# DEVELOPMENT OF AN OMNIDIRECTIONAL SOURCE FOR ACOUSTICAL SCALE-MODEL MEASURMENTS

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## 1 INTRODUCTION

Scale model measurements enable wave-effects such as diffraction, interference effects and the seat-dip effect to be analysed, acoustical aspects which are challenging to simulate using geometrical acoustics computer models. At full scale, the most commonly used omnidirectional sources are dodecahedrons, but these are problematic at common acoustical model scales such as 1:50, 1:20 or even 1:10 because of the necessary equivalent size of the loudspeakers.

Based on the research of Jean-Dominique Polack[1] and Nikolaos M. Papadakis[2], this paper describes the development of an omnidirectional source for scale model measurements using an inverted cone-shaped horn driven by a single loudspeaker. In order to optimise the omnidirectional performance, the geometrical parameters of the cone, such as the aperture width, height and curvature of the cone walls, were initially optimised using BEM simulations, and then via several stages of prototyping using 3D printing.

## 2 SOURCE DESIGN AND OPTIMIZATIONS

### 2.1 Shape of the source and loudspeaker selection

Based on the research of Leishman[3] and Tarnow[4], it is shown that the omnidirectionality of polyhedral sources is reduced at high frequencies above $f_{cut\text{-}off} = k*a$ where $k$ is the acoustic wave number and $a$ the effective radius. At 1:20 scale, a cut-off frequency of 30 kHz (equivalent to 1.5 kHz 1:1 frequency) results of an effective radius of less than 1cm, which is much too small for the integration of cone loudspeakers.

As an alternative to polyhedral sources, a solution utilizing a single larger speaker attached to an inverted cone-shaped horn sound source has been tested at scale 1:1 by J.D. Polack[1] and N.M. Papadaksi[2] and gave good results regarding omnidirectionality. Due to the tapering of the horn, the loudspeaker used for the source can be bigger than the polyhedral requirements, so this concept has been chosen as a starting point for the scale model source.

For our scale model measurements, the requirement to carry out measurements on a 1:20 scale model requires the loudspeaker to emit at frequencies from 2 kHz to 60 kHz (equivalent to 100 Hz to 3 kHz full scale). To achieve this, piezoelectric ultrasonic tweeters with a diameter of 50mm were chosen. Two different tweeters with the exact same sizes were tested and gave sufficient signal level but not a flat response, one from Pofet (see Figure 1), the other one from Meetoot. The variation in frequency would be equalized with signal processing, and so the main criterion was that the loudspeaker could generate sufficient sound level.

Figure 1: POFET ultrasonic piezoelectric tweeter selected for the source.

In terms of omnidirectionality, the aim was to comply with the maximum deviations defined in the standard ISO 3382-1[6].

## 2.2 First prototypes and analysis of omnidirectionality

To design the inverse horn attached to the loudspeaker, a parametric 3D-model using the modelling software Rhinoceros with Grasshopper was created. The solution is similar to the work of Ibarra[5] but here applied to measurements of 1:10 to 1:20 scale models rather than the full-scale cones presented in that research. The first four pavilions resulting from the modelling experiments were 3D-printed (Figure 2) with different opening sizes, shapes, and heights.

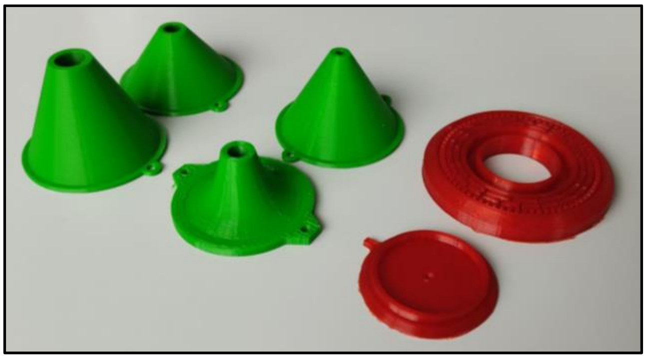

Figure 2: Four prototypes 3D-printed (left) and the omnidirectionality testing bench (right)

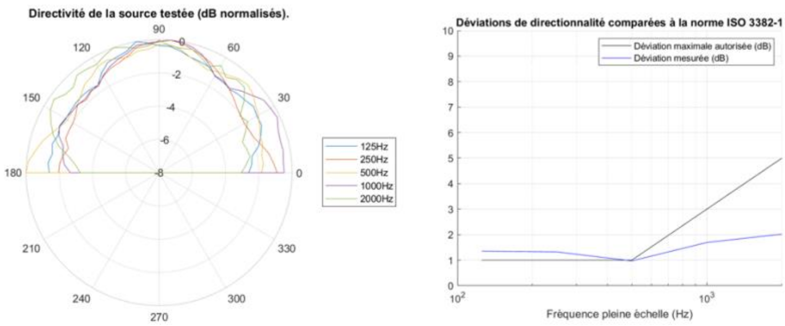


Figure 3: Polar plot of the directivity measured for the horn with an aperture radius of 1mm (left), and deviation of directivity compared to the standard ISO 3382-1 (right)

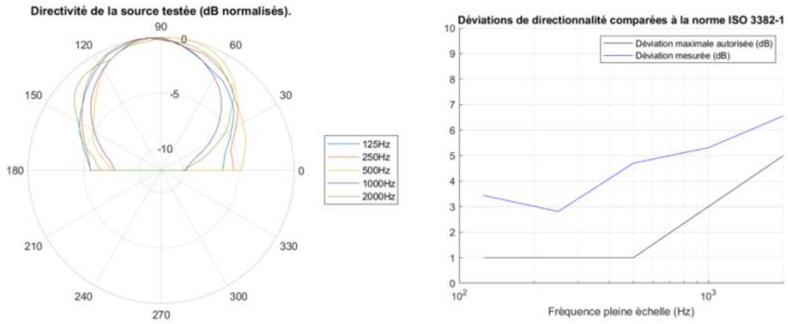


Figure 4: Polar plot of the directivity measured for the horn with an aperture radius of 4mm (left), and deviation of directivity compared to the standard ISO 3382-1 (right)

The directivity of each horn was measured and compared to the maximum authorized deviation of directivity given by the standard ISO 3382-1 (two examples are shown in Figure 3 and Figure 4). To meet the requirements of the ISO standard, the sound pressure level as been measured at 10cm from the source with an omnidirectional microphone (corresponding to 2 meters at full-scale), every 5°, and averaged by "gliding averages", each covering six neighbouring points. To simulate an anechoic chamber, the sound source and microphone were placed away from other surfaces in the room (at least 2 meters from walls, floor and ceiling), and a sufficiently short time window was used to avoid the reflections from the nearest surfaces and keep only the direct sound.

The acquisition system consisted of the following elements:  a DPA 4060 microphone for the recording, an external RME Fireface UC sound card, and an ART SLA-1 amplifier.

The directivity has been measured for frequencies from 2.5 kHz to 40 kHz (1:20 scale), that corresponds to frequencies from 125 Hz to 2 kHz at full-scale. It is shown that the horns with a smaller radius of aperture (1mm or 2mm) gave promising results for omnidirectionality, but pavilions with a large aperture radius (3mm or 4mm) showed excessive deviations of directivity compared to the standard. For the next steps only aperture radii under 2mm were therefore considered.

## 2.3 Optimization of the cone shape using BEM analysis

To optimize the omnidirectionality of the source while reducing the number of prototypes to be manufactured, a Boundary Element Method (BEM) analysis was carried out, first by comparing the measurements of the 3D-printed horns with the BEM simulation results (Figure 6). The measurements and BEM simulations were sufficiently close and showed the same general trends regarding directivity. Based on this, it was decided that the BEM simulations were sufficiently accurate to develop the next optimizations of the horn shape.

The sound source system is axisymmetrical so only half a plane needs to be computed. The mesh size of 1.5mm was chosen so that the largest element is at least 4 times smaller than any wavelength throughout the frequency band of interest: minimum of 1 kHz at 1:20 scale, which corresponds to 50 Hz at full-scale (Figure 5).

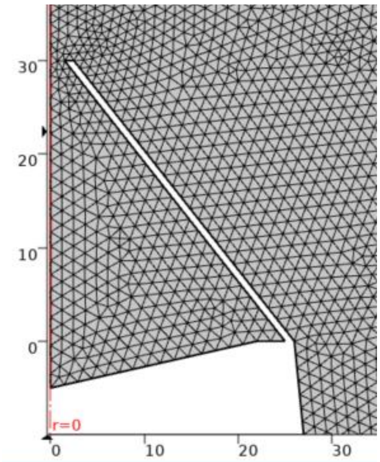


Figure 5: Simulated model of one pavilion using the Boundary Element Method with a maximum mesh length of 1.5mm.

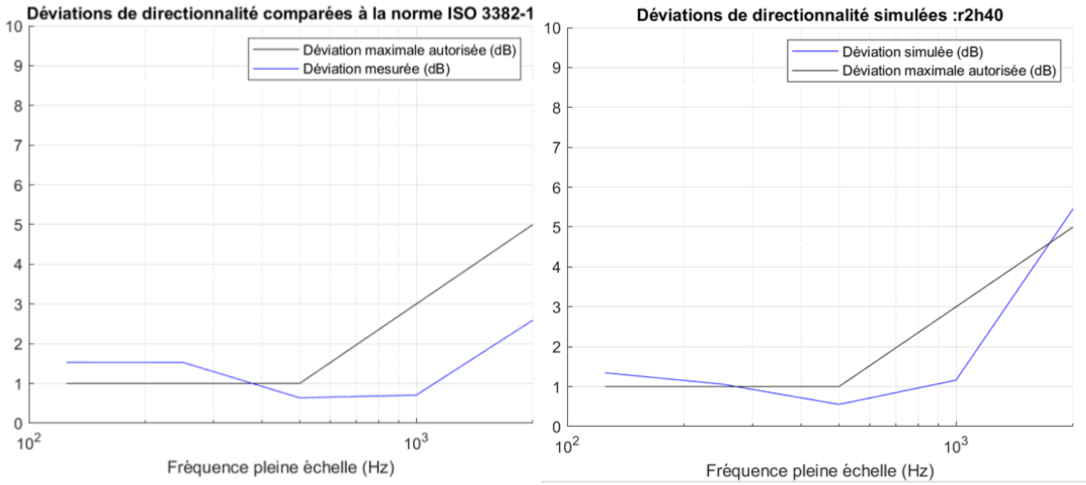


Figure 6: Comparison of measured omnidirectionality of the pavilion with an aperture radius of 2mm (left) and the BEM simulation for the same horn (right)

For the next round of BEM simulations, three parameters are evaluated: the height of the cone, the radius of aperture (the size of the opening on top), and the curvature of the horn (straight or exponentially curved). For each parameter, four values are considered, resulting in a matrix of 64 different shapes. The parameters were the following:

- h: the height of the cone was varied between 10mm, 20mm, 30mm and 40mm
- r: the radius of aperture was varied between 0.5mm, 1mm, 1.5mm and 2mm
- b: the shape of the cone was either b1 (conic), b2 (smooth exponential), b3 (stronger exponential), b4 (strongest exponential)

In order to compare the results of the 64 simulated sources, two indicators were extracted from the results of the BEM analysis. The first indicator was the sum per frequency band of each deviation of directivity when it exceeded the maximum given by the standard ISO 3382-1 (Figure 7). The second indicator was the level in dB at 2 kHz provided by the simulation software, as a reference to compare the signal level between the different horn designs (Figure 8).

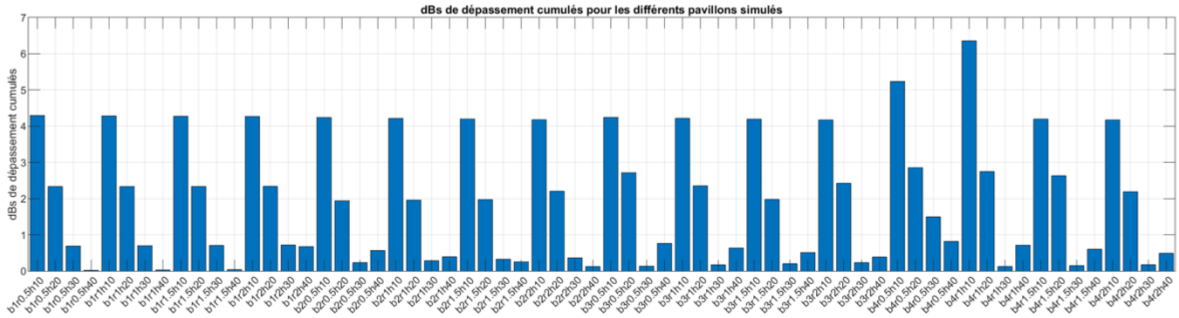


Figure 7: Comparison of the cumulative deviation of directivity for all 64 simulated models compared to the standard ISO 3382-1

It was found that none of the 64 pavilions complied strictly with the standard ISO 3382-1, but many of shapes had a cumulative deviation of less than 1 dB. This was the case for almost all of the horns with heights of 30mm and 40mm. Inverse horns with a height of 10mm showed the least good omnidirectionality (Figure 7). The curvature in section of the inverse horn (straight or exponential) had very little effect on the directivity.

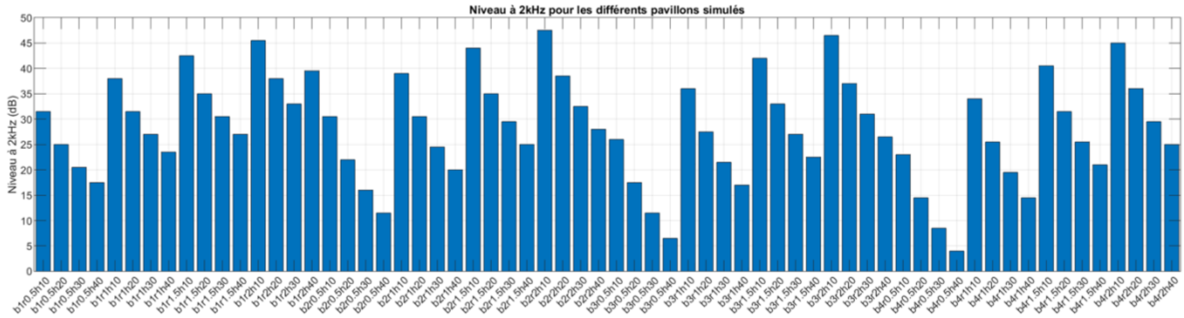


Figure 8: Comparison of the level in dB at 2kHz (scale 1:1) for all 64 simulated pavilions

It was found that the height of the pavilion and the radius of aperture have a strong impact on the level of the signal (Figure 8). The smaller the radius of aperture and the larger the size, the lower the output signal.

In conclusion, to achieve the highest degree of omnidirectionality of the source, it would be necessary to increase the height of the horn (30mm and 40mm). The radius of the aperture between 0.5mm and 2mm has little influence on directivity but has a great influence on the power level of the signal emitted. A larger radius of aperture simply provides more signal level. The exponential or conical shape has a negligible impact on the directivity but have an impact on signal level for a height of 40mm and potentially has an impact on resonances inside the horn as the volume and internal modes would be different. This aspect is discussed in the next chapter.

Following this BEM analysis, a number of additional horns were modelled and printed in 3D. Taller horns were chosen for better omnidirectionality, but with a lower signal level, and smaller horns if a stronger signal level was required (Figure 9). The results of measured deviation of directivity of one source with a height of 20mm, a radius of aperture of 1.5mm and a conic shape are shown in Figure 10. This is a promising result for use in real scale model measurements.

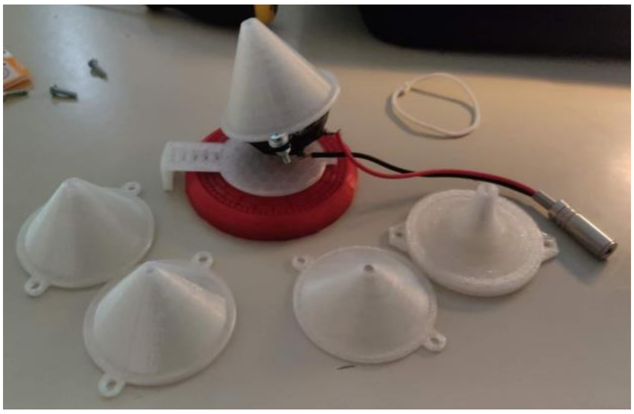

Figure 9: second set of 3D-printed cone-shaped sources

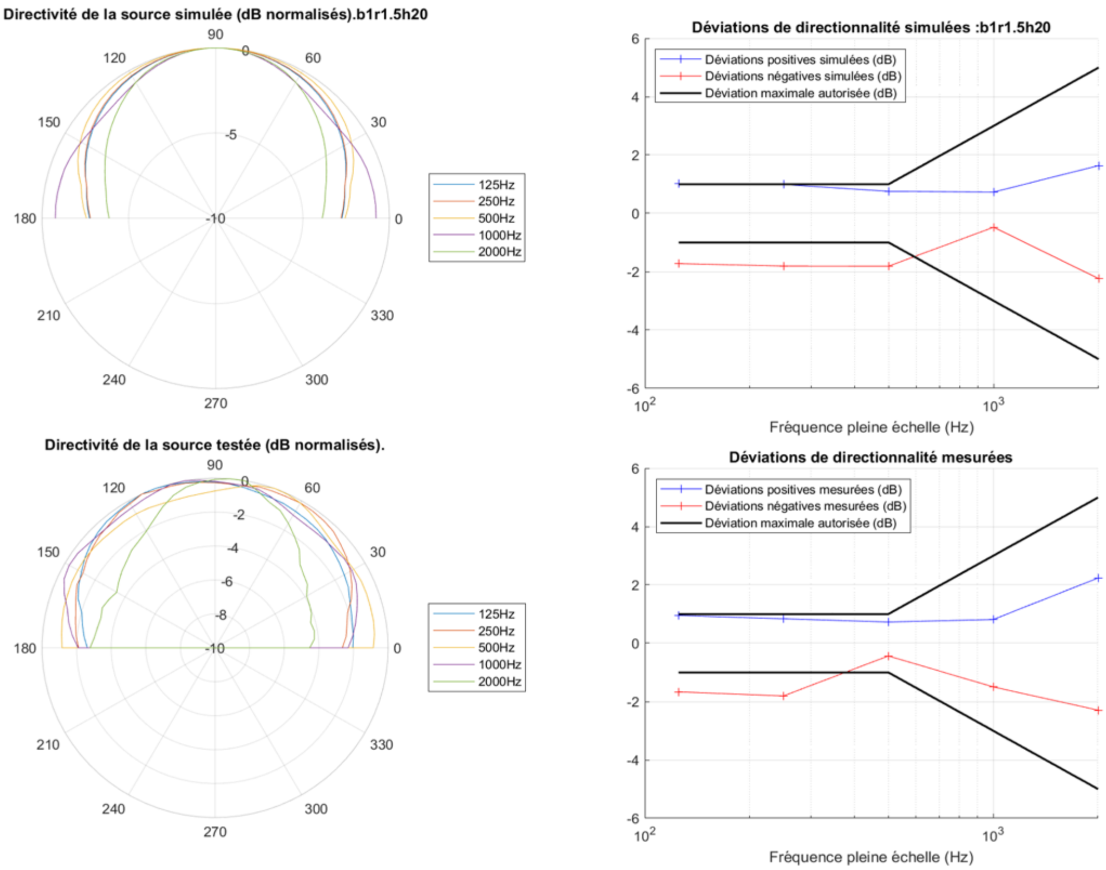


Figure 10: Comparison of the BEM simulated directivity of one source (polar plot upper left, plot corresponding to the ISO 3382-1 norm upper right), and the measured directivity of the real source on the lower left and right.

## 2.4 Resonance of the air in the cavity of the pavilion

As shown by Ibarra[5] and Cobo[7] for 1:1 scale measurement, the volume of air inside the pavilion generates significant internal resonances. This creates an inhomogeneous frequency response of the source which can be reduced with an inverse filtering method detailed in their papers. Cobo[7] measured deviations from a flat frequency response of up to 20 dB between adjacent octave bands at full-scale. The inverse filtering method shows promising results that are however highly dependent on the position of the source, but simultaneously reduces the signal-to-noise ratio, which for 1:10 or 1:20 scale-models can be insufficient and problematic. The algorithm for inverse filtering has been tested for a 3D-printed horn and the results are shown in Figure 11. The signal-to-noise ratio for some frequency bands is slightly reduced, while remaining sufficient for 1:20 scale (but potentially too low for 1:10 scale models).

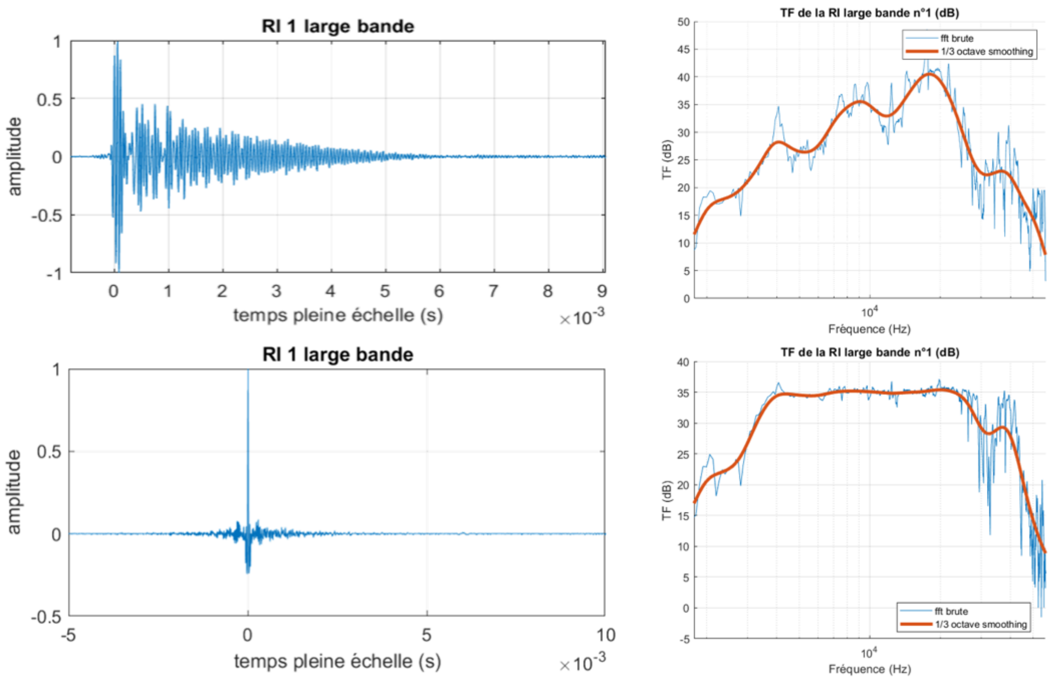


Figure 11: Impulse response without inverse filtering and correspond spectrum (upper left and upper right). A resonance of few milliseconds has been measured. Impulse response with inverse filtering (lower left and lower right) where the resonance is corrected and the frequency response has been flattened in the region of interest.

# 3 APPLICATIONS AND CONCLUSION

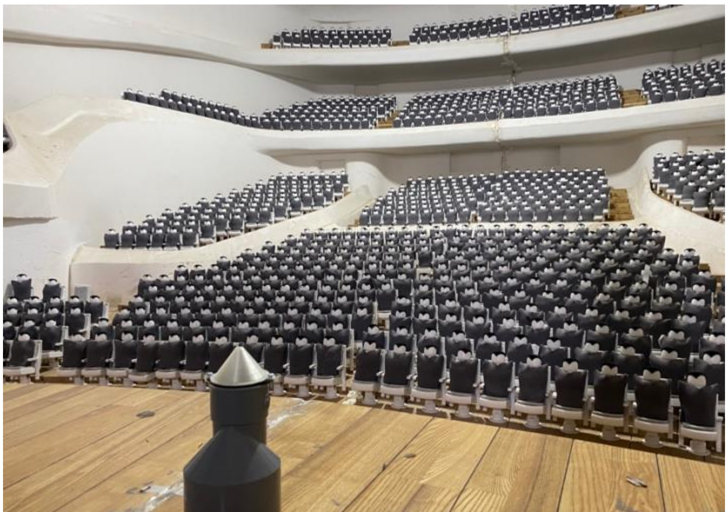

Figure 12: Scale model measurements in a 1:10 model of the Tongzhou Concert Hall in China. The source is put on a stand to raise it to a height corresponding 1.50m 1:1 scale.

One of the horns was tested during acoustical measurements of a 1:10 scale-model of the Concert Hall designed for the Tongzhou Cultural Center in the suburb of Beijing (Figure 12). In order to obtain a higher signal-to-noise ratio for the 1:10 measurements, a Visaton FRS 5 X loudspeaker has been used. As the dimensions are the same as those of the previous loudspeaker, it was possible to fix the same pavilion on top of the loudspeaker. A signal-to-noise ratio of more than 60 dB in the frequency bands from 2.5 kHz to 20 kHz was achieved, corresponding to the frequencies from 250Hz to 2 kHz at full-scale. The limitations were mainly due to the amplifier being restricted at the high frequencies.

Scale-models are generally carried out for large philharmonic concert halls or opera houses, and less frequently for smaller halls like rehearsal halls. With the source presented in this paper, it is possible to create an inexpensive, home-made scale model measurement kit. This opens up a field of possibilities for the use of such measurements in design processes of all kinds rooms and halls, to answer acoustic questions for which geometrical acoustics algorithms are known to not provide the best possible answers. Some applications could be the analysis of flutter echoes in simple rooms, or to analyse the impact of adjusting the angle of inclination of the surfaces and/or adding treatment onto them.

Some limitations and non-ideal behaviour of the source have been presented, mostly due to the quality of the loudspeaker and the effect of resonances inside the horn. Nevertheless, the various sources that have been designed, constructed, and tested display sufficient signal-to-noise ratio to be used in real scale-model measurements and with an omnidirectionality which deviates only slightly from the standard ISO 3382-1.

# 4 REFERENCES

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Scale model measurements enable wave-effects such as diffraction, interference effects and the seat-dip effect to be analysed, acoustical aspects which are challenging to simulate using geometrical acoustics computer models. At full scale, the most commonly used omnidirectional sources are dodecahedrons, but these are problematic at common acoustical model scales such as 1:50, 1:20 or even 1:10 because of the necessary equivalent size of the loudspeakers. This poster describes the development of an omnidirectional source for scale model measurements using an inverted cone-shaped horn driven by a single loudspeaker.


## I – First Prototypes and Measurements

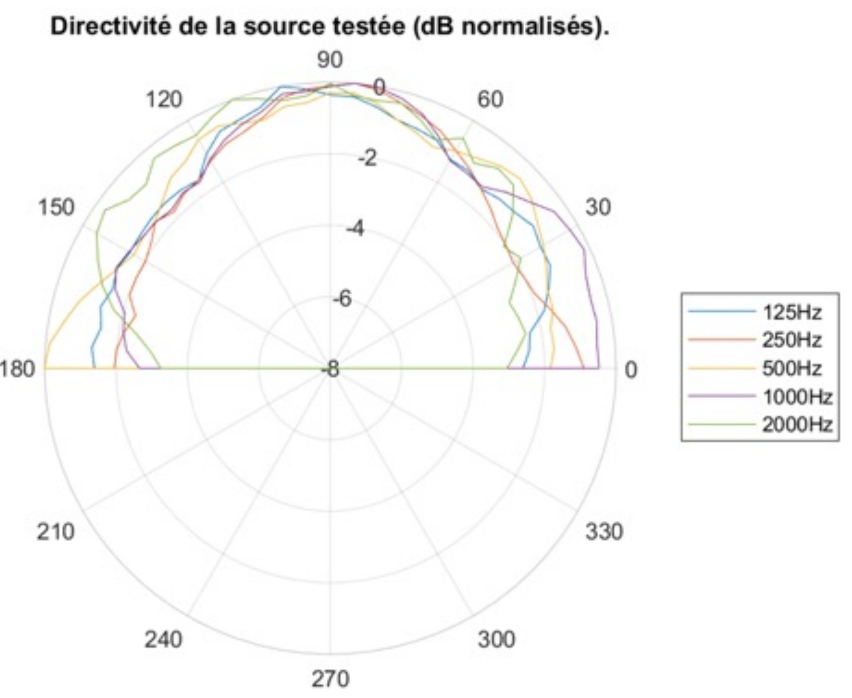
The requirement to carry out measurements on a 1:20 scale model requires the loudspeaker to emit at frequencies from 2 kHz to 60 kHz (equivalent to 100 Hz to 3 kHz full scale). To achieve this, **piezoelectric ultrasonic tweeters** with a diameter of 50mm were chosen. **Then the inverse horn** attached to the loudspeaker **has been designed using a parametric 3D-model** with the Rhinoceros and Grasshopper software **and has been 3D-printed**.

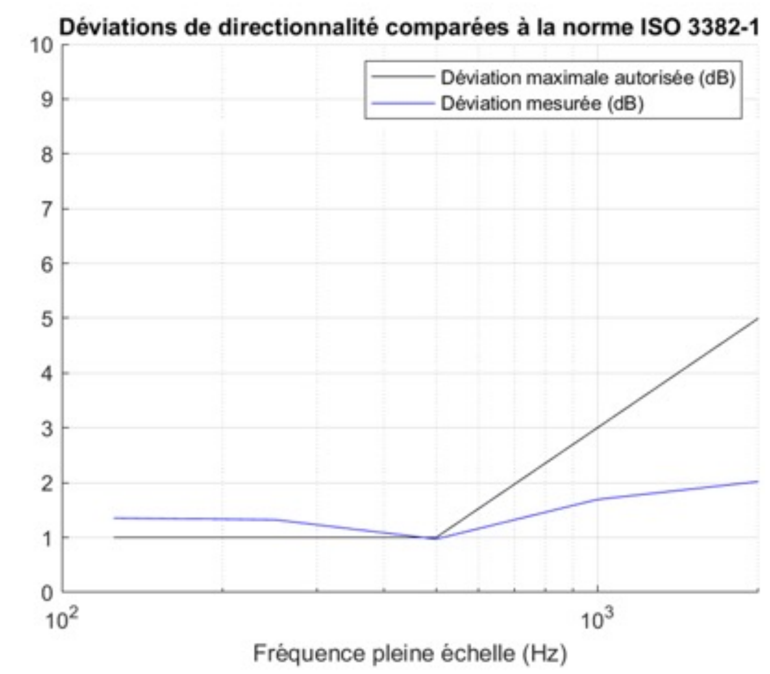
Ultrasonic piezoelectric tweeter selected for the source

Four prototypes 3D-printed (left) and the omnidirectionality testing bench (right)

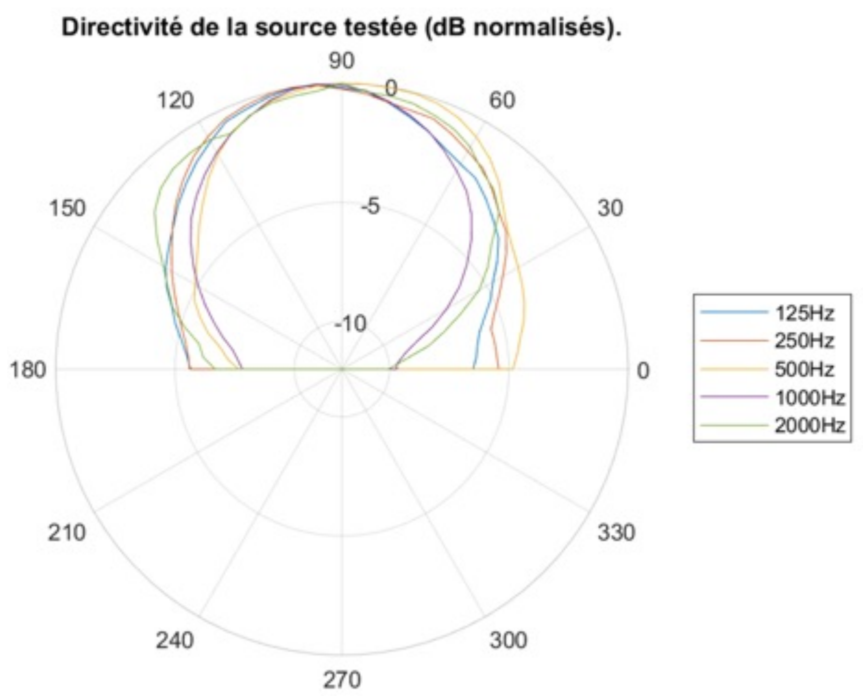
The directivity of each horn was measured and **compared to the maximum authorized deviation of directivity given by the standard ISO 3382-1** (two examples are shown below).

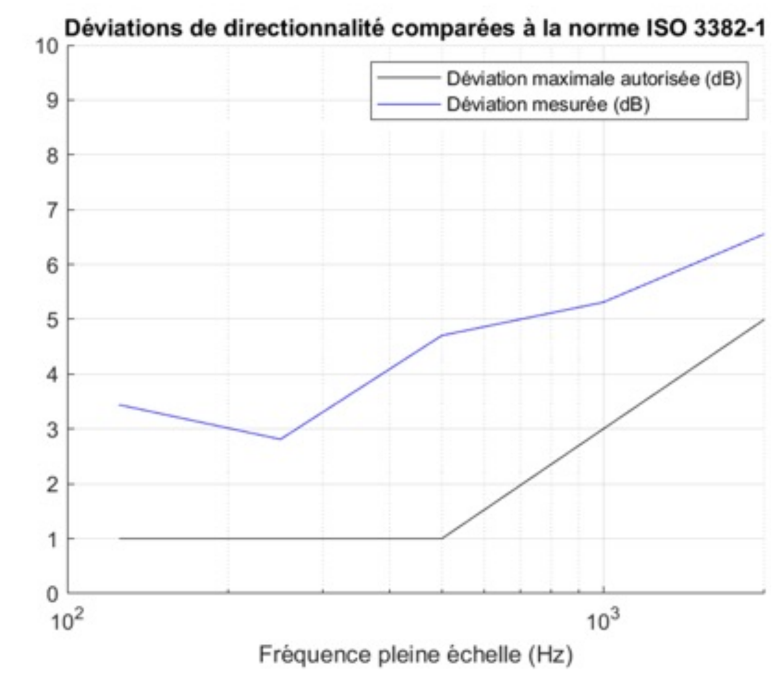
It is shown that the **horns with a smaller radius of aperture** (1mm or 2mm) **gave promising results** for omnidirectionality, but pavilions with a large aperture radius (3mm or 4mm) showed excessive deviations of directivity compared to the standard.



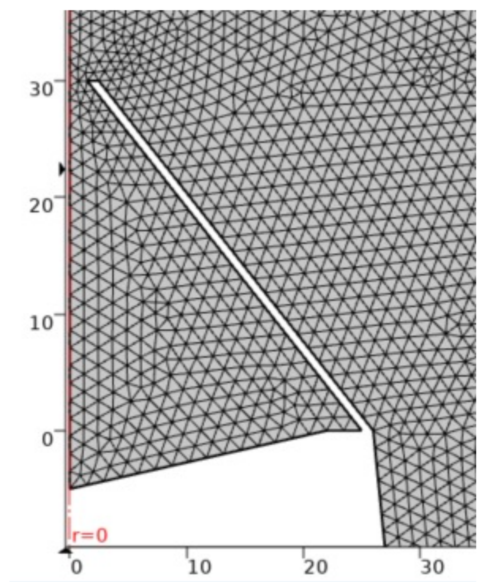

Polar plot of the directivity measured for the horn with an aperture radius of **1mm** (left), and deviation of directivity compared to the standard ISO 3382-1 (right)




Polar plot of the directivity measured for the horn with an aperture radius of **4mm** (left), and deviation of directivity compared to the standard ISO 3382-1 (right)

## II – BEM Analysis and Optimisation



Simulated model of one pavilion using the Boundary Element Method with a maximum mesh length of 1.5mm.

**To optimize the omnidirectionality of the source, a Boundary Element Method (BEM) analysis was carried out**, first by comparing the measurements of the 3D-printed horns with the BEM simulation results. The measurements and BEM simulations were sufficiently close and showed the same general trends regarding directivity. Based on this, it was decided that the BEM simulations were sufficiently accurate to develop the next optimizations of the horn shape.

Three parameters are evaluated:
- the **height** of the cone
- the **radius of aperture** (the size of the opening on top)
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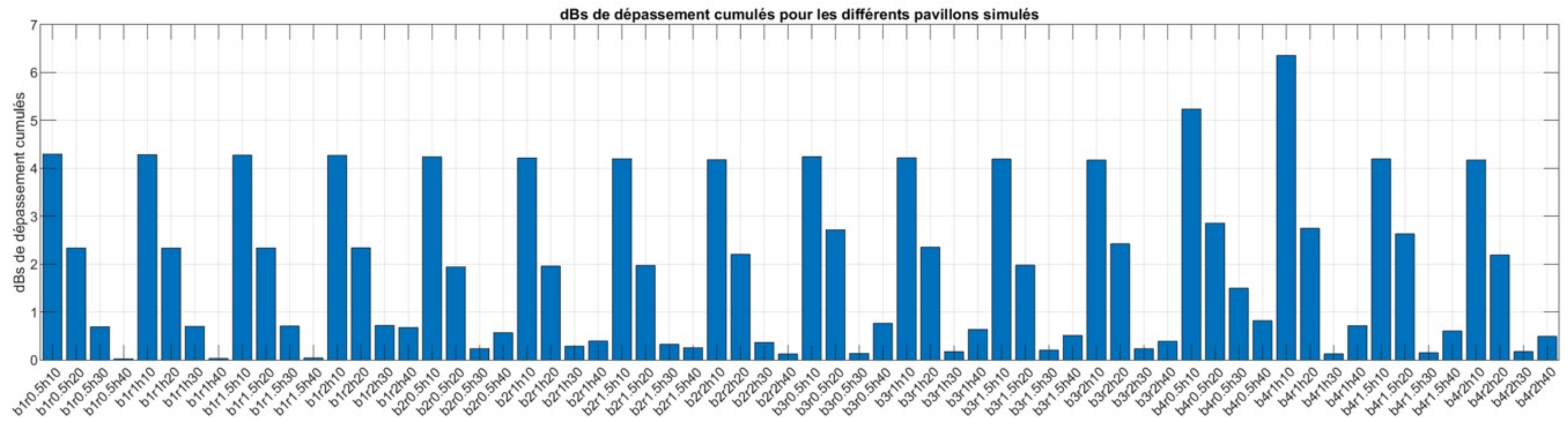
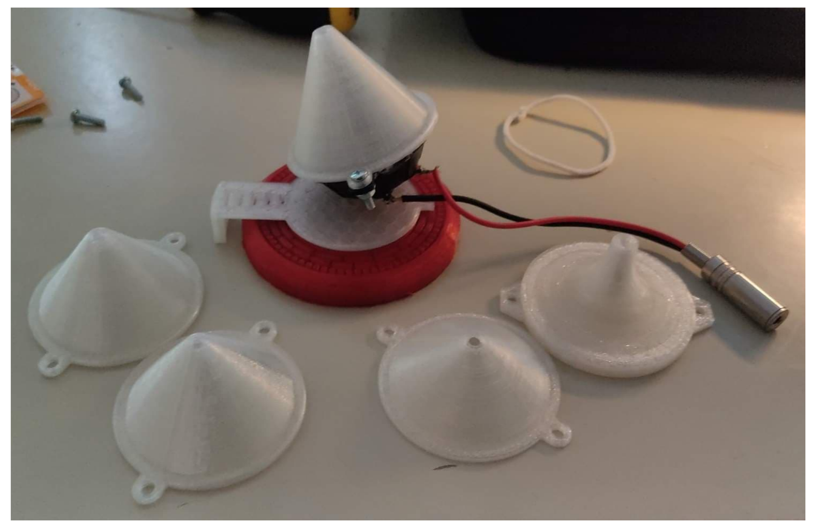
For each parameter, four values are considered, resulting in a matrix of 64 different shapes.



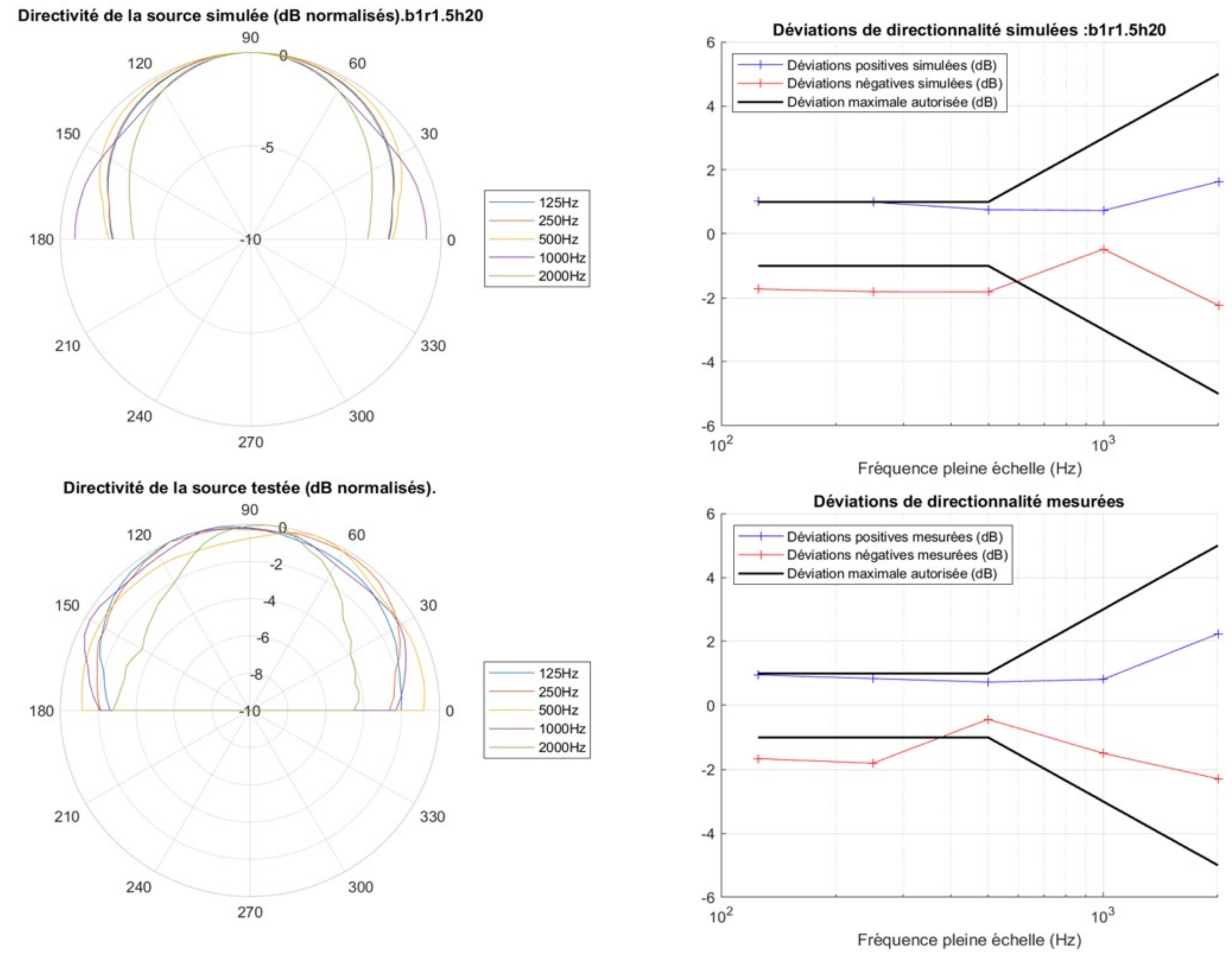

Comparison of the cumulative deviation of directivity for all 64 simulated models compared to the standard ISO 3382-1

## III – Second Physical Samples and Measurements

Following this BEM analysis, a number of additional horns were modelled and printed in 3D. **Taller horns were chosen for better omnidirectionality, but with a lower signal level, and smaller horns if a stronger signal level was required.**



Second set of 3D-printed cone-shaped sources

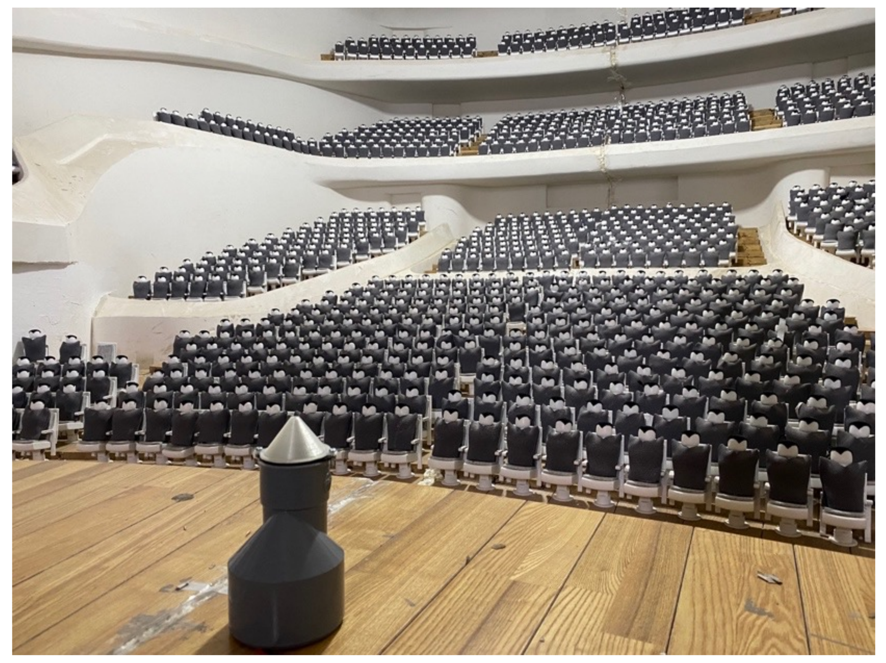



Comparison of the BEM simulated directivity of one source (polar plot upper left, plot corresponding to the ISO 3382-1 norm upper right), and the measured directivity of the real source on the lower left and right. **The pavilion has a conic shape, has 20mm height, and the diameter of the aperture is 1.5mm.**

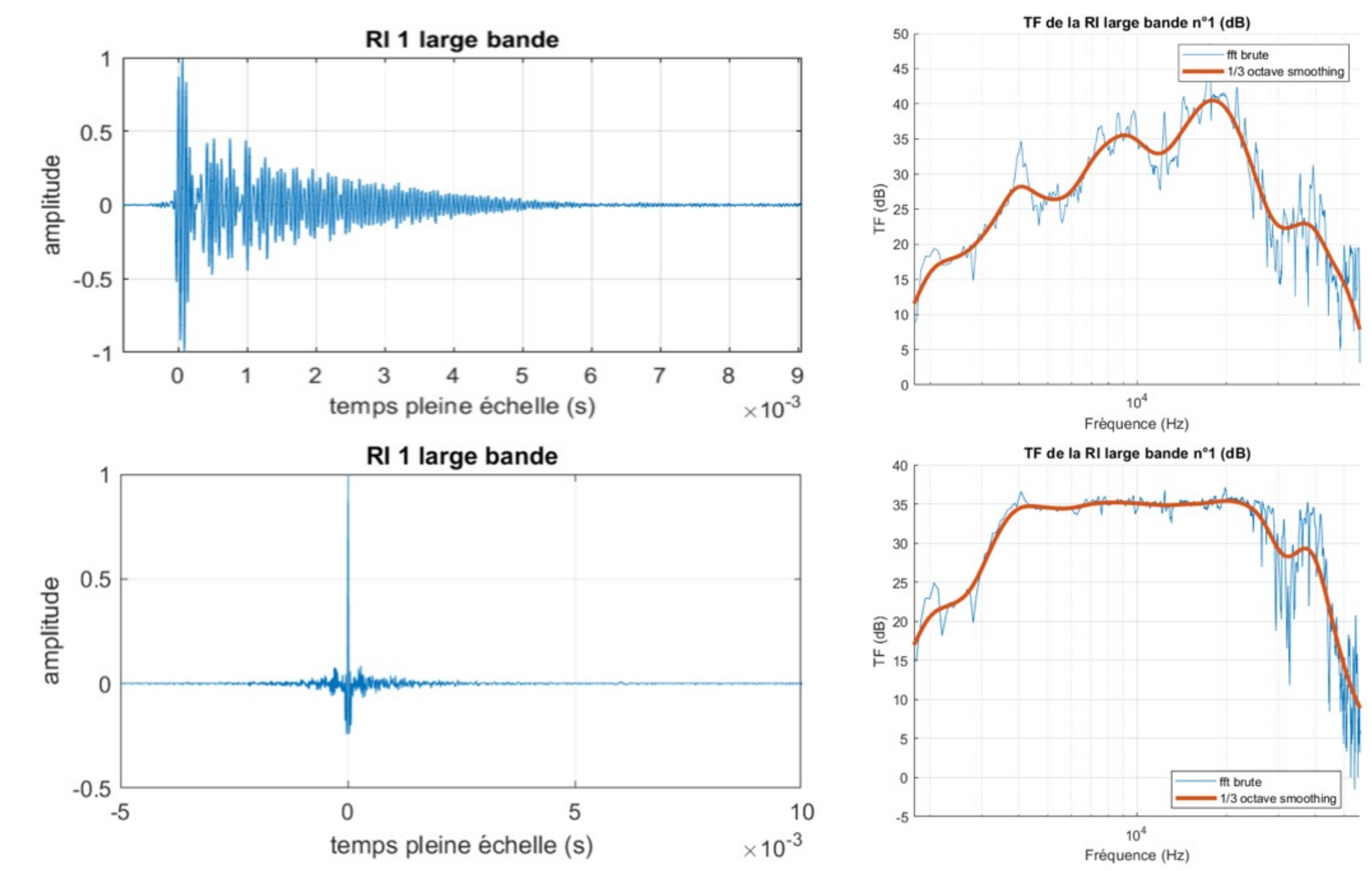
## IV - Usage

**One of the horns was tested during acoustical measurements of a 1:10 scale-model** of the Concert Hall designed for the Tongzhou Cultural Center in the suburb of Beijing.
A signal-to-noise ratio of more than 60 dB in the frequency bands from 2.5 kHz to 20 kHz was achieved, corresponding to the frequencies from 250Hz to 2 kHz at full-scale.

**The volume of air inside the pavilion generates significant internal resonances.** This creates an inhomogeneous frequency response of the source which can be reduced with an inverse filtering method.
**The algorithm for inverse filtering has been tested for a 3D-printed horn** and the results are shown in figures below. The signal-to-noise ratio for some frequency bands is slightly reduced, while remaining sufficient for 1:20 scale (but potentially too low for 1:10 scale models).



Scale model measurements in a 1:10 model of the Tongzhou Concert Hall in China. The source is put on a stand to raise it to a height corresponding 1.50m 1:1 scale.




Impulse response without inverse filtering and correspond spectrum (upper left and upper right). A resonance of few milliseconds has been measured. Impulse response with inverse filtering (lower left and lower right) where the resonance is corrected, and the frequency response has been flattened in the region of interest.