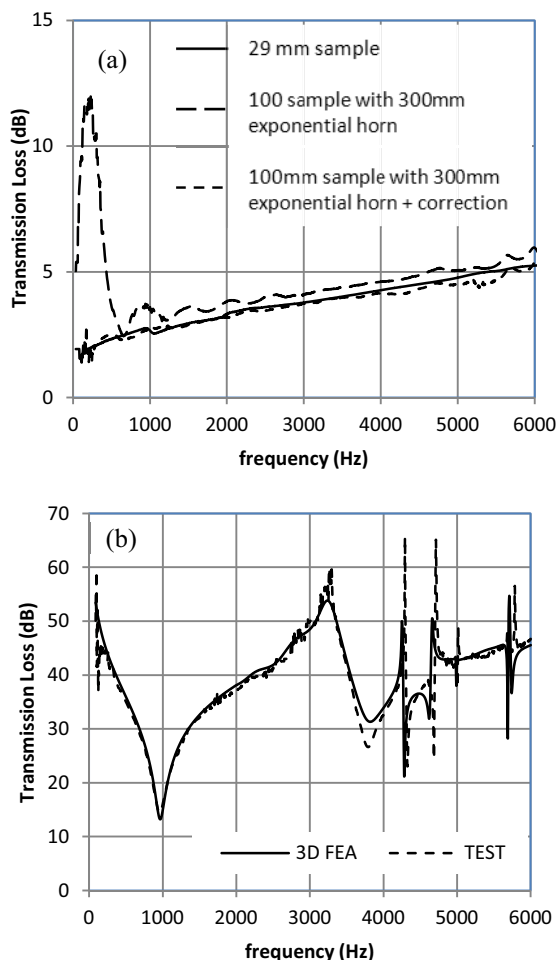


Figure 4: (a) Transmission Loss of 50mm thick PU foam, $\phi=29$ mm sample and $\phi=100$ mm sample tested with horn without and with correction. (b) Transmission Loss of a $\phi=100$ mm 3mm thick PA6 plate. Comparison between 3D FEA and test using horns with correction

3.2 Absorption

The same type of approach has been applied on absorption measurements using only one horn. Measuring impedance at the throat we can then deduce mouth impedance using plane wave theory [4]. To investigate the validity of the method different types of absorbing material have been tested:

- Rigid wall $\Rightarrow \alpha \sim 0$
- Mass-spring system $\Rightarrow, \alpha \sim 0.2$ at high frequencies
- Foam with average absorption $\Rightarrow \alpha \sim 0.6$
- Glass fiber with high absorption $\Rightarrow \alpha \sim 1$

For each case we tested a 29mm sample and a 100mm sample with the exponential horn. Case (a) provides us a reference, case (b) results between both tests supposed to be different except at high frequencies where structural behavior is not preponderant. For cases (c) and (d) results must be similar because structural absorption is very low. Note that the differences between sound absorption coefficients observed for sample (b) are due to the sample shape factors which modify the structural behavior. This example illustrates why it can be interesting to test the same sample on the whole frequency range.

The correspondence between small tube and horn set-up is good for lower frequencies but depends on the absorption above 4500Hz (figure 5). Above this frequency wave inside the horn is no longer planar, resonances from transversal modes are observed. This phenomenon is not taken into account by the 1D correction, but high absorption attenuates resonances making this issue less critical.

4 Conclusion

Current impedance tube set-ups using two diameters can handle most of material studies for industry. But for small components with important structural behavior current standards are not well dimensioned for easy and fast evaluation. The purpose of this paper is to present a test set-up based on impedance tube but with an extended frequency range. The idea is to use a small test cross section a larger sample and couple them with a horn. This method has been evaluated mainly experimentally in transmission loss and absorption. Results show that with an exponential horn we can extend the range of 100mm section from 1.6k Hz 1/3 octave to 4 kHz 1/3 octave. Above 4600Hz if the tested configuration is weak in absorption we observe resonance from tangential modes. This approach is promising but there are still some theoretical and numerical investigations to be done to optimize horn shape and length and the horn model.

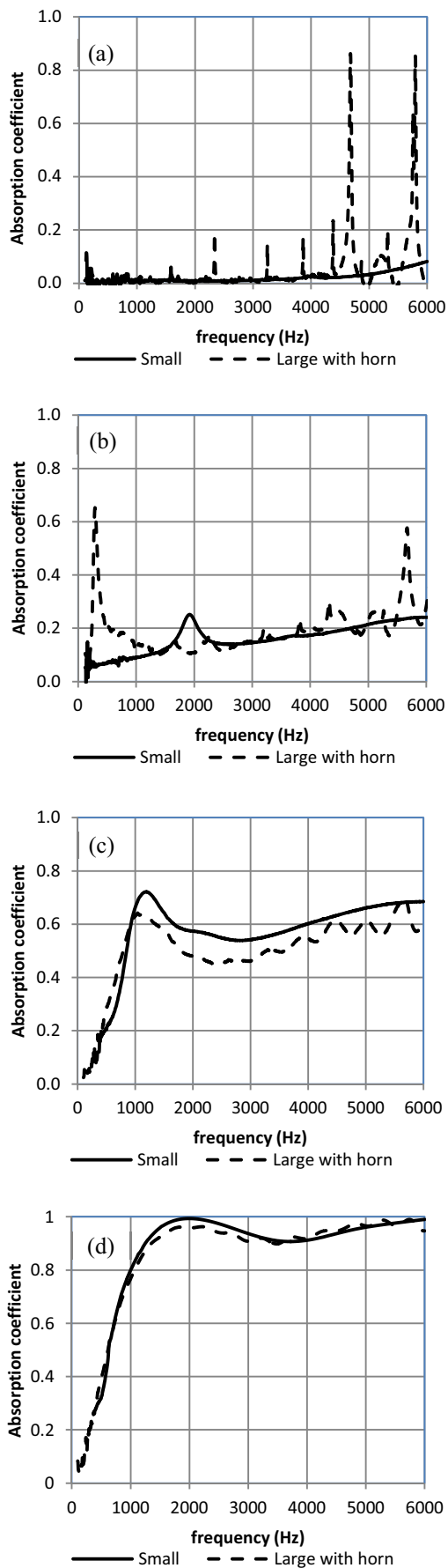


Figure 5: Absorption coefficient: 29mm sample (—) 100mm sample measured with horn set-up (- - -). (a) Rigid wall, (b) Mass-spring system, (c) Foam with average absorption coefficient, (d) Foam with high absorption coefficient

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