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In situ directivity measurement of flush-mounted loudspeakers in a non-environment listening room

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ABSTRACT

Directivity is one important parameter to define the behaviour of a loudspeaker. There are many techniques and standards about directivity measurements in anechoic chambers but in situ measurements of flush-mounted loudspeakers show some specific problems. This contribution develops a procedure to measure directivity under the special conditions of a non-environment listening room, introducing the techniques utilized, the problems found with the proposed solutions and discussing the limitations of the process. The existence of reflections, baffling effects due to adjacent walls and a comparison to theoretical models of the radiation of a piston are discussed.

1. INTRODUCTION

For many years, flush-mounted loudspeakers have been installed not only in recording studios but also for household use, where a high quality of sound reproduction is desired.

Besides frequency response, directivity is an important parameter to delimitate the sweet spot listening

area and understand how a room is excited by energy radiated from loudspeakers. Nevertheless, there is not so much publications concerning the measurement of flush-mounted loudspeakers directivity.

Even though a free field environment is required to study the direct sound radiated by loudspeakers, non-environment rooms can be considered to behave

as a limited half-space free-field room. They are enclosures with ceiling and walls having very absorbent characteristics, except the diffuse reflecting front wall where the loudspeakers are flush-mounted, and a reflective floor. This structure affects the sound radiation patterns; hence, it is important to study the limitations that in-situ measurement methods involve in this kind of rooms.

This paper is focused on directivity measurements made, trying to minimize the effect of the room and obtain the radiation patterns. On the other hand, the contribution of the room was also estimated in the final results.

2. REVIEW OF LITERATURE

2.1. Adaptation of the measurement standard

There is no standard regulation describing the whole process to measure directivity of flush-mounted loudspeakers. Nonetheless, International Standard ISO 60268 - 5 [1] includes some important considerations which were adapted to this new environment. According to this standard, and assessing the characteristics of the room, ‘Half-space free-field conditions’ were assumed with some limitations as discussed below.

The flush-mounted loudspeakers studied were Reflexion Arts 239x models, with a JBL 2235H driver and an AX2 axisymmetric horn.

Firstly, it was needed to calculate the correct distance where the measurements have to be done. In [1] it is explained that in order to obtain coherent results the measurements undertaken under half-space free-field conditions should be carried out in the far field of the source.

According to [2], the minimum distance to measure should be 3 times the maximum dimension of the source in order to consider the measurements under far field conditions. Nonetheless, the large dimensions of the flush-mounted loudspeakers under test and the room size limitations made it impossible to measure some elevation positions if the multi way loudspeakers are considered as a unique source. Therefore, the two way loudspeaker has been assessed as composed by two single sources which have a homogeneous behaviour in the far field. In

fact, they work in different spectral ranges with a small overlapped area. Consequently, they could be reasonably considered as uncorrelated sources. This assumption implies that the superposition principle could be applied in order to evaluate their individual patterns together.

2.2. Far field boundary conditions

To know where the measurements can be considered under far field conditions, a theoretical approximation can be developed. As proved in [3], the sound pressure amplitude on the axis of a harmonically vibrating circular piston in an infinite rigid baffle can be defined as

$$|p(r, 0)| = 2\rho_0 U_0 \sin \left(ka \frac{\sqrt{r^2/a^2 + 1} - r/a}{2} \right) \quad (1)$$

Then, as can be seen in Figure 1, for the distances where $r > 6a$ the sound pressure is approximately independent of the directional factor. (See Appendix 1 for a glossary of symbols)

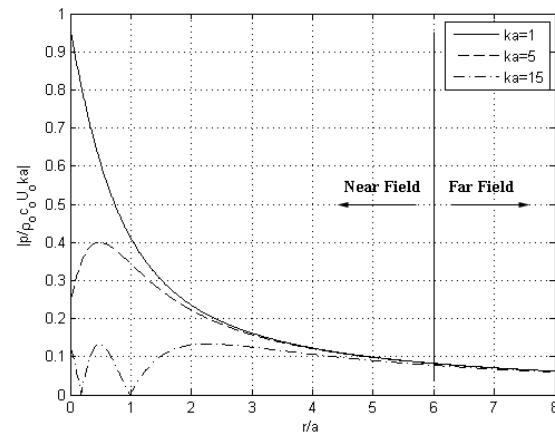


Fig. 1: Normalized pressure response at different frequencies

2.3. Alternative methods

One of the most common methods utilised in non-anechoic rooms is based on time windowing techniques to isolate the direct radiated sound before the arrival of the reflected wavefronts [2]. The principal limitation of this method is that it does not work properly for small rooms where the path difference

between direct and reflected sound is so small that provides an insufficient frequency resolution [4].

Maximum Length Sequence (MLS) based measurements could be regarded as a good solution to try to extract the features of loudspeakers. These methods are based on the cross-correlation function between the signal recorded with the measurement microphone, using a pseudo-random binary sequence which is periodically repeated to excite the loudspeakers [5]. The calculation of the DFT (Discrete Fourier Transform) of the cross-correlation is computed so as to obtain the loudspeaker frequency with an excellent signal-to-noise ratio [6]. However, the presence of local reflexions can bias the estimations [7] and data synchronization at the postprocessing stage would become very tedious, due to the large amount of signals involved in radiation pattern estimations.

3. INSTRUMENTATION AND MEASUREMENT METHOD

All measurements presented were carried out in the control listening room of the University of Vigo. It is a non-environment design by Philip Newell. The flush-mounted loudspeakers are RA 239x models (Figure 2), with a JBL 2235H woofer and an AX2 axisymmetric horn which have a 380 mm and 280 mm diameter, respectively. Both ways are fed by the output signal of the crossover Neva Audio AX23 which has its cut-off frequency at 1 kHz and decays of 24 dB per octave in the low pass filtering area, while the high pass filter decays 12 dB per octave. Pink noise was the signal utilised to excite the sources and a five channel B&K PULSE system was used to gather all data. The data was post-processed with MatLab software.

Measurements were made with a resolution of 10 degrees in both azimuth and elevation. The separations between source and measurement microphones were 1.20 metres for the woofer and 1 metre for the horn. Next, a function was designed, to calculate where the microphones have to be positioned into a virtual semi-sphere centred at the sources, using polar coordinates. Then, the microphones were placed forming an arc in elevation. The positions of the microphones were controlled both with marks in the floor and laser-guided measurements. The same function used to calculate the microphones



Fig. 2: Studied flush-mounted loudspeaker

positions was utilized to compute the references on the floor illustrating each measured azimuth. The angle nomenclature was chosen following the open CLF representation (Common Loudspeaker Format) [8].

The analysed surfaces were measured at each azimuth position defined using two series of five simultaneous measurements. Moreover, one common measurement was done at 90° elevation position. The structure shown in Figure 3 was utilized to place the five microphones for each azimuth position.

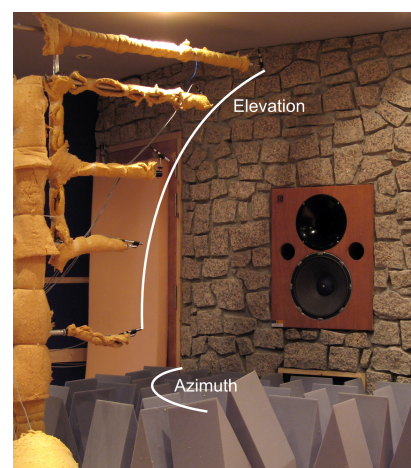


Fig. 3: Utilized structure

Furthermore, the response of the sources was measured in their 0° elevation plane in order to analyze the expected symmetry in the radiation pattern of

the monitor. As described in Section 4.1 it was concluded that, at lower frequencies, one half of the pattern was affected by the adjacent segment of the front wall. Therefore, horizontal symmetry was assumed both for the low frequency speaker and the horn in order to extrapolate unbiased patterns. Vertical symmetry was assumed too due to the impossibility to measure the bottom half of the polar pattern because of the floor proximity.

Hence, positions between 0° and -90° in azimuth and between 0° and 90° in elevation were measured, both with a resolution of 10 degrees.

On the other hand, in order to minimise the effect of the floor reflections, 0.6m foam wedges were utilised.

Effects of cancellations as notches appear when the path difference between the direct and reflected signal equals $\lambda/2$. The frequency positions of these notches depend on the measuring distance. Thus, as that distance grows, the notches are located at higher frequencies. After studying the behaviour of the wedges it was concluded that they cause a complex behaviour at low frequencies. It was observed that the foam wedges introduced variations in the notches positions below 500 Hz, probably due to the modification of the reflected path. The directivity measurements are slightly affected below 500 Hz, if octave bands are considered. Moreover, this assumption was taken into account in the frequency response analysis.

4. DISCUSSION

4.1. Influence of the room: “wall effect”

The geometry of the room is a very important feature which should be assessed carefully in order to extrapolate good radiation patterns. In our case, as it is shown in Figure 4, the non-environment room studied has a non symmetric wall from the point of view of the lateral speakers. This fact implies some bias in the measurements due to the baffling effect when the sound radiated by these loudspeakers reaches the central segment of the front wall.

Figure 5 presents the directivity pattern measured at each possible azimuth position of the left loudspeaker from -90° to 70° at 0° elevation. Regarding this figure, it can be concluded that the reinforcement becomes more significant at lower frequencies, being more evident as the positions are closer

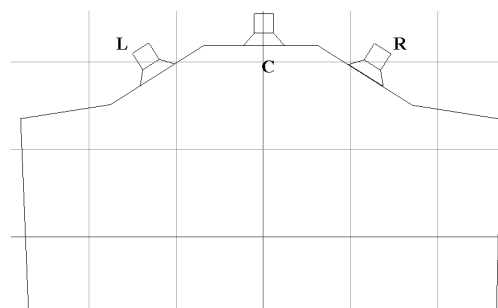


Fig. 4: Non-environment listening room under test

to this reflecting surface. Consequently, as it was said, directivity measurements were undertaken in one quadrant of the side loudspeakers, avoiding the baffling effect of the adjacent wall.

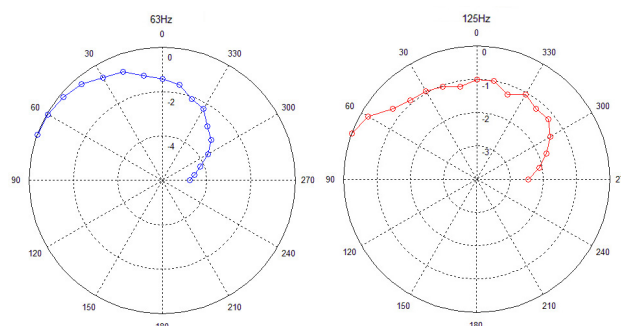


Fig. 5: “wall effect” biasing the directivity pattern

4.2. Directivity patterns obtained

Under these considerations measurements were undertaken in the left loudspeaker individually for the driver and the horn. Directivity balloons were obtained for each octave band from 63 Hz to 2 kHz for the woofer and from 500 Hz to 16 kHz for the horn. An example of these balloons can be seen in Figure 6.

4.2.1. Woofer driver

As a simplified way to represent the directivity of the source, Figure 7 provides the patterns measured at 0° degrees of elevation normalized for each octave band individually. This polar plot clearly shows how the source becomes more directive as the frequency increases. These results suggest that the whole process undertaken gives good results, such as made in a real free field environment. The lowest patterns, between

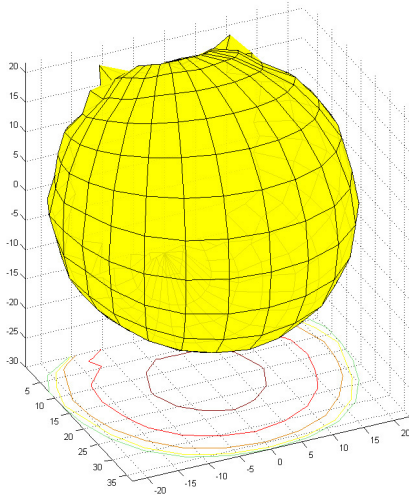


Fig. 6: 4000 Hz directivity pattern of the horn

63 to 250 Hz, were slightly affected by the reflected wavefronts because wedges do not work properly in this range; however, even with sharp cancellations in this spectral area, the global level in octave bands was not very much biased by these fluctuations because the results were expressed in octave bands.

The symmetric results obtained when using data from just one quadrant of the side loudspeakers avoids the influence due to the proximity of the wall where the center loudspeaker is.

4.2.2. Axisymmetric horn

In the same way shown in Section 4.2.1, the measured directivity patterns of the horn are presented in Figure 8. It can be seen that these patterns present a sharper directivity pattern than in Figure 7. On the other hand, regarding again the accuracy of the measurements, the horns patterns were less biased by the environment due to the intrinsic characteristics of the source. Its radiation is concentrated around the acoustic axis without any significant lateral lobe. Reflecting surfaces (front wall and floor) seems not to be a problem in this case.

Only one of the upper quadrants has been measured because there was no room to place the structure. Hence, the measurement results were extrapolated taking into account the symmetry expected and found in the 0 azimuth radiation patterns.

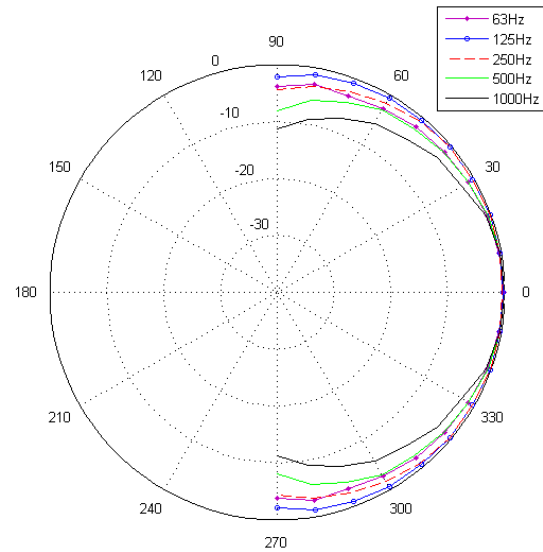


Fig. 7: Directivity pattern of the woofer at 0° of elevation

In addition, by comparing Figure 8 and Figure 7 can be seen that the directivities of the woofer and the horn are similar at the crossover frequency of 1kHz which is a desired feature for a loudspeaker.

4.3. Comparison between theoretical patterns and measurements

According to [3], the theoretical radiation patterns of the JBL 2235H could be approximated via the expression for the far field pressure generated by a circular piston in an infinite rigid baffle, which is defined as

$$p(r, \theta, t) = j \frac{\rho_0 c_0}{2} U_0 \frac{a}{r} k a e^{j(\omega t - kr)} \left[\frac{2J_1(ka \sin \theta)}{ka \sin \theta} \right] \quad (2)$$

where a is the diameter of the piston, k is the wave number, r is the distance from the source, $\rho_0 c_0$ is the characteristic acoustic impedance of the medium and J_1 is the first order Bessel function. It has to be mentioned that, to consider far field conditions, r has to be much larger than a .

Furthermore, as can be seen in Formula 3, the bracketed term determines the angular dependence of p , and this term tends to unity as θ goes to 0. Hence,

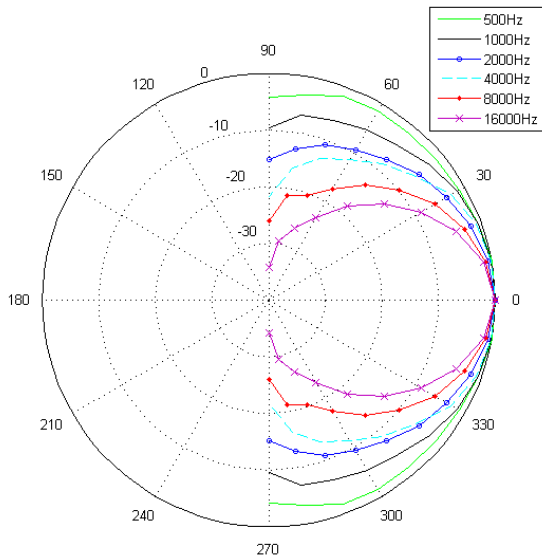


Fig. 8: Directivity pattern of the horn at 0° of elevation

we can identify the directional factor $H(\theta)$ for the piston as

$$H(\theta) = \left| \frac{2J_1(v)}{v} \right| \text{ where } v = kasin\theta \quad (3)$$

Next, the theoretical radiation patterns were calculated for octave bands from 63 Hz to 2 kHz. The difference between the measurements and the calculations are presented in Figure 9 and, as can be seen, both patterns are fairly similar, especially for 125 Hz and 1000 Hz. Only at 2 kHz they are totally different; but this mismatching is perfectly reasonable because the simplification of the driver as a pure piston is not longer true at this frequency band, where the details of the shape become comparable to the wavelength and hence, significant in the final result. Furthermore, the theoretical radiation patterns differ from the measurements less than 2 dB in the 50 first degrees of azimuth below 1 kHz. Therefore, it could be stated that the theoretical radiation patterns are very useful even utilizing only one parameter to define the source, which is the radius of the loudspeaker.

On the other hand, Figure 10 provides the radiation pattern of the studied horn measured in ane-

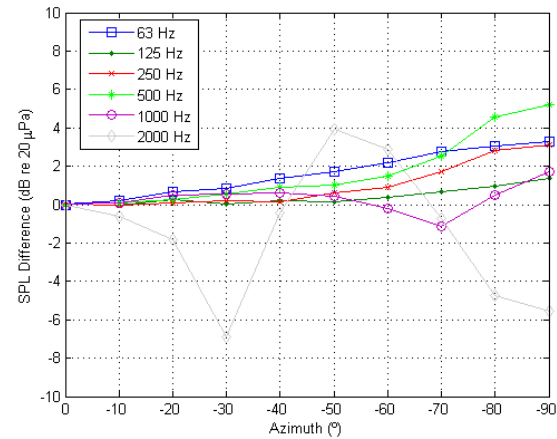


Fig. 9: Difference between theoretical patterns and measurements

choic chamber [9]. The values from the graph can be directly compared with the measured patterns shown in Figure 8 only at 8 kHz and approximated at 500 Hz, being both results very similar. Furthermore, the trend is similar for intermediate frequencies, becoming less directive for lower frequencies with a smooth progression. Hence, it can be concluded that the measurements fit external measurements made in a free field environment.

5. CONCLUSIONS

This paper presents a measurement procedure in order to obtain the directivity patterns of flush-mounted loudspeakers.

Problems with the reflection on the floor in the spectral range above approximately 500 Hz were mitigated successfully by placing absorbent wedges of 0.6 metres high. Furthermore, results indicate that the bias produced by the reflected wavefront below 500 Hz does not significantly modify the estimated level of the octave bands, so the in situ measurement seems reasonably valid.

After analysing the expected symmetry in the radiation pattern of the monitor, it was found that at lower frequencies one half of the pattern was affected by the adjacent segment of the front wall. Then, horizontal symmetry was assumed both for the low frequency loudspeaker and the horn in order to extrapolate unbiased patterns. Vertical symmetry was

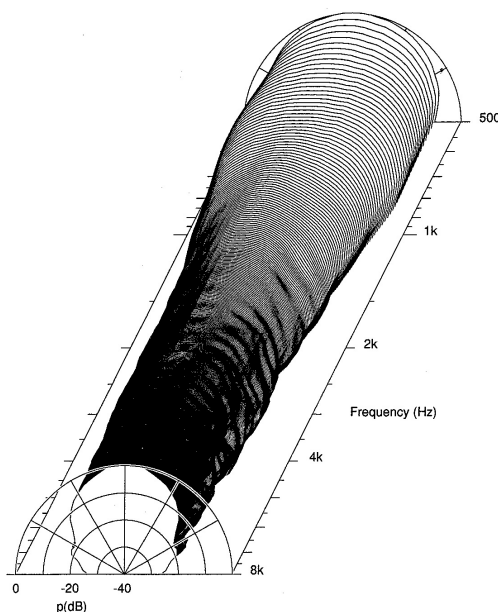


Fig. 10: Radiation pattern of the studied horn measured in anechoic chamber([9])

assumed too because of the impossibility to measure the bottom half of the polar pattern due to the floor proximity. Consequently, directivity measurements were undertaken in one quadrant of the side loudspeakers, avoiding the baffling effect of the adjacent wall. Symmetry was assumed to extrapolate the missing data.

Furthermore, the theoretical radiation pattern of a plane circular piston in an infinite rigid baffle was calculated between 63 Hz and 1 kHz. The measurements were very similar to the theoretical model output, especially between 0° and 50° azimuth. On the other hand, by comparing the patterns obtained with external measurements undertaken in a free field environment [9] can be stated that they led to almost the same results.

The measured directivity patterns of the horns were less biased by the environment due to the intrinsic characteristics of the source. Their radiation is concentrated around the acoustic axis without any significant lateral lobe. Reflecting surfaces (front wall and floor) seems not to be a problem in this case.

In conclusion, a measurement of flush-mounted loudspeakers in a non-environment room was developed

in situ. Results are discussed and corrected after identifying some problems. A measurement procedure is suggested.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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8. APPENDIX 1: GLOSSARY OF TERMS

a	piston radius
c_0	velocity of sound in air, = 343m/s
$H(\theta)$	directional factor
J_1	first order Bessel function
k	wave number, = ω/c
p	sound pressure

r	distance from the centre of the piston
t	time variable
U_0	piston velocity
ρ_0	density of air, $= 1.21 \text{ kg/m}^3$ at 20°C
θ	angle from source axis
ω	radian frequency $= 2\pi f$