FREQUENCY RESPONSE VARIATIONS OF AN OMNIDIRECTIONAL PARAMETRIC LOUDSPEAKER DUE TO CHANGES IN THE CARRIER FREQUENCY

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An omnidirectional parametric loudspeaker (OPL) is a sound source that consists in hundreds of ultrasound transducers set on the surface of a sphere. Each transducer emits an ultrasonic collimated beam consisting of an audible signal modulated in amplitude. Thanks to non-linear propagation in air, the signal is automatically demodulated to the audible range. This results in hundreds of audible beams emitted in all directions, thus obtaining an omnidirectional source of sound. One of the key parameters to be configured in the OPL is the carrier frequency \(f_c\) at which the audible signal is modulated. The choice of \(f_c\) is related to the resonance frequency of the ultrasound transducers in the OPL. At resonance is where each transducer performs better but, unfortunately, substantial variations are encountered between them. In this work, exponential sine sweeps (ESS) are used to measure the influence of the \(f_c\) on the OPL frequency response. Compared to other broadband excitation signals (e.g., white noise), ESS allow us to focus all the OPL power in a single frequency, producing higher ultrasonic power levels and therefore higher audible sound pressure levels. The results reveal that selecting one \(f_c\) or another can critically modify the shape of the OPL frequency response and the emitted sound pressure level.

omnidirectional parametric loudspeaker, parametric acoustic array, carrier frequency, exponential sine sweep, frequency response

1. **Introduction**

Omnidirectional sources of sound are needed to perform several acoustic tests of importance in the industrial and building sectors. The most common ones are those consisting of regular polyhedron loudspeakers (RPL) and in particular of dodecahedrons (see e.g., [1, 2]). However, these type of sources are known to lose omnidirectionality with increasing frequency, so alternatives to overcome that difficulty have been proposed in recent times. A large variety of devices based on different physical grounds have been explored: producing a point sonic impulse using a laser beam [3], generating spark discharges [4, 5], employing dielectric elastomer actuators [6, 7, 8], exploiting inverse horn designs [9] or using an omnidirectional parametric loudspeaker (OPL) [10, 11, 12], which is the topic of this paper (see [13] for a comparison of devices).

The OPL in Fig. 1 corresponds to the prototype in [12] and consists of hundreds of ultrasound transducers set on a 3D printed spherical casing. Each transducer functions according to the parametric array (PAA) phenomenon in which an ultrasonic carrier wave is modulated by an audible signal and jointly emitted in air. As a result of nonlinear wave propagation, the air itself demodulates the emitted sound.
and a strongly focused audible signal is produced \cite{14}. This has been exploited for various applications, see e.g., \cite{15, 16, 17, 18, 19}. In what concerns the OPL, the PAA guarantees a high level of omnidirectionality at higher frequencies, as hundreds of sound beams leave the spherical surface in all directions. This has been proved experimentally \cite{10, 12} and in numerical models \cite{11}. Being a secondary nonlinear effect, however, the main problem of the OPL is its difficulty to generate strong pressure fields at the low audible frequency range. This is a critical point if the OPL is to be used for real world applications in room acoustics. In fact, the OPL’s capability to produce low frequency noise depends on many factors. Recently, the advantage of exciting the source with exponential sine sweeps (ESS) instead of broadband noise has been investigated showing a noticeable improvement in the OPL’s performance \cite{20}. In this work, we concentrate on the effects the carrier frequency $f_c$ has on the emitted sound. While in \cite{12} a fixed value of $f_c = 41$ kHz was used in all tests, we herein analyze the consequences of its variation in terms of pressure frequency response and emitted 1/3 octave band levels.

The remaining of this paper is organized as follows. In section 2 we describe the experimental setup, while results are presented and discussed in section 3. Conclusions close the paper in section 4.

## 2. Experimental setup

All measurements were performed in the anechoic chamber of La Salle, Universitat Ramon Llull (see Fig. 1). The OPL was located on top of a computer-controlled turntable using a narrow stand. A 1/4 inch free-field microphone (G.R.A.S 40BF) was positioned pointing to the middle of the sphere that conforms the OPL, at a fixed distance of 1.5 m from its center, as required by the ISO 3382-1 \cite{21}. The protective cap of the microphone was removed to achieve a flatter response of the microphone at the high frequency range. The microphone was connected to a B&K Nexus conditioning amplifier, and its output to a Data Translation 9832 card.

An exponential sine sweep (ESS) was generated with the Data Translation 9832 card. It was next driven to the OPL through an Ecler XPA300 amplifier, configured to provide an output voltage of 17 Vpeak. In particular, we used the following ESS

$$x(t) = \sin \left[ K \left( e^{t/L} - 1 \right) \right] K,$$

(1)
with
\[ K = \frac{2\pi f_1 T}{\ln f_2/f_1}, \quad L = \frac{T}{\ln f_2/f_1}. \] (2)

The values \( f_1 \) and \( f_2 \) respectively stand for the lower and higher measured frequencies in Hz and \( T \) for the time duration in seconds. The ESS was configured with \( f_1 = 20 \) Hz, \( f_2 = 14 \) kHz and \( T = 20 \) s. A linear fade-in window from 20 Hz to 80 Hz and fade-out window from 12 kHz to 14 kHz were next applied to the generated EES to minimize the possible artifacts that can appear in the measured impulse response [22]. One second of silence was added at the end of the EES to ensure that the generated signal reaches the microphone. The ESS was finally modulated with USBAM and emitted to the OPL. A custom software was developed in Matlab for controlling the different devices and for performing the signal processing during the measurements.

One of the parameters required in a USBAM modulation is the carrier frequency \( f_c \). Its influence on the performance of the OPL was examined by testing 16 different carrier frequencies that range between \([40, 43]\) kHz with steps of 200 Hz. The OPL frequency response was computed every 5° for each \( f_c \) configuration. This gave a total of 1152 frequency responses (16 \( f_c \times 72 \) degrees).

3. Results

The OPL frequency responses for \( f_c = 40.6, 41, 41.4, 41.8 \) and 42.2 kHz are displayed in Fig. 2. Only the audible range below 10 kHz is analyzed as it is the frequency range typically considered in room acoustics. The light blue curves represent the frequency responses measured for each angle, whereas the dark blue curve in each subfigure corresponds to the mean frequency response, obtained from the energy average of all light curves. As expected, the frequency response depends on the angle. However, note that all frequency responses are close to the mean. The closer the frequency response to the mean curve, the more omnidirectional the OPL becomes. This behavior is quite similar for all \( f_c \) configurations. Yet if we compare the latter one to another, we can observe that the \( f_c \) produces significant variations of the OPL mean frequency response. A flat frequency response is typically desired for loudspeakers. If this was the criteria considered for selecting the carrier \( f_c \), the flatter frequency response is obtained with \( f_c = 42.2 \) kHz.

Overlapped results of mean frequency responses for different \( f_c \) are shown in Fig. 3 to facilitate comparison. Focusing on frequencies below 4 kHz, we can observe that a prominent peak appears in the frequency response curves with \( f_c = 40.6, 41 \) and 41.4 kHz. The peak moves to lower frequencies as \( f_c \) increases, mostly disappearing for \( f_c = 42.2 \) kHz. Note that although \( f_c = 42.2 \) kHz presents the flatter frequency response, it also produces the lowest sound pressure level (SPL). Therefore, this configuration would not be a good choice if one aims at high SPL values.

The 1/3 octave band levels produced by the OPL are also computed for each \( f_c \) configuration. They are obtained from the energy summation of the pressure values of the frequency response curves that lie within each band. We have represented them in Fig. 4 together with the overall SPL value corresponding to the addition of all 1/3 octave bands. The highest total sound pressure level emitted by the OPL corresponds to \( f_c = 41.4 \) kHz, followed by \( f_c = 41 \) kHz. The carriers \( f_c = 40.6 \) kHz and \( f_c = 41.8 \) kHz produced almost the same overall SPLs, whereas \( f_c = 42.2 \) kHz generated the lowest one. For frequencies below 630 Hz, the largest values are obtained with \( f_c = 41.4 \) kHz while from 800 Hz to 2 kHz the carriers \( f_c = 41 \) kHz and \( f_c = 40 \) kHz dominate. Above 2 kHz the highest levels are attained with \( f_c = 41.4 \) kHz. In room acoustic applications it is important to achieve not only high overall SPLs but also high SPLs at low frequencies, so the configuration with \( f_c = 41.4 \) kHz would be probably the best candidate. As opposed, while \( f_c = 42.2 \) kHz produces the flattest frequency response, it generates very low SPL and it should be discarded for this type of applications.
Finally, it is also interesting to examine the directivity of the OPL when changing $f_c$. The directivity index (DI) is computed as defined in the ISO 16283-1 [23], for all $f_c$ configurations. It reads

$$ DI_i = L_{360^\circ} - L_{30^\circ,i}, $$

with $L_{360^\circ}$ being the mean pressure level around the OPL and $L_{30^\circ}$ the mean pressure level in a $30^\circ$ arc. The index $i = 0, 5, 10, 15, 20, \ldots, 355$ is used to denote the degree at which the $30^\circ$ arc is centered. In Fig. 5, we show the maximum (circle), mean (square) and minimum (triangle) values of the DI for each $f_c$ configuration. Moreover, the maximum and minimum limits that the ISO 16283-1 establishes are represented in bold black lines. A low value of DI indicates that the sound source is omnidirectional, so the lower $|\text{max}(DI)|$ and $|\text{min}(DI)|$ the more omnidirectional the OPL is.

For frequencies below 500 Hz, $\text{max}(DI)$ and $\text{min}(DI)$ are out of the limits established by the reg-
Figure 3: Mean frequency response of the OPL for the cases with carrier frequencies $f_c = 40.6, 41, 41.4, 41.8$ and $42.2$ kHz.

Figure 4: 1/3 octave band levels of the OPL for the cases with carrier frequencies $f_c = 40.6, 41, 41.4, 41.8$ and $42.2$ kHz.

ulation, for all $f_c$ configurations. This can be attributed to the fact that the OPL has some difficulties to generate high SPLs at these frequencies. In contrast, for mid-high frequencies the OPL performs better, the DI getting smaller. It also fulfills the regulation in this frequency range. Note, however, that the regulation is more permissive for higher frequencies than for lower ones. This favours standard dodecahedron loudspeakers which loss its omnidirectional behaviour for the former (see e.g., [24]).

Let us next analyze the DI behaviour when changing $f_c$. For frequencies above 1 kHz the DI values are similar regardless of $f_c$, respecting the established limits. However, some differences appear below 500 Hz. The smallest values of $|\max(DI)|$ are obtained for $f_c = 42.2$ kHz (close to the regulation maximum threshold), but it is the configuration with $f_c = 41$ kHz the one that produces smallest $|\min(DI)|$ (close to the regulation minimum threshold). Larger deviations are observed for $|\min(DI)|$ than for $|\max(DI)|$, so the former is used as an indicator to select the most appropriate $f_c$ value.
Figure 5: Directivity Index (DI) of the OPL for the cases with carrier frequencies $f_c = 40.6, 41, 41.4, 41.8$ and $42.2$ kHz.

As said, $f_c = 41$ kHz would be the best configuration in terms of DI given that it provides the smallest $|\min(DI)|$. However, the configuration with $f_c = 41.4$ kHz is favored because it provides a better frequency response and higher sound pressure levels. It gives slightly worse results for the DI as compared to $f_c = 41$ kHz, although these are not significant.

4. Conclusions

Exponential sine sweeps have been used to evaluate the performance of an OPL of 750 ultrasound transducers. It has been shown that the carrier frequency $f_c$ at which the ESS is modulated has a large influence on the OPL acoustic behaviour. It not only changes the overall sound pressure levels, but it also modifies the shape of the spectrum. Some variations have also been observed in the Directivity Index, but they were only significant for frequencies below $\sim 500$ Hz. The configuration with carrier $f_c = 41.4$ kHz has been finally selected because it provides the highest SPLs at low frequencies and also the highest overall SPL, while also achieving an acceptable omnidirectional sound field as compared to other $f_c$ configurations. This opens the door for the use of an OPL for room acoustic applications. Measurements such as the reverberation time of a room or the airborne sound insulation will be performed in the future using the OPL and comparing the results with those obtained with a standard omnidirectional dodecahedron loudspeaker.

REFERENCES


