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Directivity of dodecahedral sound sources using a hybrid experimental-numerical approach

Brum, R.¹; Nogueira, L. M.¹; Rizzatti, R. S.¹; Lenzi, A.¹

¹ Vibration and Acoustics Laboratory, Universidade Federal de Santa Catarina, Florianópolis, SC, Brasil.

Abstract

Standardized room acoustics measurements require a sound source as omnidirectional as possible with sound power large enough to excite the environment. ISO 3382 defines the maximum acceptable directivity deviations, and the most common geometry used is the dodecahedron to comply with these requirements. The deviation of the loudspeakers frequency response affects the directivity patterns of the sound source and manufacturers should be careful about it. In this work, the frequency response of the twelve loudspeakers attached to a dodecahedral sound source was measured using a laser vibrometer. Next, these results were applied to prescribe the velocities in a sound radiation model using Boundary Elements Method (BEM). Convergence analysis of the model showed the best match between acoustic field accuracy and computational cost using four elements per wavelength, with a divergence less than 0,05 dB. Directivity patterns showed an omnidirectional behavior up to the frequency in which the source circumscribed diameter times the wavenumber (ka) is 3. Up to this frequency, the sound source can be represented as a pulsating sphere. For frequencies above this limit, the directivity lobe of each speaker exerts a strong influence on the radiation pattern of the sound source. The frequency response deviation of the loudspeakers causes stronger effects within this frequency range. Perfectly coupled vibration between loudspeakers presents deviations up to 12 dB at 4 kHz, while the decoupling effect is prescribed in the BEM model, a deviation of 25 dB is obtained. This effect is much less prominent in lower frequencies. At 1 kHz a deviation of 1,2 dB was observed. The main conclusion about the coupling of loudspeakers resonance affects directivity patterns for shorter although the sound source can be considered omnidirectional for wave number times source diameter ka less than 3.

Keywords: Room acoustics; omnidirectional source; acoustic measurement.

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1. INTRODUCTION

In room acoustics characterization many parameters are used, such as reverberation time (TR), early decay time (ETD), definition, clarity, and central time. These quantities are very important in the room's project and can be derived directly from the room impulse response (RIR). Also, for room auralization purposes, the convolution of the RIR with an anechoic signal allows an estimation of how this signal sounds in the room.

The idea behind this formulation is assuming a source-receiver position in the room can be considered a linear and time-invariant (LTI) system [1, 2]. So, each source-receptor configuration can be completely characterized by its impulse response. Standard measurements require source and receptor to be as omnidirectional as possible, while for high fidelity applications, the directivity of specific sound sources and receivers can be reproduced using the spherical harmonics decomposition technique, as largely studied by Pollow [3].

For reverberation time and acoustic isolation measurements, the standards ISO 3382 [4] and ISO 16283-1 [5] respectively, define the maximum directivity deviations to be accepted in each octave band between 125 Hz and 4 kHz. If the sound source is not perfectly omnidirectional, the directivity patterns cause different uncertainty levels in the room acoustic parameters obtained in the measurements [6].

Normally, to achieve the omnidirectionally requirements, dodecahedral sources containing a speaker attached to each face are used. Another option is to use open tubes as radiators, but the low sound power obtained in this case makes dodecahedral sources more attractive [7]. Normally, polyhedral-based sound sources provide high levels of sound power, producing a good signal-to-noise ratio (SNR) in most cases.

Nevertheless, due to the nature of the dodecahedral source geometry, directivity lobes are created with increasing frequency, even though the speakers have FRFs perfectly matched in magnitude and phase. This happens due to the complex acoustics effects of diffraction and the directivity lobe of the loudspeakers. A good empirical

method to define the transition between omnidirectional and directional regions of the sound source in the spectrum is to use the frequency which corresponds to $ka = 3$, being k the wave number and a the source diameter [7].

Furthermore, investigations about the effects of the difference between loudspeakers' frequency response function (FRF) are still sparse. In practical applications, is impossible to build loudspeakers with identical FRF, so a difference in magnitude and phase is always observed. The difference is more prominent in low-cost loudspeakers because the manufacturing process must be projected to reduce costs, increasing the uncertainty of the final parameters of the product.

In this context, the objective of this work is to compute the acoustic field generated by a dodecahedron sound source using a numerical and experimental method. This research was performed following the steps:

1. Measure the FRF of the 12 loudspeakers attached in the sound source under study using a laser vibrometer;
2. Use this results to prescribe the velocity in a boundary elements method model (BEM);
3. Compare the acoustic field with computed by BEM with an analytical pulsating sphere model.

2. EXPERIMENTAL VIBRATORY RESPONSE OF THE SOUND SOURCE

The first step of this study was to measure the vibratory response of the twelve loudspeakers of a sound source using the workbench shown in the Figures 1 and 2. The sound source used was a Brüel & Kjaer dodecahedron type HP 1000 and the devices used was:

- Brüel & Kjaer amplifier type 2716;
- Audio interface Behringer UCA 222;
- Doppler laser vibrometer Ometron type 8338;

This experiment allowed to obtain the frequency response between each loudspeaker and the input voltage of the sound source, as the reference signal.

So, an exponential sweep signal was generated by the computer and sent to the digital-to-analog converter (DAC). Using the amplifier, the sound source is excited and the laser vibrometer measures the velocity of the loudspeaker membrane. The sound source input voltage and velocity signals are acquired by the analog-to-digital converter (ADC) and registered in the computer. The frequency response is obtained dividing the velocity spectrum spectrum by input voltage spectrum.

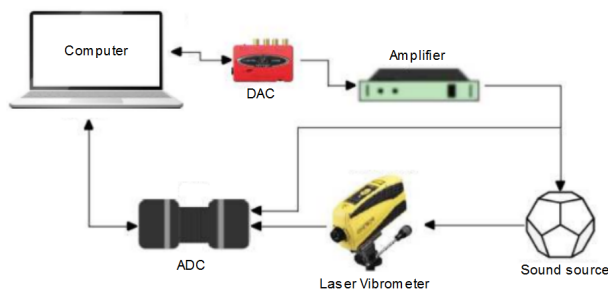


Figure 1: Schematic diagram illustrating the measurement workbench.

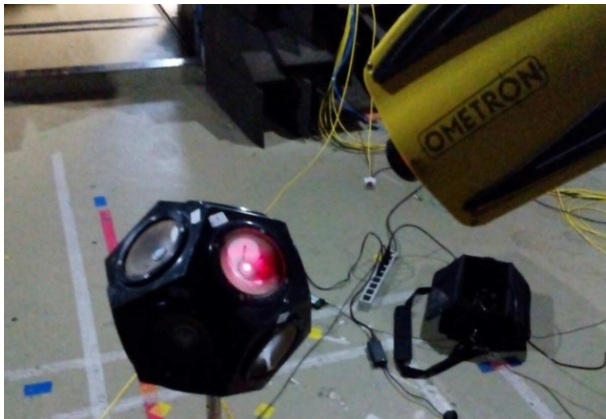


Figure 2: Speaker's measurement in hemi-anechoic chamber.

Figure 3 shows the frequency response of the vibratory response of the loudspeakers for the measurement performed in hemi-anechoic room. There is a large dispersion between the loudspeakers response, and this effect happens probably by the long usage time of the sound source.

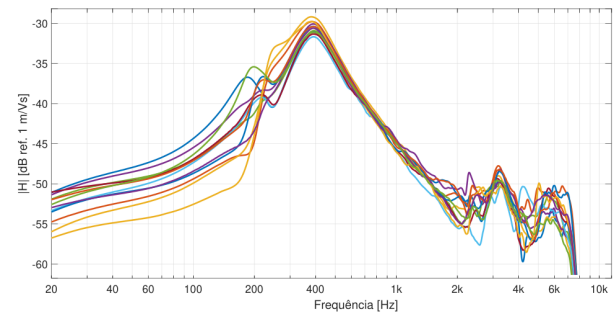


Figure 3: FRF of the 12 loudspeakers in hemi-anechoic room.

In the Figure 7 is shown the comparison between the FRFs obtained in hemi-anechoic and reverberant rooms. There are a very few difference of the vibratory behavior of the sound source in the different rooms. So this results allows to observe with the coupling between the loudspeakers and acoustic field is weak. So, it is possible to measure the vibration FRF experimentally and use this results to prescribe the velocities in a numerical radiation model.

3. NUMERICAL MODEL

As cited previously, a numerical model was elaborated using the boundary elements method (BEM). The objective of BEM is to compute the Helmholtz-Kirchoff equation numerically, using a mesh to build a discretization of the geometry. Details of the method are largely discussed in the literature [8, 9]

A simplification of the sound source was used to build the mesh, as shown in Figure 8. Four different meshes were built, one for each frequency range using triangular elements.

To find an optimal match between processing time and measurement accuracy, a convergence analysis was performed with different discretization levels and parameterized in elements per wavelength. Figure 4 shows the sound pressure level (SPL) difference in different meshes obtained in a circular array concentric to the sound source (Figure 9). The discretization used was the mesh with a minimum of four elements per wavelength, assumed as the best match between processing time and numerical accuracy.

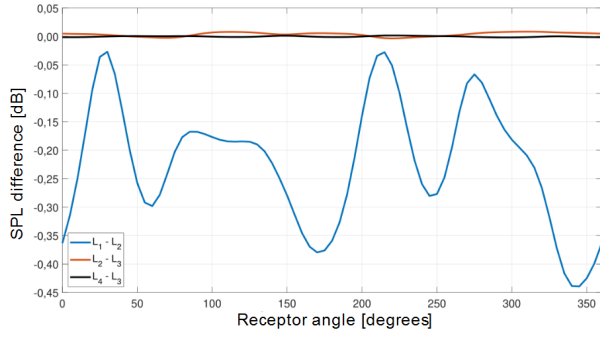


Figure 4: SPL difference in function of the radiation angle for different meshes discretization.

For the calculus of the sound field radiated by the sound source, two arrays of points were used as field points as shown in Figure 9. The first was the same circular array used in the converge analysis, with 72 points, reaching a five degrees step in angle discretization. The second was a spherical array with a large number of points used to obtain the radiation patterns of the sound source in the 3D space. Both arrays were built with the radius of 1.5 m.

The analytical model of a pulsating sphere was implemented to compare the results with the BEM model. The radiated sound pressure is given by:

$$\tilde{p} = \frac{j\omega\rho\tilde{Q}e^{jk(r-a)}}{1 + jka}, \quad (1)$$

being j the imaginary unity, ω the angular frequency, k the wavenumber, a the source diameter, r the source-receptor distance. $\tilde{Q}$ was computed as the equivalent volume velocity, given by:

$$\tilde{Q} = 12\tilde{U}\pi a_{ls}^2, \quad (2)$$

where $\tilde{U}$ is the average velocity of the twelve loudspeakers and a_{ls} is the radius of the circumference representing the loudspeaker in the model.

4. MODEL RESULTS AND DISCUSSION

In Figures 5 and 6 is shown the SPL computed for unity and experimental velocities, respectively and in circular and spherical arrays. The SPL corresponding to the spatial average sound pressure and a equivalent pulsating sphere sound

source is shown, as well.

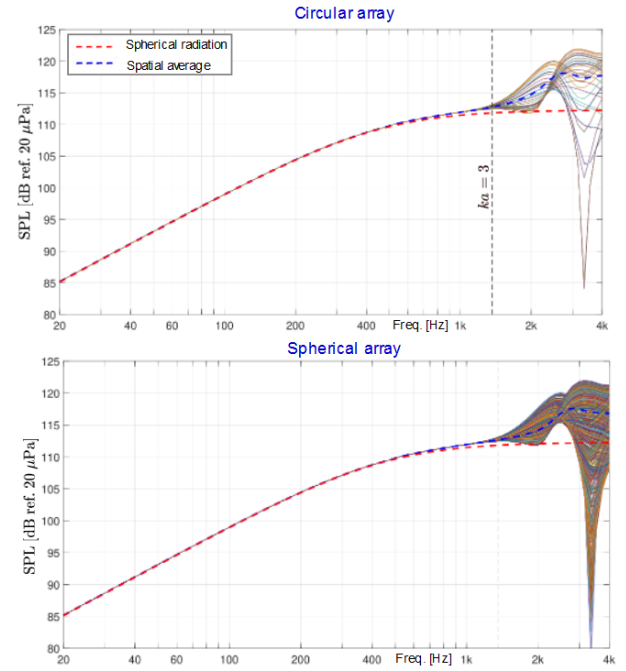


Figure 5: SPL calculated of the sound source in circular and spherical arrays of points using unit velocity in all faces.

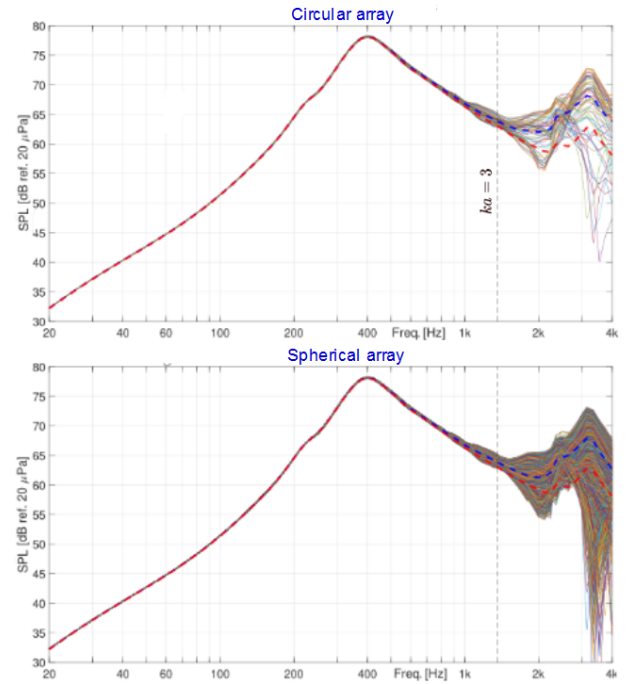


Figure 6: SPL calculated of the sound source in circular and spherical arrays of points using experimental velocity in each face.

There was not observed large differences caused by using circular or spherical arrays. This mach between the results is expected in polyhedral sound sources an is very benefit in experimen-

tal characterizations, because circular arrays demands much less transducers and test time.

In all cases, it is possible to observe that the sound pressure discrepancy is very low for frequencies up to $ka = 3$ and the sound source can be well represented by a pulsating sphere. At this frequency range, the most prominent difference between unit and experimental velocities is the shape of the curves.

Nevertheless, in frequencies above this point, it is observed most prominent discrepancies. In the Figure 10 is shown the directivity patterns obtained for unit velocity in all faces and experimental velocities. At 1 kHz, the radiation can be assumed as constant, since the SPL range is 0.1 dB for unity velocities and grows to 1.2 dB in the experimental velocities case.

For the frequencies of 2 and 4 kHz, the directivity lobes is prominent, due the source geometry and the proportion between its dimensions and wavelength. Another interesting phenomenon is the effect of loudspeakers velocity in this frequencies. The mismatch between transducers causes a kind of "splotch" in the directivity patterns, breaking the spherical periodicity of the sound source radiation.

Furthermore, the SPL range is increased in this frequencies due to the velocity mismatch. In 2 kHz the SPL range is 5 dB and 8 dB for unit and experimental velocities, respectively. In 4 kHz the difference increase, reaching 12 dB and 25 dB for unit and experimental velocities, respectively.

5. CONCLUSIONS AND FURTHER INVESTIGATIONS

In this work, a hybrid numerical-experimental model was implemented to investigate the radiation patterns of a dodecahedron sound source. It was observed that up to frequencies in with $ka = 3$, corresponding to a half wavelength close to the geometry circumscribed diameter, the sound source radiates energy like an acoustic pulsating sphere and loudspeakers velocity mismatch do not cause observable effects in the directivity patterns. Above this frequency, both the source geometry and velocities mismatch af-

fects the radiation patterns reasonably. In further works it is intended to characterize the individual loudspeakers behavior using microphone in near field measurements and compare with the laser vibrometer results. Also, the effects of the modal behavior of the loudspeakers membrane will be added in the BEM model to analyze this effect on the radiation patterns.

6. ACKNOWLEDGMENTS

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REFERENCES

- [1] Heinrich Kuttruff. *Room acoustics, fourth edition*. Spon Press, London, England, 4 edition, August 2000.
- [2] Eric Brandão. *Acústica de Salas: Projeto e Modelagem*. Blucher, São Paulo, 1 edition, 2016. ISBN 978-8521210061.
- [3] Martin Pollow. *Directivity patterns for room acoustical measurements and simulations*. Aachener Beiträge zur Technischen Akustik. Logos Verlag Berlin, Berlin, Germany, September 2015.
- [4] European Standards. BS EN ISO 3382-1:2009 Acoustics. Measurement of room acoustic parameters Performance spaces. URL <https://www.en-standard.eu/bs-en-iso-3382-1-2009-acoustics-measurement-of-room-acoustic-parameters-performance-spaces/>.
- [5] 14:00-17:00. ISO 16283-1:2014. URL <https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/05/59/55997.html>.
- [6] Pascal Dietrich. Modeling measurement uncertainty in room acoustics. *Acta Polytechnica*, 47(4-5), 2007.
- [7] Christopher Quedsted, Andy Moorhouse, Ben Piper, and Bin Hu. An analytical model for a dodecahedron loudspeaker applied to the design of omni-directional loudspeaker arrays. *Applied acoustics*, 85:161–171, 2014.
- [8] Finite element and boundary methods in structural acoustics and vibration. In *Finite Element and Boundary Methods in Structural Acoustics and Vibration*, pages 9–20. CRC Press, April 2015.
- [9] R D Ciskowski and C A Brebbia, editors. *Boundary element methods in acoustics*. Kluwer Academic, Dordrecht, Netherlands, 1991 edition, October 1991.

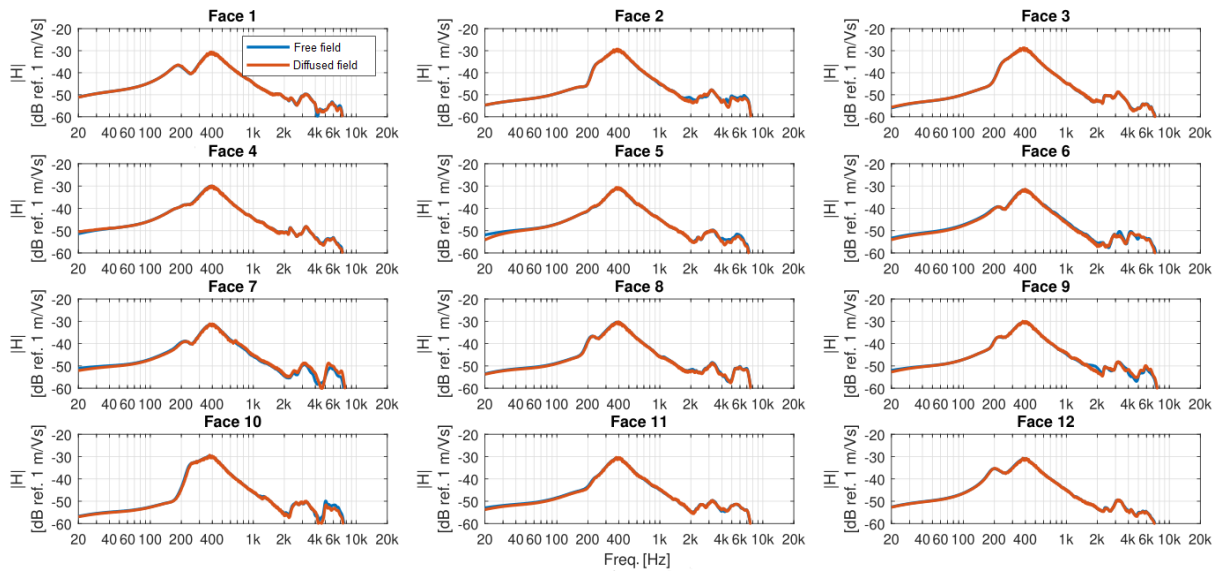


Figure 7: FRF of the 12 loudspeakers in hemi-anechoic and reverberant room.

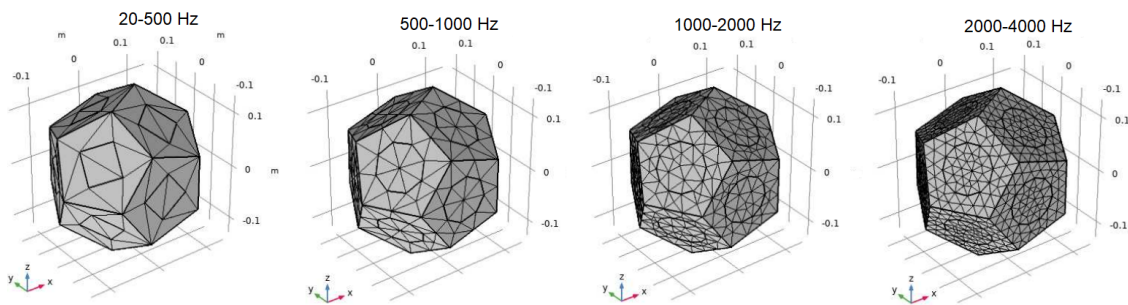


Figure 8: Meshes used for the different frequency ranges in the simulations.

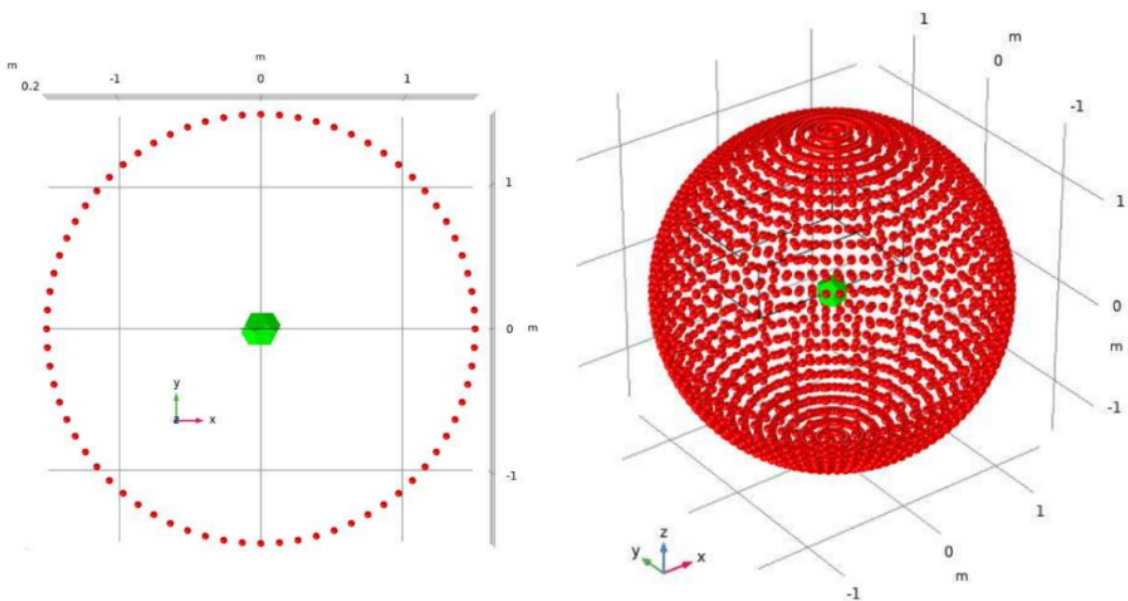


Figure 9: Circular and spherical array used to compute the SPL radiated by the sound source.

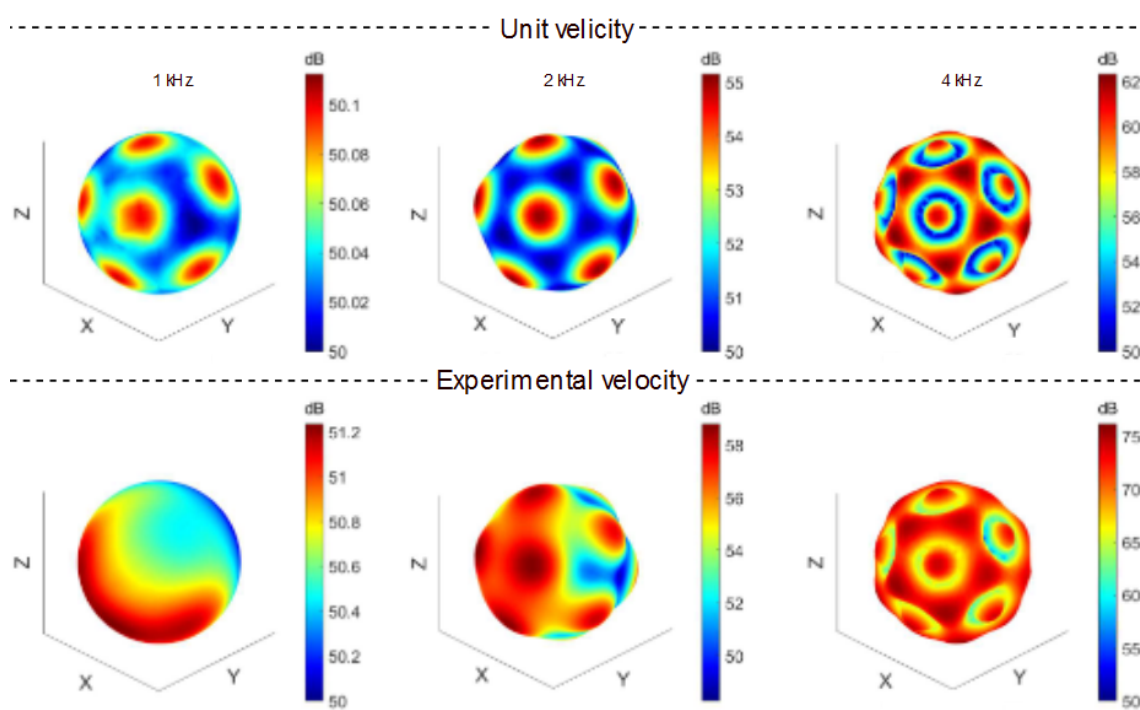


Figure 10: Comparison between directivity patterns using unit and experimental velocities.