7 - 12 SEPTEMBER 2014, KRAKÓW
FORUM ACUSTICUM

Application of acoustic horns for the amplification of a p-v probe velocimetric signal

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Summary

The present paper shows the comparison between experimental data and simulated results for the amplification factor of acoustic horns. The experimental setup was based on a sound insulation enclosure and a Microflown p-v probe, while COMSOL 4.4 software package has been used for numerical simulation. Apart from systematic errors, due to the mismatch between the simulated and experimental sound fields, the behavior of the obtained results shows a good agreement with the COMSOL modeled ones, so confirming the effectiveness of the horn device as a natural amplifier of the velocity signal.

PACS no. 43.58.+z

1. Introduction

Acoustic horns have been widely used in the first half of the last century both for civil and for military purposes, and have recently found a renewed interest from acousticians after the development of velocimetric acoustic sensors. In fact, thanks to their acoustic-fluid-dynamics properties, the particular boundary conditions of these devices give rise to a particle velocity amplification of the order of 20 dB just with horns measuring ten centimetres in length.

While on the one hand the fast progress in electronics and precision manufacturing resulted in highly sensitive microphones, on the other hand, the particle velocity sensors have not reached a degree of audio fidelity capable of taking full advantage of acoustic amplification.

This fact has raised the interest on the study of the acoustic effects of the horns both on the velocimetric and the pressure signals so that also intensimetric techniques can be relied upon particularly under conditions when the particle velocity signal is very unbalanced compared to the pressure one.

In order to experimentally verify the effectiveness of such devices and in particular their amplification factor on the velocity signal, the CNR-IDASC acoustic group in Ferrara has built and tested some conical horns made of carbon fiber.
The present paper first illustrates their operation on a pressure-velocity (p-v) Microflown® match-size probe it then shows the results obtained in a laboratory test and the comparison with the COMSOL-based numerical analysis.

2. Materials and methods

Webster's equation, discovered in 1919 [1] describes the operating principle of the acoustic horns but, through a number of simplifications and assumptions, reduces the source signal to a plane wave perpendicular to the horn's axis and travelling along the axial direction.
This equation is expressed as:

$$\frac{\partial^2\varphi}{\partial x^2}+\frac{\partial \ln S(x)}{\partial x}\frac{\partial\varphi}{\partial x}-\frac{1}{c^2}\frac{\partial^2\varphi}{\partial t^2}=0 \qquad (1)$$

where:

x is the axial coordinate [m];
ϕ is the velocity potential [m^2/s];
c is the speed of the sound [m/s];
$S(x)$ is the horn's cross-sectional area variation at position x [m^2/m^2].

The solutions of the wave equations are determined by the horn's geometry, and in this case, for the conical shape [$S(x)\sim x^2$]:

$$\varphi=\frac{A}{x}e^{-i(\omega t-kx)}+\frac{B}{x}e^{-i(\omega t+kx)} \qquad (2)$$

where:

A e B are constants determined by the boundary conditions;
ω is the circular frequency [Hz];
k is the wave number [m^{-1}];
t is time [s];
i is the imaginary unit.

The simplifications introduced for equation (1) don't take into account neither the directional effects nor the inevitable diffractions that appear when the wavelengths of the incident sound become comparable to the spatial parameters that characterize the horn's geometry. That's the reason why, in view of future improvements and practical implementations of the device, the numerical simulation based analysis of geometry turns out to be very useful.
As clearly stated in [1], when the acoustic horn is used as a pressure amplifier, its size has to be large compared to the sound wavelength and the throat impedance needs to be as large as possible. On the contrary, the velocimetric horns must be open at the throat and conical in shape. In fact, the authors in [1] demonstrate that the amplification factor is proportional to $K=R_2/R_1$, R_2 and R_1 being the radius of the mouth and the throat respectively.
With these preconditions the Deltatech company in Sogliano al Rubicone (FC, Italy) collaborating with the CNR-IDASC research section of Ferrara the SIHT project, has built a carbon fiber conical horn 75 mm long, with a mouth radius of 30 mm and a throat radius of 6 mm (Fig. 1). As a consequence, the first resonance frequency is 1825 Hz as given in:

$$f_{res}^{horn}=\frac{c}{2(l+0.613R_1+0.613R_2)} \qquad (3)$$

where:

l is the length of the horn [m];
R_1 is the radius of the throat [m];
R_2 is the radius of the mouth [m].

In order to verify the gain factor, we have compared the pressure and velocity signals measured with a p-v match size Microflown® probe in a configuration with and without horn.

Figure 1- Horn made of carbon fibre applied to the p-v probe.

We have arranged some preliminary tests by measuring the pressure and velocity signals generated by pure tones emitted by the source (Technics SB7000 loudspeakers system) while keeping the horn and the loudspeaker 1 m apart. In order to reduce the great variability of the acoustic signals, we have built a 1 m^3 noise-insulating chamber (Fig. 2) surrounding the probe and placed the source outside at a distance of 4 m: in so doing we were able to receive a more homogeneous wavefront from the window with little background noise. The measurement setup has allowed us to evaluate the amplification effect of the velocimetric horn and, in particular, to assess the optimal position of the probe within the horn throat..

The test consisted in the emission of three different kinds of signals: pure tones at the central frequencies of the reference octave bands (31-63-125-250-500-1000-2000-4000-8000 Hz), and white noise filtered both in third octave and octave bands.

Figure 2- Noise-insulating chamber

3. Results

The following plots show the obtained results relative to the amplification factor. In particular we have calculated the gain in dB of the probe-horn system compared to the probe without the conical device.

Figure 3 shows the amplification factor of the pressure signal (blue, continuous line) and that of the velocity signal (red, dotted line), for the three different stimuli: pure tones (3a), 1/1-octave filtered noise (3b) and 1/3-octave filtered noise (3c). The test sounds were generated by the loudspeaker facing the window of the noise-insulating chamber (fig. 2, right).

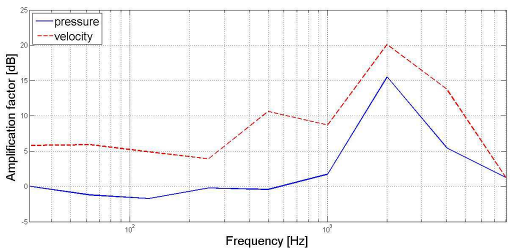

Figure 3a- Amplification factor for pure tones

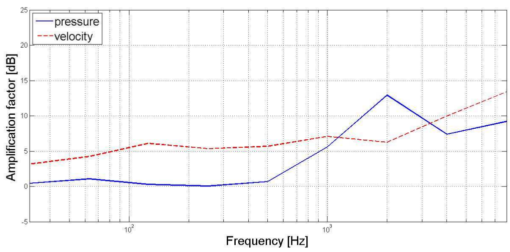

Figure 3b- Amplification factor for octave bands

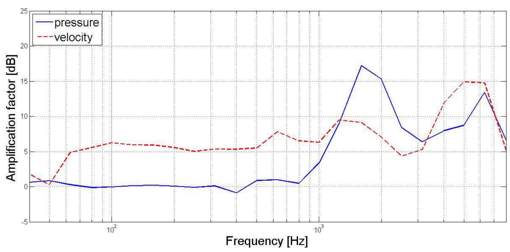

Figure 3c- Amplification factor for third octave bands

A preliminary analysis points out a peak of the amplification factor both for the pressure and the velocity, which presumably corresponds to a resonance frequency around 2 kHz in the pure tones measurements. The same behavior is confirmed by the measures with the filtered noise for the pressure signal only, while for the velocity a more stable gain in the 2 kHz region is followed by an increase at higher frequencies.

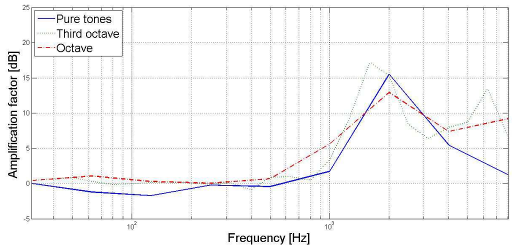

Figure 4a- Amplification factor of the pressure signal

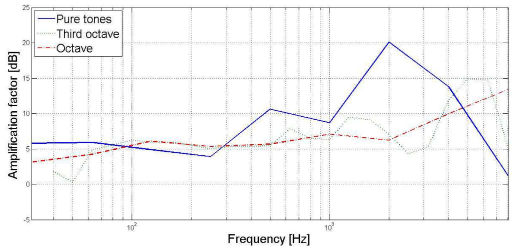

Figure 4b- Amplification factor of the velocity signal

Figure 4 shows the direct comparison of the amplification factor for pressure and velocity measuring the three different signals.
The plots clearly illustrate how the pressure amplitude is not altered by the horn except within a region around the resonance frequency.
This result confirms the theory exposed in [2] according to which the throat affects the velocity but not the pressure. Looking at figure 4b it may be noticed how velocity is amplified by more than 5 dB at all frequencies: the effect appears more evident when using pure tones, where the gain factor reaches a maximum of 20 dB at 2 kHz.

4. Numerical simulation with COMSOL

The simulation was done using the numerical solutions modeled with COMSOL 4.4 aeroacoustic module. In particular we used the linearized potential flow module in frequency domain, where the wave equation, in the coordinate system moving with the fluid (air) at velocity **v**, is given in terms of the velocity potential ϕ as:

$$-\frac{\rho}{c_{mf}^2} i\omega(i\omega\phi + \mathbf{v}\cdot\nabla\phi) + \nabla\cdot\left(\rho\nabla\phi - \frac{\rho}{c_{mf}^2}(i\omega\phi + \mathbf{v}\cdot\nabla\phi)\mathbf{v}\right) = 0 \qquad (4)$$

where:
ρ is the density of the air [kg/m^3];
c_{mf} is the velocity of sound in the material (air) [m/s].
In our simulation we set the fluid velocity **v**=0.
Since the flow is assumed to be irrotational, it is possible to describe the pressure field $p(\mathbf{r},t)$ and the velocity field $v(\mathbf{r},t)$, in terms of the potential ϕ:

$$v(\mathbf{r},t) = \nabla\phi, \qquad p(\mathbf{r},t) = -\rho\frac{\partial\phi}{\partial t}.$$

In order to simplify the model, we adopted the two-dimensional axisymmetrical geometry. All the surfaces were assumed to be acoustically rigid, and the values for air density and speed of sound were set to 1.2 kg/m^3 and 343 m/s. The simulated sound field was a 94 dB SPL plane progressive wave incident at the horn's mouth.
The results of the simulation are shown in figure 5 where the RMS values of the particle velocity are reported for octave bands centre frequencies. The amplification effect of the throat compared with the mouth is evident, so confirming the experimental results.
Table 1 and figure 6 show the comparison between the velocity amplification factors found through measurements and simulation.
It can be noticed that the resonance peak is shifted to lower frequencies in the simulation results, while the overall amplification of the velocity signal is confirmed. The systematic higher values obtained by simulation (see column 5 in table 1), can be explained recalling that a plane progressive field has been used in the simulation, a condition which is unlikely to have been satisfied by the experimental setup (see figure 2).

5. Conclusions

The measures carried out by applying a carbon fiber horn on a p-v probe, have shown the effectiveness of such device as a particle velocity natural amplifier, while it doesn't affect the pressure field.

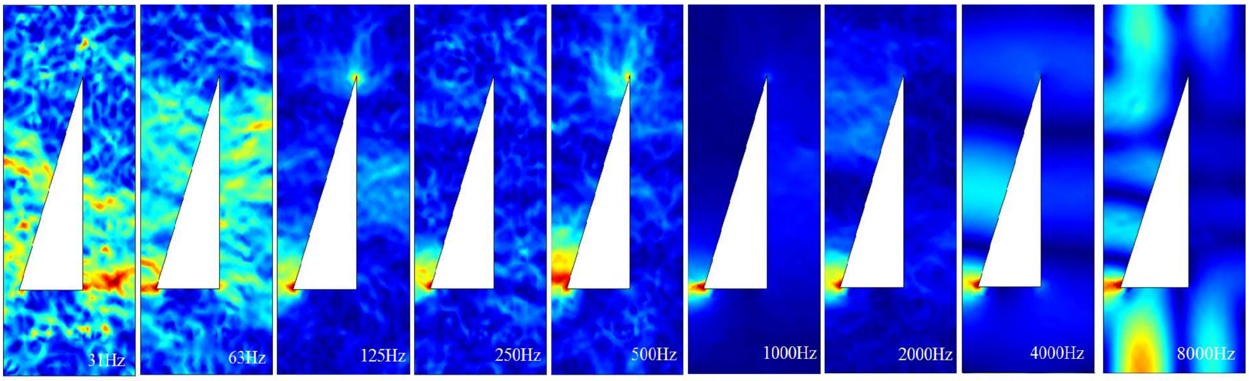

Figure 5- (Color online) COMSOL modeled particle velocity (RMS) within an horn with the same dimensions of the one used for the measures, scaling different for each frequency.

Frequency [Hz]	Gv_pure tones [dB]	Gv_octave [dB]	Gv_third octave [dB]	Gv_COMSOL [dB]
31	5.8	5.3	5.3	0.67
63	5.9	6	6.9	7.59
125	4.9	6.7	7.04	12.63
250	3.9	5.02	5.15	13.73
500	10.6	5.33	5.15	13.38
1000	8.7	6.11	6.15	18.22
2000	20.1	5.19	6.4	10.72
4000	13.8	7.15	8.9	8.65
8000	1.2	5.6	4.42	12.19

Table 1- experimental and simulated amplification factors

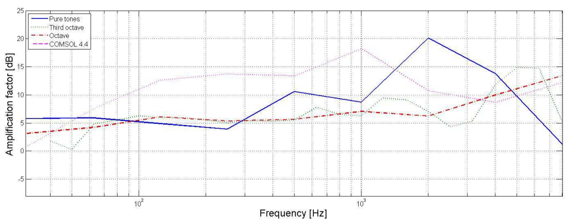

Figure 6- (Color online) Amplification factor for the velocity signal

This result confirms the theory illustrated in [2] also in air, where the use of p-v probes is important both for intensimetry and for acoustic impedance measurements. The numerical simulations with COMSOL 4.4 not only support the experimental results, but can also be considered a very useful tool, helping in designing the optimal geometry for any acoustical application.

Acknowledgement

The authors wish to thank DELTATECH Srl-Sogliano al Rubicone (FC) - Italy, for providing the horns.

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