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ON THE USE OF A P-U SOUND INTENSITY PROBE FOR THE QUALIFICATION OF COMPLEX SURFACE PROPERTIES

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Abstract

With the advent of novel *p-u* probes the sound intensity technique is having a new flourishing. In particular this approach can be used also in the characterization of the acoustical properties of surfaces. This work applies the “transfer matrix” notation to obtain the complex surface properties after sound intensity measurements are performed inside a plane wave tube. The theoretical background is recalled and several measurement results are presented for typical porous sound absorbing materials. Moreover different experimental implementations of the intensimetric technique based both on the *p-p* and on the *p-u* principle are compared. Finally the signal processing implementation is also discussed.

INTRODUCTION

The description of the interaction between sound waves and absorbing materials requires the knowledge of the surface impedance, or alternatively the complex reflection coefficient.

The standardized method for measuring the above-mentioned parameters at normal incidence is based on the transfer function [1] within a plane wave tube. As an alternative to the previous technique it is possible to measure strictly sound absorption coefficient by using an intensimetric approach [2].

Thanks to the recent advances in the miniaturized anemometer technology, particle velocity sensors are now replacing the conventional approach using *p-p* probes. Several studies have been carried out to calibrate these transducers [3] and recently a formulation to calculate surface impedance [4] [5] were proposed.

In this paper a modified transfer matrix approach, based on energetic parameters (i.e. active and reactive intensities and potential and kinetic energy densities), is proposed for the case of plane waves propagation. The method will be tested by using different probes and results will be compared with the values obtained by using the transfer function method.

THEORETICAL BACKGROUND

Let's consider plane waves propagating within a tube whose length is *l*. As depicted in Figure 1, the sound source is located at one end, while at the other side it is put the absorbing material which complex surface properties have to be determined. Sound pressure *P* and particle velocity *V* are measured at the position *x=0* and the distance between measurement point and the surface of the material is *d*.

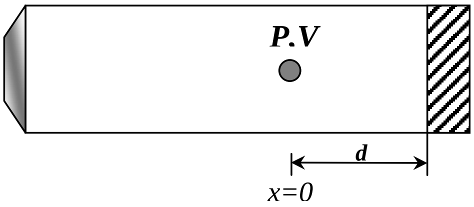


Figure 1 - Sketch of the measurement set-up

Once pressure and particle velocity are known in a fixed position, their value in any other point is univocally determined by using acoustical complex properties of the medium between the two points. It is possible to prove that for an homogeneous and isotropic material is:

$$\begin{pmatrix} P \\ V \end{pmatrix}_{x=d} = \begin{pmatrix} \cos(k_c d) & jZ_c \sin(k_c d) \\ \dfrac{j \sin(k_c d)}{Z_c} & \cos(k_c d) \end{pmatrix} \begin{pmatrix} P \\ V \end{pmatrix}_{x=0} \tag{1}$$

where Z_c is the characteristic impedance, k_c is the complex wave number and *d* the thickness of the medium.

By applying the definition of active and reactive intensity and potential and kinetic energy densities [6], it can be demonstrated that the transfer of these parameters through a layer of air from *x=0* to *x=d* is determined by using following matrix:

$$\begin{pmatrix} AI\\ RI\\ E_p\\ E_{kin}\end{pmatrix}_{x=d} = \begin{pmatrix} 1 & 0 & 0 & 0\\ 0 & \cos(-2kd) & -c\sin(-2kd) & c\sin(-2kd)\\ 0 & \dfrac{\sin(-2kd)}{2c} & \cos^2(-kd) & \sin^2(-kd)\\ 0 & -\dfrac{\sin(-2kd)}{2c} & \sin^2(-kd) & \cos^2(-kd)\end{pmatrix}\begin{pmatrix} AI\\ RI\\ E_p\\ E_{kin}\end{pmatrix}_{x=0} \tag{2}$$

Now, the acoustic impedance at a generic position x is :

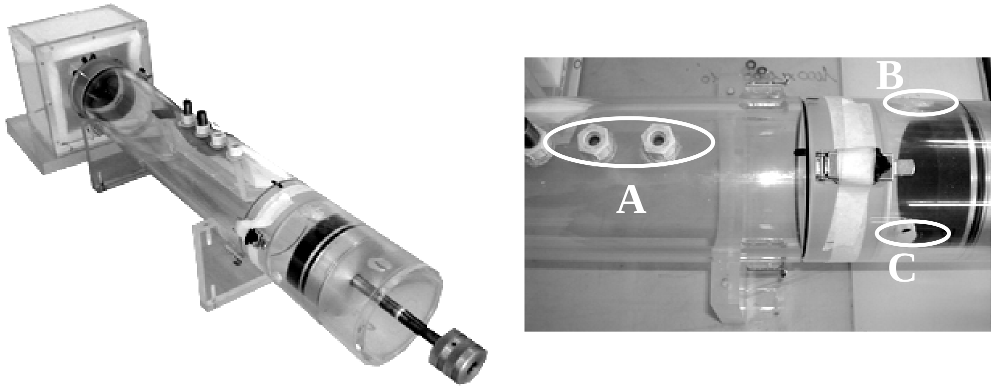
$$Z\big|_x = \frac{P}{V}\bigg|_x = \frac{AI\big|_x + i\,RI\big|_x}{2c\,E_{kin}\big|_x} \tag{3}$$

By using this equation for calculating the surface impedance at $x=d$, it is possible to determine the complex reflection coefficient and the normal incidence sound absorption coefficient by simple manipulation.

MATERIALS AND METHODS

The experimental set-up (Fig. 2) consists of a plane wave tube equipped with microphones and intensity probes holders. Different intensity probes were tested, in particular:

- 1 dimensional commercial *p-u* probe;
- 3 dimensional commercial *p-u* probe;
- hybrid probe, assembled by matching a ¼’’ condenser microphone and a velocity sensor;
- a *p-p* probe, realized through 2 condenser microphones (¼”) B&K type 4939.



a) Measurement tube

b) microphones and probes holders

Figure 2 – Experimental set-up and some details. a) measurement tube; b) ***A*** *: microphone holder;* ***B****: p-u hybrid probe holder;* ***C****: 1D and 3D p-u probes holder*

1D p-u probe **3D p-u probe** **Hybrid p-u probe** **p-p probe**

Figure 3 – The tested probes.

It has to be emphasized that the hybrid probe was assembled in order to optimize the S/N ratio of the *p* sensor. Sound pressures and particle velocities were measured by means by impulse responses, obtained by exponential sine sweep method. For the signal generation and acquisition the software Adobe Audition® was used.

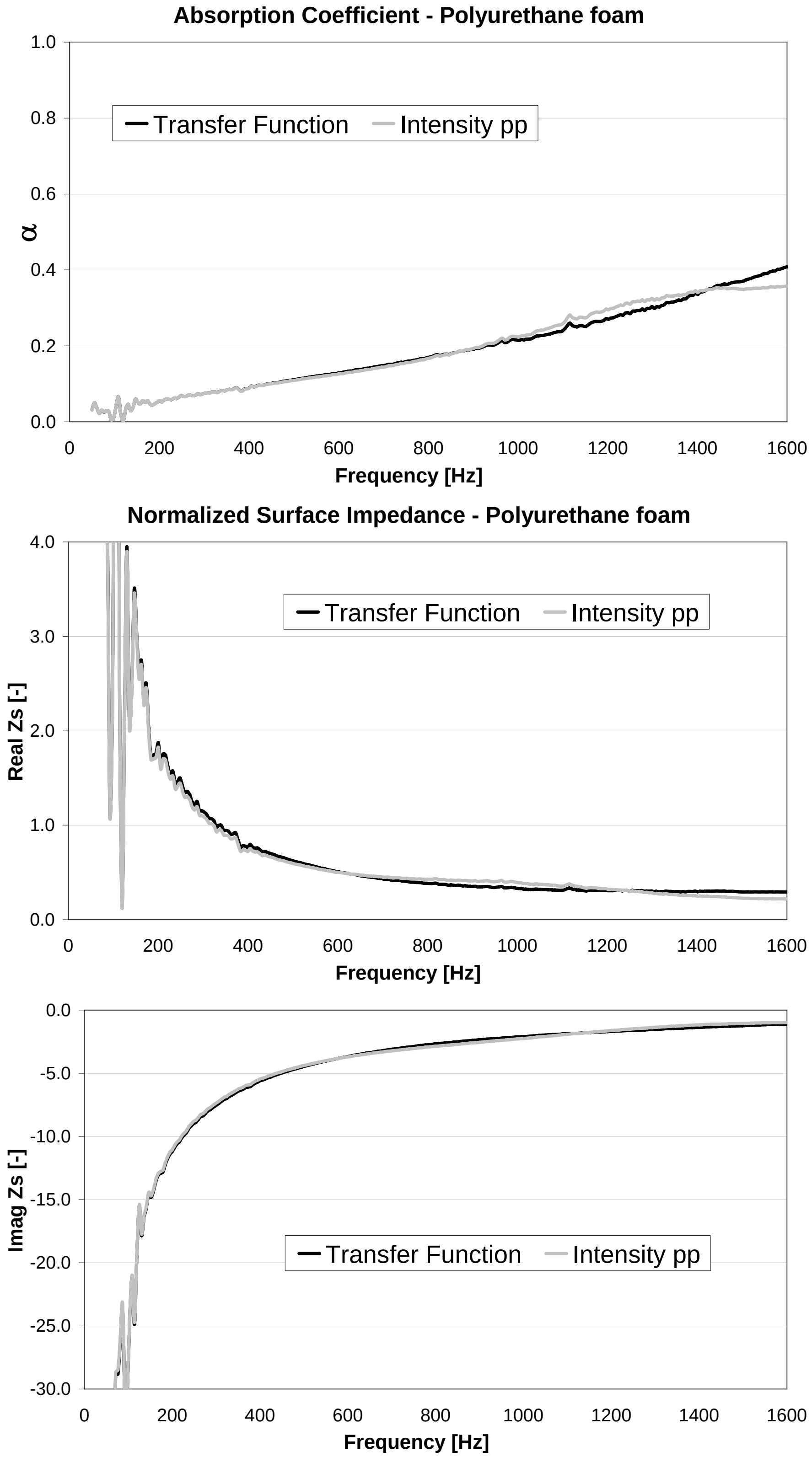
Firstly microphone and velocity sensor were calibrated within the measurement tube; to this end a procedure based on the transfer matrix in (1), through a layer of air on a rigid termination, was implemented as suggested in [4]. According this formulation the ratio between velocity and pressure has to be:

$$\frac{V}{P} = \frac{i}{\rho_0 c} \boldsymbol{tan}\left(kd\right) \tag{4}$$

where *d* [m] is the thickness of the layer of air. Initially the post-processing operations were carried out using Matlab® codes. Then, because of the numerical noise introduced by FFT routines in Matlab, a special plug-in (Aurora) was implemented in Adobe Audition®. The procedure allows to measure the acoustical properties by convolving the pressure and velocity signals with special waveforms obtained by using the (5). In the paper a comparison between results obtained through the above-mentioned procedures will be also shown.

EXPERIMENTAL RESULTS

Figure 4 reports the comparison of absorption coefficient and normalized surface impedance, between TF method and intensity method by means of a *p-p* probe. In this case a polyurethane foam (20mm thick) was tested. For frequencies lower than 700-800 Hz the agreement is good whereas for higher frequencies some discrepancy can be noted due to the "finite differences approximation". On the whole the two measurement principles seem quite in agreement.



Absorption Coefficient - Polyurethane foam

Normalized Surface Impedance - Polyurethane foam

Figure 4 –Comparison between Transfer Function and p-p intensity methods

Figure 5 reports α and Z_s for an open cell synthetic rubber material (24mm thick) obtained by TF and intensity method implemented by means of a *p-p* probe and of the 3D *p-u* probe are compared. In the same figures a zoom in the low frequency range is included. It can be noted that the *p-u* approach provides more reliable results at lower frequencies and resolves the finite difference approximation problems. Moreover TF and *p-p* approaches require a second measurement for frequencies lower than 100 Hz with an increased spacing between the microphones.

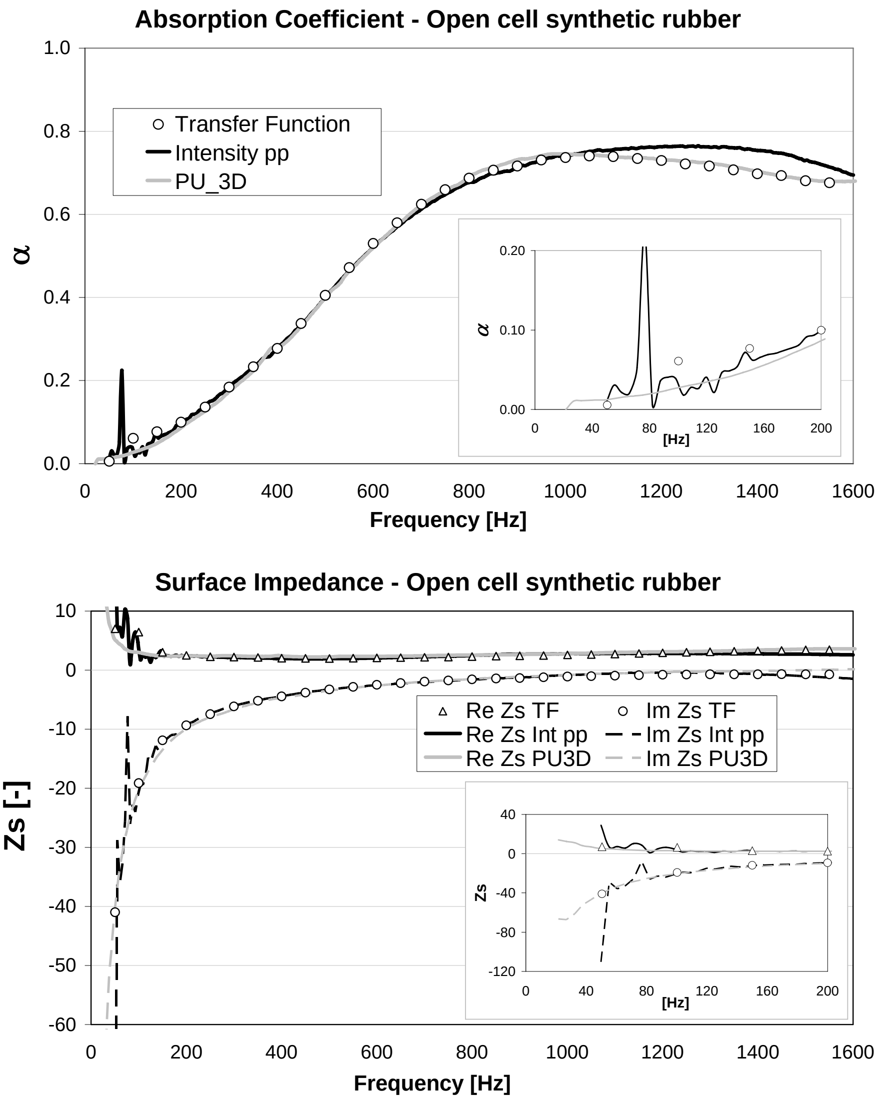


Figure 5 –Comparison between TF method, p-p intensity and p-u approaches

In Figure 6 the comparison of to the tested *p-u* probes is shown for a polyester fiber (30mm thick). Only minor discrepancies are found in the Z_s plots and slight deviations are reported in the α plots below 600Hz. In this respect the 3D *p-u* probe seems to provide the most robust result for this application.

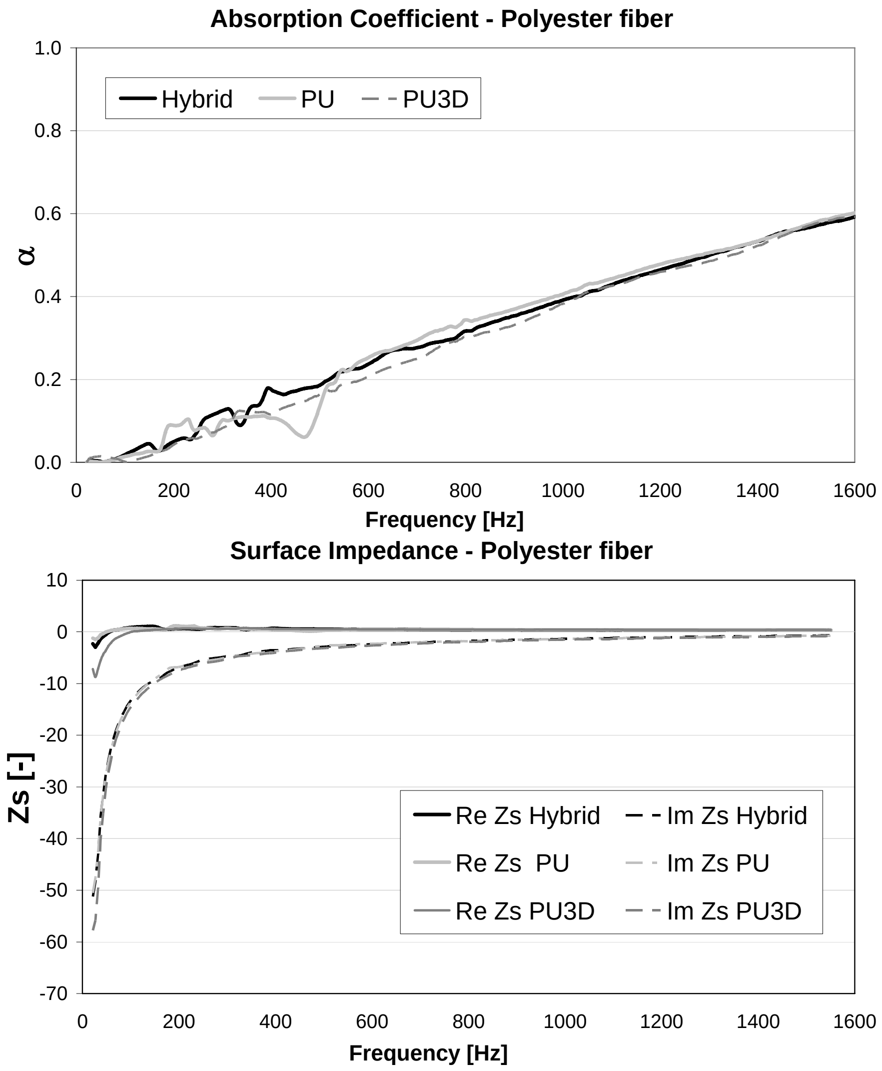


Figure 6 –Comparison between p-u probes.

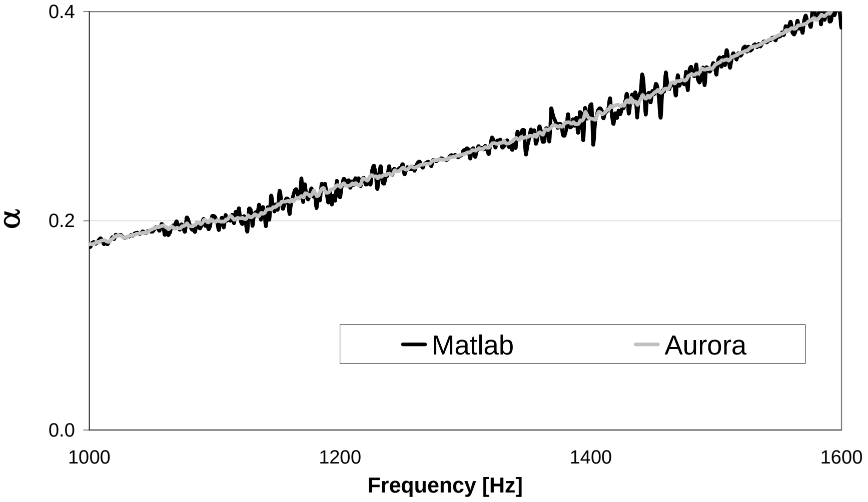


Figure 7 – Comparison between Matlab and Aurora post-processing operations

Finally, in Figure 7, the comparison between Matlab and Aurora post-processing procedures is reported in the frequency range between 1000 Hz and 1600 Hz, where *p-u* probes have exhibited a low signal to noise ratio. The analysis was performed with a frequency resolution equal to 1.35 Hz. It is clear that Aurora provides definitely more reliable results respect on Matlab algorithm. This is probably due to the numerical precision of the programming language which is critical when several FFT processes are done in series.

CONCLUSIONS

The main results of this work can be summarized as follows:

- The transfer matrix approach applied by means of a *p-p* measurement principle yelds results for the complex quantities quite equal to the well-established TF method;
- The adoption of *p-u* probes greatly improved the measurement procedure;
- Though the performance of the p-u probes is substantially similar, the use of a 3D probe seems to output a more robust set of data;
- Due to the great number of spectral operations involving FFT it is recommended to operate in C language for the best numerical performance.

ACKNOWLEDGEMENTS

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