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Directional Landscapes: Using Parametric Loudspeakers for Sound Reproduction in Art

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Abstract

As new technologies appear, the expressive palette of creators broadens. Parametric loudspeakers are one of such new technologies that makes it possible to direct sound as though it were a light beam. Since their debut in the market, they have thus far received little attention from part of the artistic world. Some peculiarities concerning the sound reproduction might explain why musicians in particular are hesitating to use an otherwise highly attractive acoustic innovation. Due to such peculiarities, a proper use of parametric loudspeakers in art must start with investigating a whole array of different topics (i.e. non-linear acoustics and ultrasonic transducers) in order to understand how this technology works and utilize it at its best. The result of our project is ultimately a sound installation that makes use of directional sound to ruminate on issues concerning sound perception and the responsible use of our sound environment.

Keywords: non-linear acoustics, parametric loudspeaker, directional sound, ultrasound, art installation

1. Introduction

Parametric loudspeakers allow sound to be projected in a directional fashion by taking advantage of non-linear effects of the propagating medium. Such effects are mostly notable in the demodulation of an ultrasonic wave and the generation of an end-fire array of virtual sound sources (Gan, Yang, & Kamakura, 2012b).[1] The perceived result is a very focused sound with a narrow high band frequency spectrum that is heard as though it was being reproduced right at the tip of the listener's nose. Despite some of these features being quite attractive, parametric loudspeakers are still far from being widely employed in art. One might think that musically trained artists would be the first to be fascinated with this technology, but in actuality its primary users are frequently conceptual and tech-artists with a background other than music. The hardware is neither expensive nor hard to find and build. Yet, to control the output and make sound reproduction crisp and clear is another matter that pertains more to the software side (the Digital Signal Processing [DSP]).

We believe that an artistic project aimed to make proper use of parametric loudspeakers must start with a thorough understanding of how these kinds of emitters reproduce sound. Hence, a brief historical survey and an explanation of the chain of acoustic processes used in parametric loudspeakers are provided. A short case study on pieces of art that employed parametric loudspeakers follows. Finally, the ultimate goal of our project is presented: a sound installation (*The Soundhouse*) along with the field experiments conducted during the building of the work.

2. A concise history of directional sound through parametric loudspeakers

The ability of human beings to develop techniques that focus and direct sound to specific locations is very old. For instance, the natural gesture of cupping hands around one's mouth to prevent the sound of the voice from being diffused is a clear example of our intuitive understanding that sound needs to be guided in order to arrive at a specific target. Irish physician Helsham (1682–1738) proved this in his study of the so-called exponential horn, a waveguide

[1]The expression 'end-fire array' comes from the antenna theory and describes a specific kind of emitters configuration used to maximize radiation along the main axis of the antenna. The same expression is used as an analogy in the theory of parametric loudspeakers since, as it will be explained further on in the text, they behave in a similar way.

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structure that allows sound amplification and enhances the directionality of its output (Post & Hixson, 1994, pp. 165–166; Raichel, 2000, p. 6).

As cupped hands and the exponential horn demonstrate, there are some geometric shapes that are more suited to the focussing of sound than others. This applies when either emitting or receiving processes are at work. For example, the auricle, that is, the visible part of the ear is conveniently shell shaped not only to receive audible signals and funnel them into the ear canal, but also to act as a resonator and sound localizer (Stach, 2010, p. 57). The outer ear's anatomy has inspired other applications as well: since the beginning of the XX century through the end of WWII, many devices (e.g. acoustic localizers and acoustic mirrors) were designed and built to capture sounds at long distance (Vinokur, 2004; Volcler & Volk, 2013). This now extinct technology served the military purpose of detecting enemy planes and anticipating their attack. Yet, their parabolic shape has since then been employed in the construction of other devices such as, for example, the sound domes, that is, loudspeakers that can attain directionality by projecting sound against a parabolic surface. Finally, both functions of an emitter and a receiver are nicely summed up in a simple double-shell structure located in a public park (Figure 1) where other similarly interactive installations are used to engage visitors in the hands-on learning of the laws of physics.

Although sound domes, wave guides, flat panel speakers and linear arrays are all techniques conceived to direct sound (Kuutti, Leiwo, & Sepponen, 2014), in this article we shall concentrate exclusively on parametric loudspeakers, the only kind that uses ultrasonic carriers to modulate incoming signals. Table 1, by no means exhaustive, traces what we consider to be the main steps in the literature concerning parametric speakers' development and research.

The history of parametric speakers begins with some observations made by Helmholtz at the end of the XIX century. The German physicist realized that the transmission of acoustic pressure in air is not linear, so much so that, given two frequencies, more frequencies are generated that are the sum and the difference of the original signals.

Fig. 1. Acoustic shells in *Parque de los Deseos* (Medellín, Colombia).

Such an effect must not be confused with the linear psychoacoustic principle of beatings that mathematically (but not physically) works in a similar way. In fact, this is a non-linear effect well known in radio communications as heterodyning (Roads, 2001, pp. 33–34). The non-linear action of the medium over acoustic vibrations when they propagate through it is of paramount importance for the existence of parametric speakers, as it is the main condition for them to work.

Other studies on non-linearity in air (Thuras et al. from the Bell Labs. and Black) were carried on after Helmholtz. They mainly investigated the distortion generated during sound propagation and the effect this impresses on the shape of the wave. However, it is since Westervelt in the early 1960s 'showed that it is theoretically possible to obtain an end-fire array of virtual sources of the difference frequency arising from the interaction of two collimated intense beams with slightly different high frequencies', (Gan, Yang, & Kamakura, 2012a; p. 1209) that research in non-linear acoustic transmission was revived. After Westervelt, Berktay introduced the concept of modulation to emphasize how the demodulated signal derived from the combination of two primary waves is a function of their amplitude rather than their spectrum. The equation Berktay arrived at is known as 'Berktay's Far-Field Solution' (see Appendix 1, Equation 1).

Both Westervelt and Berktay were mainly concerned with non-linearity in underwater transmissions. The challenge of demonstrating that Berktay's envelope function was operative not only in water but also in air was undertaken a few years later by Bennet and Blackstock. However, the first researcher to have actually implemented their results in the construction of a parametric loudspeaker using an array of ultrasonic transducers was Yoneyama. Despite being able to generate a collimated sound beam by modulating an audible signal with an ultrasonic carrier, Yoneyama could not prevent a large amount of distortion in the demodulated output. This is why, since then, particular efforts have been made to discover what the most suited modulation scheme is. After the widely used double-sideband amplitude modulation, Kamakura achieved better control of total harmonic distortion (THD) both with single-sideband and square-root amplitude modulation (Gan et al., 2012b).[2]

High costs of production and persistent issues in reducing the harmonic distortion delayed the commercial release of parametric loudspeakers until the end of the 1990s when both Elwood G. 'Woody' Norris and Pompei independently developed the first models for sale. The former's patent is the HyperSound™ marketed by the Turtle

[2]More modulation schemes have been tested since then, e.g.: modified amplitude modulation, and quadrature, recursive and hybrid modulation methods (Gan & Ji, 2010).

Table 1. Main research on parametric speakers.

1856	Hermann von Helmholtz, 'Ueber Combinationstöne'
1934	A.L. Thuras, R.T. Jenkins, and H.T. O'Neil, 'Extraneous Frequencies Generated in Air Carrying Intense Sound Waves'
1940	L.J. Black, 'A Physical Analysis of Distortion Produced by the Non-Linearity of the Medium'
1963	Peter Westervelt, 'Parametric Acoustic Array'
1965	Hasan Orhan Berktay, 'Possible Exploitation of Non-Linear Acoustics in Underwater Transmitting Applications'
1974	Mary Beth Bennett and David T. Blackstock. 'Parametric Array in Air'
1983	Masahide Yoneyama, Jun-ichiroh Fujimoto, Yu Kawamo, and Shoichi Sasabe, 'The Audio Spotlight: An application of nonlinear interaction of sound waves to a new type of loudspeaker design'
1984	Tomoo Kamakura, Masahide Yoneyama, and Kazuo Ikegaya, 'Developments of Parametric Loudspeaker for Practical Use'
1999	Joseph Pompei, 'The Use of Airborne Ultrasonics for Generating Audible Sound Beams'
2001/2002	James J. Croft and Joseph O. Norris, 'Theory, History and the Advancement of Parametric Loudspeakers'
2012	*Applied Acoustics*, 73 (12), Woon-Seng Gan, Jun Yang and Tamoo Kamakura (eds.)

Beach Corporation, and the latter's is the Audio Spotlight® (a name actually coined by Yoneyama back in Yoneyama & Fujimoto, 1983) sold by Holosonics. In our project we used an Audio Spotlight®, but some testing—not reported here—has been made also with a Soundlazer kit that American inventor Richard Haberkern commercializes through his Kickstarter campaign.

3. Physical principles operating behind a parametric loudspeaker

As mentioned above, air's non-linear behaviour is a key factor in parametric loudspeakers' sound transmission. Yet, what makes ultrasonic beams audible, and, above all, why are they so directional? A convenient approach to the understanding of this phenomenon starts with the wave equation (see Appendix 1, Equation 2) that describes the propagation of a vibrational disturbance in a medium after a certain pressure is exerted on it. However, the wave equation is an idealized description of what happens when energy propagates in a medium. The simplification consists in pretending that this medium is isotropic. In fact, in an isotropic medium there are no variances of magnitudes (density, temperature and local pressure) along all axes and the speed of sound is assumed to be constant. However, in the real world, changes of density, temperature and local pressure are always present and do affect the speed of sound (i.e. the speed of sound where the acoustic pressure is higher is different from the phase velocity of the wave). As a consequence of such a non-linear behaviour, harmonics start appearing that affect also the wave form (Figure 2) by altering its normal shape (Black, 1940; Croft & Norris, 2002).

Non-linear behaviours are always operative in real life, but the effects of absorption and dispersion are usually greater than those of self-distortion. However, the opposite occurs in the ultrasonic range, where a signal previously amplitude modulated with an ultrasonic carrier generates by self-distortion an audible signal with the directional property that shorter wavelengths have over longer wavelengths. This effect is known as self-demodulation.

The equation that describes the directional pattern of acoustic waves like those emitted by a parametric loudspeaker is the KZK, after Kokhlov–Zabolotskaya–Kuznetsov (see Appendix 1, Equation 3). Unfortunately, there is no explicit analytical solution of the KZK, although methods such as frequency domain, time domain or time-frequency algorithm can be used to solve it (Yang, Tian, & Gan, 2014). For this reason, Berktay's far-field equation is more commonly employed in calculations concerning acoustic pressure in a non-linear medium.

As a direct consequence of what Helmoltz initially envisioned, it is exactly the non-linear behaviour of the medium that is responsible for the demodulation within the audible range of a signal carried on by an ultrasonic frequency. This is shown in Figure 3: when two frequencies $f1$ and $f2$ pass through a non-linear medium the output will be composed of both of the original frequencies and the sum, the difference and the harmonic components of $f1$ and $f2$.

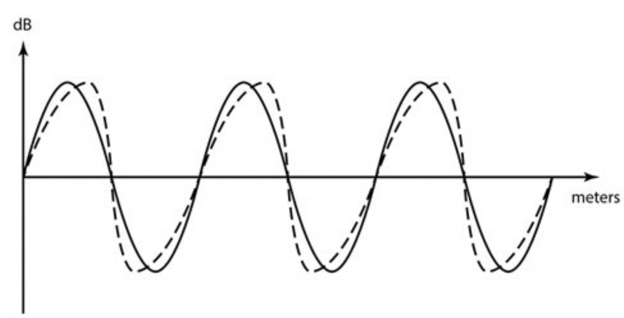

Fig. 2. Deformation of a sinusoidal wave (continuous line) into a sawtooth wave (broken line) due to changes of speed during sound propagation.

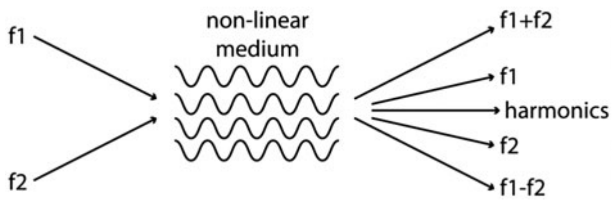

Fig. 3. Result of passing two frequencies through a non-linear medium.

Since in parametric loudspeakers one of the two frequencies is an ultrasonic carrier, what is really of interest here is the difference between the audible and the ultrasonic frequencies. In fact, the convolution between the two will shift the audible frequency to the domain of the ultrasonic carrier. When the resulting signal is demodulated what we hear is neither the convoluted wave nor the additive frequency because they are both beyond the limit of our acoustic perception. What we really hear is the difference frequency.

A long series of experimental tests suggests that the optimum frequency for the ultrasonic carrier lies between 30 and 70 kHz. In that range, higher demodulation efficiency is attained in terms of both control of distortion in the demodulated signal and safety for human ears. Nonetheless, medical studies (Pompei, 2002, pp. 95–119) seem to confirm that the higher the carrier the better for the human acoustic apparatus. After all, in order to make the demodulating signal audible, amplitudes of at least 100 dB (Pompei, 2002, p. 21) must be used. In fact, high amplitudes are necessary because, as Berktay's equation predicts, there is a 12 dB slope per octave during demodulation. In other words, if we start at, say, 40 kHz, it will take four octaves before falling in the full-blown audible range at 2.5 kHz. Consequently, if the amplitude of the ultrasonic signal was 100 dB, four octaves below it will be 52 dB, which is almost half the initial value.

High-amplitude ultrasonic signals may affect the eardrum more when their frequency is in the low ultrasonic range. As a result, Pompei's Audio Spotlights® employs a 60 kHz carrier, whereas other parametric loudspeakers usually inject a lower ultrasonic frequency into more common 40 kHz transducers. On the other hand, ultrasonic frequencies are in general not harmful to the human body, because the large impedance difference between air and skin allows just a small portion of acoustic energy to be absorbed (Gan et al., 2012b).

Let us see in detail, now, how the whole process of producing audible signals from ultrasonic carriers works.

Figure 4 shows two major stages, one before and one after the ultrasonic emitter (the heavy-bordered box in the diagram). The former reproduces the processing circuitry and includes the DSP, the amplifier and the ultrasonic emitter itself, while the latter (Gan, Tan, & Kuo, 2011) describes the demodulation effect occurring in the air. Once a signal in the audible range enters the DSP, it goes through a series of pre-processing steps that make it 'suitable' for being properly demodulated: the dynamic range controller compresses and limits the input signal, and then the distortion processor reduces the level of THD by anticipating the non-linear characteristics of the medium.[3] Eventually, the ultrasonic carrier is called in and finally convoluted with the original signal through one of the modulation schemes already mentioned in the previous section. Now the new wave is ready to be amplified before being sent to the emitters. Two kinds of transducers can be used in this case: traditional ceramic ultrasonic transducers or piezoelectric polymeric films. The transducers (like those made of lead zirconate titanate) are typically disposed in a honeycomb array (Figure 5). In fact, by maximizing space occupancy, the distance among the propagation axes of each transducer is reduced and thus is the aliasing effect due to the interference among the wave fronts that each transducer generates (Shi, Nomura, Kamakura, & Gan, 2014). On the other hand, piezoelectric films such as PVDF (polyvinilydene fluoride) conveniently provide a continuous vibrating surface, but also have the drawback of making more difficult to attain well-ordered modes of vibration (Sugimoto et al., 2009; Limei et al., 2005).

What happens in front of the loudspeaker is the generation of a series of virtual sound sources that behave like an end-fire array (hence, the 'parametric' adjective applied to this type of loudspeaker). The absorption length indicates where the end-fire array terminates, while the Rayleigh distance shows how far non-linear effects of the medium can travel. Within the Rayleigh distance, both primary and secondary waves are produced (Shi et al., 2014). However, the former are completely absorbed before the end of the near field, whereas the latter keep propagating for a much longer stretch. An interesting effect yielded by the end-fire array somehow contradicts what usually occurs with conventional omni-directional loudspeakers, i.e.: the typical—6 dB slope per doubling distance due to a spherical expanding of the sound wave is now replaced with an increasing amplitude of the signal in the near field due to the summation of each virtual source's amplitude. Moreover, while diverging from the propagation axis the virtual sources go out of phase and act destructively. Therefore, secondary waves also manage to inherit the directional property of ultrasonic primary waves, thus giving to the demodulated beam the tightness conventional sound emitters cannot achieve. Finally, notice that no frequency below 400 Hz ca. will be reproduced by currently commercially available parametric loudspeakers.[4] According to Gan et al. (2011), the reason for this is found in the reduced volume of air molecules an end-fire array of virtual audio sources is capable of

[3]THD as well as poor performance in the low spectrum of audible frequencies may be real issues at the moment of using this kind of loudspeaker. Both aspects will be discussed in Section 6.

[4]As mentioned in note 2, such a major problem, in particular with regard to music reproduction, will be addressed in Section 6.

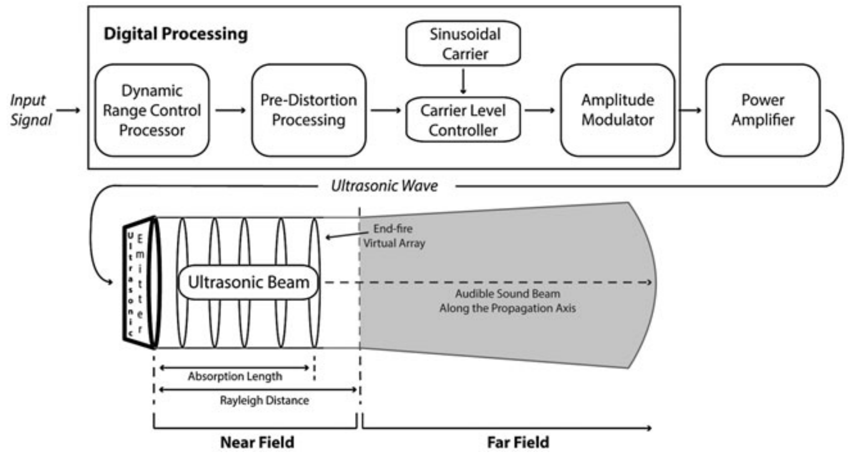

Fig. 4. Reproduction of an audible signal after being convoluted with an ultrasonic carrier.

Fig. 5. Transducer's honeycomb array in a Soundlazer's mini parametric speaker board.

moving, whereas the large diaphragm of a conventional cone-based loudspeaker, by making vibrate a wider portion of space, allows low audio frequencies to be reproduced (more on this point in Sections 5 and 6).[5]

4. Art examples

Museums, along with libraries and commercial centres, have understandably been one of the first targets for the producers of directional speakers.[6] The possibility of both projecting sound unobtrusively where silence is needed and directing audio messages without adding extra noise in places that may potentially be very crowded is certainly appealing. (The video game industry is clearly another interested client.) That said, there are actually very few examples in art where this technology has been used.

The earliest example we could find of a piece of art using directional sound is $A = P = P = A = R = I = T = I = O = N$[7] by conceptual Welsh artist Cerith Wyn Evans. This sound sculpture is now permanently installed at Centre Pompidou, but was first exhibited at the Yokohama Triennale in 2008. It features 16 shiny metal discs hanging from the ceiling and gently swaying when people pass by, as in one of Calder's giant mobiles. Some of these reflecting discs are actually custom-made Audio Spotlight® speakers by Holosonics that are used by Evans to reproduce a piece by the UK experimental band Throbbing Gristle. In 2009, American artist Bruce Nauman presented *Days* at the Venice Biennale (then installed at the MoMA in New York). The sound sculpture employs 14 Sound Shower® speakers by the Finnish Panphonics reproducing female, male and children's voices while reciting the days of the weeks in random order. The speakers are displayed in two parallel lines, creating an aisle visitors may walk through. Australian media artist Adam Donovan has a more kinetic approach to directional sound: he mounts parametric loudspeakers on robots that make them spin at high speed in order to give the impression that there are multiple sound sources spread in the ambient (see e.g. *Multiplexing Tautophone*, 2014, first exhibited at the Jurassic Lab IV in Luzern, Switzerland). Again in 2014, the German artist Nik Nowak presented *Echo* at the Berlinische Galerie. In this complex, installation that explores issues of privacy in a post-NSA scandal era, one parametric loudspeaker is used, among other things, and mounted on a tank drone that moves around in the gallery space. The tank approaches visitors and a microphone captures their conversation that the loudspeaker casts to them with a delay, as a sort of echo.

[5]Gan et al. set the cut-off frequency at 1000 Hz. No laboratory measurements are needed to claim that, at least with an Audio Spotlight® as the one we used (the AS-24i), frequencies lower than 1000 Hz can be clearly heard that are not the by-products of a missing fundamental effect. After some measurements, we decided to set the cut-off at 400 Hz, as it is also suggested by Holosonics.

[6]As early as 1983, Yoneyama and Fujimoto suggested using these 'acoustic spotlights' in museums, exhibits or any place where building sound barriers would be too expensive and unnecessary.

[7]The title is a reference to Stéphane Mallarmé's poem of the same name.

In their review of directional sound in media art, Kuutti et al. (2014) mentioned two other installations, one by the Finnish sculptor Markus Kåhre and the other by the Scottish artist Susan Philipsz. Kåhre realized the *Restaurant Symposium* (2009) a sound installation that creates 'an illusion of a restaurant space where the visitor can sit down and listen to influential, contemporary cultural persons sharing their thoughts around love' (Panphonics, 2011, p. 2). Philipsz's work is *When Day Closes* (2010), a piece of art that projected the artist's voice while singing Sibelius' *The Song of My Heart* a cappella to the vaulted ceiling of the Helsinki Central Railway Station. Both installations employed Panphonics Sound Shower®. In addition, the Finnish directional speakers have been used also by sound artist O'Keeffe since 2006, e.g. in *Spaces of Sound and Radio Spaces* (2014), a sound installation exhibited at the Leitrim Sculpture Centre in New Line (Ireland). She used them to project 'a representational or imagined space of memory and experience collected from participants of this project' (O Keeffe, 2014).

Only two composers seem to have paid attention to directional sound technology: the Italian Michelangelo Lupone and the Argentinian Juan Pampin. The former designed and constructed in 1999 a variably sized array of parabolic loudspeakers named holophones, to be used, for example, in *Ludi multifonici* (Lupone and Bianchini, 2015) installed in the Trajan's Markets in Rome. In this work the holophones project music from the classical and contemporary repertoire as well as music by Lupone and Bianchini themselves. Pampin, instead, worked initially with a Holosonics' Audio Spotlight® and then moved to build a custom-made parametric loudspeaker for specific use in body-triggered sound events (Pampin, Kollin, & Kang, 2007). This resulted in the design of some applications for interaction with dancers and passers-by, one of which is *Sanctum* (Coupe & Pampin, 2013), a multimedia installation created for the Henry Art Gallery of Seattle. In *Sanctum*, directional sound is used to send voice messages to people who stare at one of the screens that are part of the artwork.

Finally, a work that stands on the border between art and scientific research is the recreation of Roderick Denman's exponential horn (based on Helsham's horn, see Section 2) by English musician and composer Aleksander Kolkowski. As a prototype of modern waveguide speakers, Denman's exponential horn was partially destroyed in 1949 and rebuilt between 2013 and 2014 by Kolkowski for the Science Museum in London.

5. *The soundhouse*

The Soundhouse (Figure 6(a) and (b)) is a sound installation with the shape of a lighthouse (hence, the play on words in its title).

It was conceived at the end of 2014, with no knowledge that 2015 would be proclaimed by the UN as The International Year of Light. However, it found its rightful spot during that year's celebrations since, coincidentally, it was conceived from the very beginning as a metaphor of light through sound. Indeed, the main concept came from elaborating on how parametric loudspeaker manufacturers, such as Holosonics, constantly refer to light as a way to explain the functioning of this technology: 'Just like *visual spotlights*, beams of sound … ', 'Just as with *lighting*, the Audio Spotlight® speaker … ', 'Just as with light, sound from these systems … ', etc. (Audio Spotlight®'s user's manual, 2015, pp. 11–12, emphasis added). *The Soundhouse* attempted to concretize this concept by building an art object with a clear reference to a well-known structure (a lighthouse) and with a very similar function: as a sort of spotlight, the beam of a lighthouse crops a porthole out of the darkness; likewise, the rotating head of *The Soundhouse* projects a sonic space through a sound beam and, thus, reveals a concealed acoustic world, one that is usually suffocated by the constant, transversal noise of daily life.

The ideal location for this installation is any large space, preferably indoors (to minimize sound contamination from the environment), and possibly with several reflecting surfaces enhancing another singular feature of parametric

Fig. 6. (a) Rendering of *The Soundhouse.* (b) Prototype of *The Soundhouse.*

Table 2. Music programme of *The Soundhouse.*

7:00 AM	Light rain [603]
8:00	Birds in the forest [1260]
9:00	Stream 1 [786]
10:00	Waves against a boat on the lake shore [323]
11:00	Stream 2 [861]
12:00 PM	On the beach [818]
1:00	Rolling vessel [several peaks over 440]
2:00	Midday cicadas [4339]
3:00	Marimbas and gaitas [183 and 248]
4:00	Mountain wind [646]
5:00	Wind chimes [441]
6:00	Summer night [5297]

loudspeakers: the sound beam bounces against objects just as a light beam would. This is more effective, of course, if materials have a low absorption coefficient, as is the case, for example, with concrete or acrylic.[8] Reflecting surfaces may perceptively puzzle the viewer as to where sound actually comes from even more than when sound is directly heard in front of the loudspeaker. For the virtual sources guarantee that sound is perceived as originating from the very spot where it is reflected, and not necessarily from the loudspeaker that casts it.

With regard to sound, the basic idea was to project an acoustic space that opposed the sound environment in which the installation was exhibited (for the prototype the contrast was urban vs. rural sounds). To this end, a sonic journey was edited that moved through twelve different atmospheric and/or geographic areas, one per hour, as shown in Table 2:

Central (highest amplitude) frequencies in Hertz are shown in square brackets. All sounds were chosen to match as much as possible the reproductive characteristics of a parametric loudspeaker: just two (at 10 AM and 3:00 PM) have a central frequency lower than 400 Hz, which, as previously said, it was established as the cut-off frequency.

Even though our sound installation has a size that cannot go unnoticed (2.5 m high), it is hoped that the perceptive experience offered to the passers-by when walking by *The Soundhouse* is of being surprisingly intercepted by the sound beam. To this end, some field experiments were conducted both to test the loudspeaker's features and to estimate how effective the whole project would be.

5.1. Previous experiments

Tests on the Audio Spotlight® were carried out both indoors and outdoors with an AKG C451 B condenser microphone, a Fireface 800 audio interface and the iZotope's RX spectrum analyser plugin for Logic Pro.

Indoor measurements were taken in the computer lab of our Music Department (Figure 7).

Although not an ideally insulated space, this room has walls covered by phono-absorbent panels. We also took care in positioning the speaker at a height of 2 m in order

Fig. 7. Indoor setup.

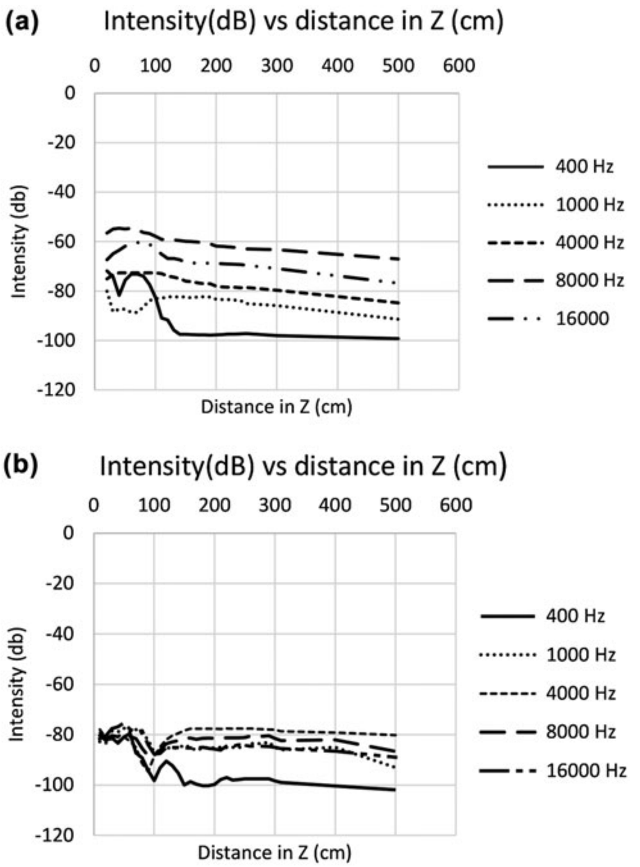

Fig. 8. (a) Indoor characterization of the intensity of the acoustic field generated by an Audio Spotlight® along the propagation axis. (b) Outdoor characterization of the intensity of the acoustic field generated by an Audio Spotlight® along the propagation axis.

[8]In fact, the space where the prototype was first exposed—the front foyer of our University's Humanities School—contains four concrete columns and other concrete structural elements.

to avoid issues concerning sound reflection on the floor and we made sure that no highly reflecting materials were present in front of the sound beam. We did not take many precautions with regard to sound reflections during outdoor measurements since in that condition they are barely present. The following two figures (Figure 8(a) and (b)) describe the amplitude behaviour of five frequencies (all above the cut-off frequency) at different distances along the propagation axis, both indoor and outdoor.

Our data confirmed what is expected for these kinds of speakers, namely that the radiation pattern is characterized by both a relatively stable amplitude (except the sudden slope around one meter in the outdoor diagram) in an area —between 1 and 3 m—contained within the Rayleigh distance and a slow decay in the far field, as it occurs also with conventional emitters.

Indoor and outdoor measurements were taken at different angles on both sides of the Audio Spotlight® to verify that the aperture of the side lobes is actually minimal when compared to an omni-directional speaker. The following figures (Figure 9(a) and (b)) illustrate the result at a radial distance of 3 m.

The different shapes between measurements and, above all, the irregularity of the Figure 9(a) vs. the symmetry of the Figure 9(b), must be ascribed again to sound reflections that significantly altered the values taken indoors. Otherwise, the sound beam emitted by the Audio Spotlight® is nicely symmetrical.

Orthogonal and radial measurements were made necessary by the very nature of the sound installation that may be experienced from different distances and angles.

5.2. The construction

Our requirements for the installation's structure stipulated that it had to be light, firm, movable and easy to store once it was dismounted. It was initially planned to be waterproof, too, so that it could be exposed outdoors. However, the heavy rain showers typical of tropical latitudes induced us to search for an indoor venue for the exhibition of the prototype and forget waterproofing.

The Soundhouse is composed of two parts: the body and the rotating head. The body is an octagonal aluminium stand with telescopic legs (four of which have wheels to conveniently move the installation). At the neck (the top side of the stand) we placed the mechanical parts for the head's rotation: a 24 rpm motoreducer and a 20:1 power reducer box to further slow down the rotation speed to

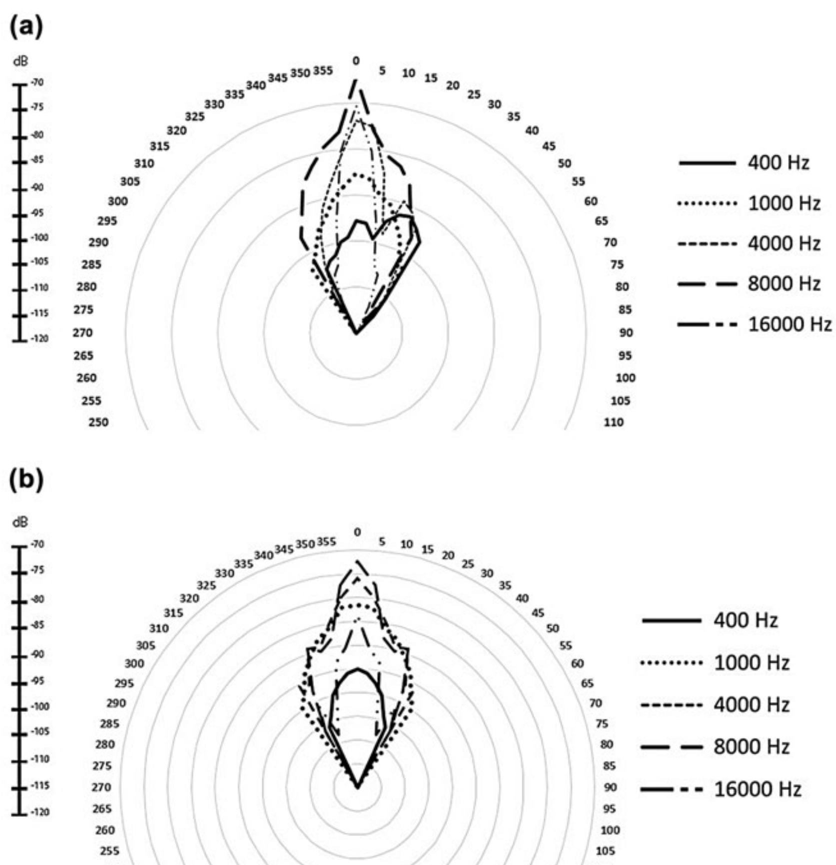

Fig. 9. (a) Indoor characterization of the intensity of the acoustic field generated by an Audio Spotlight® at different angles. (b) Outdoor characterization of the intensity of the acoustic field generated by an Audio Spotlight® at different angles.

1.2 rpm. The speaker's power cable descends from the head inside a steel axis that connects the top with the bottom part of the installation, crosses the reducer box and, eventually, ends in a slip ring that prevents it from getting tangled during rotation.

The head is formed by two octagonal aluminium shells that contain the loudspeaker, and eight rods that support the top shell. The inside of the head is hidden by acrylic fabric but, due to issues concerning sound absorption, only five sides have been covered. For the other three in front of the speaker, a thin stretched spandex has been used.

The body is also covered by a 'cape' attached to the neck with Velcro and made with the same acrylic fabric used in the head. Unfortunately, it smooths out the corner of each leg, thereby rounding the octagonal shape observed in the shells. On the other hand, it makes the whole structure much lighter than it would be had stiff materials (e.g. aluminium or wood) been employed instead.

A timer turns the installation on and off every 12 hours.[9]

6. Conclusions about the use of parametric loudspeakers for sound reproduction in art

In our opinion, two main issues are preventing parametric loudspeakers to be extendedly employed in art, especially in music: a hard-to-control harmonic distortion and a narrow frequency bandwidth. The former can be easily noticed while testing the output of the speaker with a microphone; in fact, the amplitude of the harmonic components might equal or even surpass the amplitude of the fundamental. Moreover, the amplitude of the fundamental varies along with frequency thus making the frequency response of these speakers barely flat. Since part of the distortion is generated during the demodulation in air, it is hard to picture what technique could be used to avert it other than the pre-processing already existing in the DSP.

That parametric loudspeakers cannot reproduce frequencies below, at best, 400 Hz ca. makes them ideal for speech reproduction (between 300 and 3400 Hz), but not so much for music. Indeed, just a few artists (e.g. Cerith Wyn Evans) have used them for something different than projecting mere voice. Expanding the reproduction range to the audio bass frequencies is something that Croft and Norris (2002) considered unsolvable, but it could possibly be achieved by significantly increasing the size of the speaker or its energy output. In fact, if bandwidth has to do with the volume of displaced air molecules, the larger the radiating surface the lower the frequency reproduced.[10] On the other hand, increasing the energy would result in decreasing conversion efficiency due to saturation. In any case, producers of parametric loudspeakers keep suggesting that this limitation may be circumvented by complementing the system with a subwoofer; however, this is just a meagre palliative because if the diffusiveness of low frequencies shares with parametric loudspeakers the property of concealing the physical source of sound, a conventional subwoofer is far from being directional, which is why one would use parametric loudspeakers in the first place. To our knowledge, only Shi, Mu, and Gan (2013) both addressed this major problem (at least for music) and proposed a quite imaginative and interesting solution. They did a sort of inverse engineering and thought to generate the sensation of low frequency sounds by boosting their harmonic components (a psychoacoustic phenomenon known as 'residue pitch' or 'missing fundamental' [Schouten, 1938; Gelfand, 2015, pp. 80–81]). Thus, they split the input signal at 500 Hz, processed the lower portion to artificially reconstruct its harmonic components, recomposed the input signal by summing the pre-processed lower band to the higher band and, finally, fed with it the DSP of the parametric loudspeaker. In the end, they overcame a physical problem through a psychophysical approach.

Studies conducted to measure the appreciation of a general audience with respect to parametric loudspeakers (Furhmann & Amon, 2014) report that none of the participants, no matter how positively surprised by this technology, would buy such a device for personal use unless noise floor and overall quality of the sound would be improved.[11] Although the authors used an Acouspade™ by Ultrasonic and not an Audio Spotlight® for their research, we understand why some participants were sceptical about getting a parametric loudspeaker as a new music gadget in their house.

Proprietary algorithms implemented in commercially available loudspeakers can dramatically improve sound quality, but there is still much work to be done on THD and bass reproduction before this technology can be seriously appealing for a wide range of artists. However, such momentary limitations must not induce the reader to think that parametric loudspeakers are nothing more than a transient technology. We are convinced that they have a future, no matter whether it will be possible to reduce the THD or expand the frequency range. The unique characteristics of these devices—i.e. high directivity and in-body presence of sound—may be not long lived in and of themselves, but they are certainly invaluable features when we come down to expanding the perceptive experience of the art goer and satisfying the contemporary artist's longing for new expressive means.

[9]A video of the setup can be watched at https://www.youtube.com/watch?v=QGJGeWxAMVw.

[10]Also Holosonics seems to be claiming the same when it says that its larger speaker (the AS-24i we used) has an extra low octave range with respect to the other two, smaller models (the AS-168i and the AS-16i).

[11]The experiments carried on by the authors deserved a much larger amount of testers than the only eight subjects who actually took part in them.

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Appendix 1

• Berktay's far-field equation:

$$P_2 = \frac{\beta P_o^2 a^2 m}{16 \rho_o c_o^4 r \alpha} \frac{d^2}{dt^2} E^2(t) \tag{1}$$

(P—acoustic pressure; β—coefficient of nonlinearity; a—effective source radius; m—modulation index; ρ_o—density of the medium of propagation; c_o—speed of sound; r—axial distance from the source; α—coefficient of absorption; $E(t)$—envelope function).

This equation establishes that the demodulated signal is proportional to the second-time derivative of the squared envelope.

• Wave equation:

$$\nabla^2 P(2\vec{r}, t) = \frac{1}{c^2} \frac{\partial^2 P(2\vec{r}, t)}{\partial t^2} \tag{2}$$

(∇—Laplace operator; P—acoustic pressure; r—position vector; t—time; c—speed of sound).

The left expression of the equation shows that the intensity of pressure of the acoustic field (P) is operated by the Laplacian (∇)which, in turn, is directly proportional to the second derivative of the same field with respect to time (t) and inversely proportional to the squared speed of sound (c). The way how the energy is scattered in space is modelled according to the reference system and the consequent shape taken by the Laplace operator (e.g. spherical, Cartesian, cylindrical, etc.).

• KZK:

$$\frac{d^2 P}{\mathrm{d}z\mathrm{d}t'} = \frac{c_o}{2} \nabla_T^2 P + \frac{\delta}{2c_o^3} \frac{\partial^3 P}{\partial t'^3} + \frac{\beta}{2\rho_o c_o^3} \frac{\partial^2 P^2}{\partial t'^2} \tag{3}$$

(P—acoustic pressure; z—coordinate in the propagation's axis; t—delay time ($t' = t - \frac{z}{c_o}$); ρ_o—density of the medium of propagation; c_o—speed of sound; β—coefficient of non-linearity).

This equation is composed of three terms: the first expresses the parabolic diffraction, the second the dissipation and the third the non-linear contribution (Beyer, 1960).[12] ∇_T^2 is a Laplacian operator that operates in the plane perpendicular to the axis of propagation z ($\nabla_T^2 = \partial^2/\partial x^2 + \partial^2/\partial y^2$). The dissipation term was introduced later by Kuznetsov and added the sound diffusivity (δ) to the originally lossless KZ equation (Rozanova-Pierrat, 2006). δ is related to the thermoviscosity absorption of the medium and is defined by the following expression:

$$\delta = \frac{1}{\rho_o}\left(\frac{4}{3}\mu_s + \mu_B\right) + \frac{k}{\rho_o}\left(\frac{1}{c_v} - \frac{1}{c_p}\right)$$

(μ_s—shear viscosity; μ_B—bulk viscosity; k—thermal conductivity; c_v and c_p—specific heat at constant volume and pressure respectively).

[12] Nonlinearity can be quantified by a single value known as parameter of non-linearity. In diatomic gases like air at a temperature of 293.15 K (20 °C) that value is 0.4. At this same temperature, the velocity is 343.2 m $s^{-1.}$