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Short overview in parametric loudspeakers array technology and its implications in spatialization in electronic music

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ABSTRACT

In late December of 1962, a Physics Professor from Brown University, Peter J. Westervelt, submitted a paper called Parametric Acoustic Array [1] *considered primary waves interacting within a given volume and calculated the scattered pressure field due to the non-linearities within a small portion of this common volume in the medium* [2]. *Since then, many outputs of this technology were developed and applied in contexts such as military, tomography, sonar technology, artistic installations and others.*

Such technology allows perfect sound directionally and therefore peculiar expressive techniques in electroacoustic music, allowing a very particular music dimension of space. For such reason, it's here treated as a idiosyncrasy worth to discuss on its on terms.

In 2010-2011 I composed the piece "A Anamnese das Constantes Ocultas", commissioned by Grupo de Música Contemporânea de Lisboa, that used a parametric loudspeakers array developed by engineer Joel Paulo. The same technology was used in the 2015 acousmatic piece "Jeux de l'Espace" for eight loudspeakers and one parametric loudspeaker array.

This paper is organized as follows. A theoretical framework of the parametric loudspeaker array is first introduced, followed by a brief description of the main theoretical aspects of such loudspeakers. Secondly, there is a description of practices that use such technology and their applications. The final section describes how I have used it in my music compositions.

1. Introduction

The fundamental theoretical principles of a parametric loudspeaker array (PLA) were discovered and explained by Westervelt [1]. Interestingly, this was in the same year of the publication of an article by Max Mathews where the author said there were "no theoretical limits to the performance of the computer as a source of musical sounds" [3], a text that then was mentioned by composers who changed the history of computer music, such as John Chowning, as very promising ideas [4], who certainly influenced this and other composers.

A relation between Westervelt discoveries and further developments in parametric loudspeakers array technology were described by Croft and Norris [2], including the technological developments by different scientists and in different countries and how it has moved from theory and experimentation to implementation and application.

It's important to clear that such terminology isn't fixed and that it's possible to find different definitions to similar projects (commercial, scientific or of other nature), uses, products and implementations of such theoretical background, sometimes even by the same authors and in the same articles. Some of them being "parametric loudspeakers" [2], [5], "parametric speakers " [6], [7], "parametric acoustic array" [1], [8], "parametric array" [5], [7], "parametric audio system" [9], "hypersonic sound" [10], "beam of sound" [1], "audible sound beams" [11], "superdirectional sound beams" [12], "super directional loudspeaker" [13], "focused audio" [14], "audio spotlight" [15], [16], "phased array sound system" [17], among others. The term PLA is being used here since it seems to reunite the main concepts that converge in this technology. Nevertheless, it isn't meant to be presented as an improved terminology over others. This discussion solely has the purpose of showing that one who might not be familiar with such technology, and wish to research more about it, will find different terms that were originated due to particular historical contexts, manufacturers patents and arbitrary grounds.

2. Theoretical framework

A parametric loudspeaker is guided by a principle described by Westervelt as:

> two plane waves of differing frequencies

generate, when traveling in the same direction, two new waves, one of which has a frequency equal to the sum of the original two frequencies and the other equal to the difference frequency [1].

However, to trace a proper theoretical framework of the parametric acoustic array in modern applications, Gan et al. makes a more clear description, based on Westervelt's theory:

> When two sinusoidal beams are radiated from an intense ultrasound source, a spectral component at the difference frequency is secondarily generated along the beams due to the nonlinear interaction of the two primary waves. At the same time, spectral components such as a sum-frequency component and harmonics are generated. However, only the difference-frequency component can travel an appreciable distance because sound absorption is generally increased with frequency, and amplitudes of higher-frequency components decay greatly compared with the difference frequency. The secondary source column of the difference frequency (secondary beam) is virtually created in the primary beam and is distributed along a narrow beam, similar to an end-fire array reported in antenna theory. Consequently, the directivity of the difference-frequency wave becomes very narrow. This generation model of the difference frequency is referred to as the parametric acoustic array [8].

The result is that the sound projection from a PLA becomes very narrow, much more than with the use of a regular moving-coil loudspeaker (figure 1).

The dispersion pattern of a loudspeaker may also vary broadly, from omnidirectional to superdirectional. Although it's rare for a speaker to have a truly constant directionality across its entire passband, in part from the fact that most are at least somewhat directional at mid and high frequencies, and, because of the long wavelengths involved, almost unavoidably omnidirectional at low frequencies [18]. Loudspeaker systems exhibit their own radiation patterns, characterized by the technical specification called *dispersion pattern*. The dispersion pattern of a front-projecting loudspeaker indicates the width and height of the region in which the loudspeaker maintains a linear frequency response [19]. Most conventional loudspeakers are broadly directional and one can say they typically project sound forward through a horizontal angle spanning 80 to 90 degrees [12].

Tests in PLA systems have demonstrated angles of circa 15 to 30 degrees at 1 kHz, depending on the used model [20]. Loudspeakers that act as superdirectional sound beams behave like an audio spotlight, focusing sound energy on a narrow spot, typically about 15 degrees in width, making possible that a person can hear a sound, while someone nearby, but outside the beam, does not [12]. Such systems are quite peculiar, even when compared to the so-called *narrow coverage loudspeakers,* that feature dispersion in the 50 degree range, such as some Meyer Speakers [21], and potentially have new applications in many diverse fields.

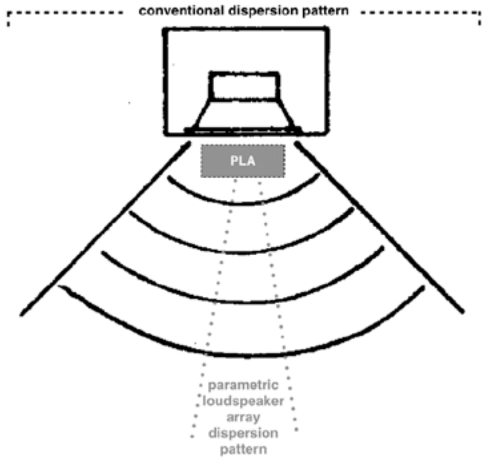

Figure 1. Comparison between hypothetical dispersion patterns for a conventional loudspeaker and for a PLA.

3. Parametric Loudspeakers applications

The proposed applications for such technology vary greatly within the manufacturers of PLA, scientific and artists based proposals, creating a rich interdependence between all fields and hopefully inspiring all involved actors in the creation of new products and synergies. Proposals range from: applications in museum or art galleries, private messaging in vending and dispensing machines, exhibition booths, billboards, multilanguage teleconferencing [5]; acoustic metrology in non destructive testing used on ancient paintings [22]; estimation of acoustical parameters [23]; mobile communication environment creating possibilities for stereo phone calls having a high level of privacy [13]; public safety, security / alarm systems, public speaking [6]; digital signage, hospitals, libraries [15]; control room, tradeshows [14]; automotive applications, slot machines, mobile applications [24]; underwater acoustics, measurement of environmental parameters, sub-bottom and seismic profiling and other naval appliances [25]; and many others, some of them to be further discussed.

While many of the applications use self built devices, there are commercial products that sell PLA, namely, ® Soundlazer [6], ® Holosonics [15], ® Brown Innovations [14], ® Acouspade (by Ultrasonic Audio) [24], ® Hypersonic Sound (LRAD corporation) [26], and others.

Defining the application of PLA in *artistic fields* or within musical practices isn't obvious. In that sense, Blacking clears that "no musical style has 'its own terms': its terms are the terms of its society and culture, and of the bodies of the human beings who listen to it, and create and perform it" [27]. In such terms, is Hiroshi Mizoguchi human-machine interface (named 'Invisible Messenger'), that integrates real time visual tracking of face and sound beam forming by speaker array [28], an *art work*? For the purpose of the present paper, Mizoguchi's work will not be considered as an *art form*, since the authors don't consider themselves as doing *art.* As Bourdieu mentions, one may view the 'eye' as being a product of history reproduced by education, being true for the mode of "artistic perception now accepted as legitimate, that is, the aesthetic disposition, the capacity to consider in and for themselves, as form rather than function, not only the work designated for such apprehension, i.e. legitimate works of art, but everything in the world, including cultural objects which are not yet consecrated" [29].

For the purpose of the present paper, the perspective of the creators will be the base to integrate the use of PLA technology as an application in their *artistic expression* or as other form of expressive behavior. The importance of clearing such categorization is not to imply any form of hierarchy, but merely to formulate a context in presentation, order and grouping of the presented and discussed works.

Other forms of applications are explicitly affirmed as *art practices*, such as the case of Yoichi Ochiai's experiments with ultrasonic levitation [30], that presents himself as a *media artist* [31]. The use of PLA may also be seen in *installations* such as Misawa's "Reverence in Ravine" [32], or "Guilt", by Gary Hill [33]–[35], and reported in *sound art* and *music* by artists such as Miha Ciglar, head of IRZU – Institute for Sonic Arts Research, Ljubljana, Slovenia and creator of several devices and works using PLA, namely a "hands free" instrument, utilizing a non-contact tactile feedback method based on airborne ultrasound or acoustic radiation pressure waves as a force feedback method [36], [37]. Darren Copland has used PLA technology extensively, having created pieces and developed spatialization techniques specific for these, placing a PLA system by Holosonics company in a metal frame with handles on the sides and a mounting point at the bottom that allows the speaker to be rotated 360 degrees on a tripod stand or using a wood frame with handles on the side which are connected with a strap that goes around the performer's neck like the strap for an accordion player [38]. Other artists that have been using such technology relate to the DXARTS - Seattle Arts and Technology, such as Michael McCrea *Acoustic Scan* [39] and Juan Pampin that have present in 2007, with other colleagues, works that were using PLA technology as *ultrasonic waveguides*, as an *acoustic mirror* and as *wearable sound* [40]. Furthermore, Pampin has used PLA technology in musical pieces such as 2014 "Respiración Artificial", for bandoneon, string quartet, and electronics using PLA, as he mentions in an interview:

> *The piece is about breathing cycles. The bandoneon has a big bellow and is able to hold a note for a very long time. The timing of the inhale and exhale of the instrument was used to define the time structure of the piece. The beginning of my piece is all in the very upper register (above 1000 Hertz, around the C above treble clef). When you hear up there, you hear in a different way. Your ear is not able to resolve what is happening with pitch, the notes tend to shimmer, it builds sensation. This piece is all sensorial it's not theoretical. Its more neurological if you want. In terms of the electronics, I am using a 3D audio system and ultrasonic speakers that we developed in DXARTS. These speakers can produce highly localized beams of sound – akin to spotlights – which can move around the audience and bounce off the architecture of the room* [41]

Despite the motivations to interfere in *space* in peculiar ways, that can be read in many of the mentioned articles and websites, the use of PLA in artistic practices hasn't been studied as something particular, possibly, because: it's too recent; such creations operate at individual levels or even when within institutions, they appear to occur locally; or simply because there may be no particular feature that makes worth of distinction by musicologists, art historians, anthropologists or other scientists in the field of social sciences. There are many other applications of PLA being developed at this very moment. The ones presented here represent only a short research about such topic and are not expected to cover the full length of the use of such technology.

Independently of using PLA technology or not, the idea of directing sound in precise ways or, one could say, the idea of working with space as a parameter in sound creation, has been a very important concept in electroacoustic music. Curtis Roads has referred to superdirectional sound beams and their developments, focusing on audio technology and on electroacoustic music [12], [42]. Among other technologies, the author emphasizes the specificity of PLA technology, explaining the involved principles of acoustic heterodyning, first observed by Helmholtz.

When two sound sources are positioned relatively closely together and are of sufficiently high amplitude, two new tones appear: one lower than either of the two original ones and a second one that is higher than the original two. The two new combination tones correspond to the sum and the difference of the two original ones. For example, if one were to emit two ultrasonic frequencies, 90 KHz and 91 Khz, into the air with sufficient energy, one would produce the sum (181 kHz) and the difference (1 kHz), the latter of which is in the range on human hearing. Helmholtz argued that the phenomenon had to result from a non linearity of air molecules, which begin to behave nonlinearly (to heterodyne or intermodulate) at high amplitudes [12].

The author continues detailing that the main difference between regular loudspeakers and loudspeakers that use acoustical heterodyning (PLA), is that they project energy in a collimated sound beam, making an analogy to the beam of light from a flash-light and giving the example that one can direct the ultrasonic emitter toward a wall and a listener in the reflected beam perceives the sound as coming from that spot. Mentioning that, however, "at the time of this writing, there has been little experimentation with such loudspeakers in the context of electronic music" [12].

4. Parametric Loudspeakers in my music

In 2010-2011, I composed the piece "A Anamnese das Constantes Ocultas", commissioned by and dedicated to Grupo de Música Contemporânea de Lisboa (GMCL). The piece was conceived for nine players - soprano voice, flute, clarinet, percussion, harp, piano, violin, viola, violoncello; with conductor and electronics: six regular loudspeakers, one directional PLA loudspeaker, amplified hi-hat, using a click track for the conductor (figure 2).

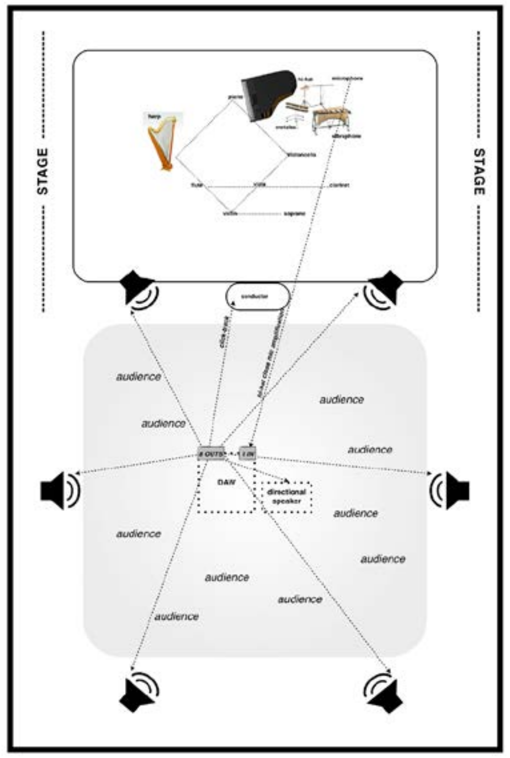

Figure 2. Schema for the disposition of loudspeakers and instruments for the performance of "A Anamnese das Constantes Ocultas".

The players are to be set on stage and the electronic diffused in the six conventional loudspeakers, to be distributed around the audience. The PLA requires an operator to play it. The score has specific instructions demonstrating at each moment where to point (what kind of surfaces to point at, or "swipe" the complete audience or just parts of the audience). One extra musician is required to operate the electronics, in order to control the amplitude of the fixed media electronics (both for the regular loudspeakers and the PLA), the hi-hat amplification and the players amplification (when necessary).

The experimentation and development of the piece was only possible by the dedication of GMCL and engineer Joel Paulo, who developed a parametric loudspeakers array for this piece. At the beginning of the composition I had only heard about such technology, but had never tested it.

Figure 3. GMCL playing "A Anamnese das Constantes Ocultas"; Salão Nobre of Escola de Música do Conservatório Nacional (Lisbon); 26th May 2012; Musicians: Susana Teixeira (voice), Cândido Fernandes (piano), João Pereira Coutinho (flute), José Machado (violin), Luís Gomes (clarinet), Ricardo Mateus (viola), Fátima Pinto (percussion), Jorge Sá Machado (cello), Ana Castanhito (harp); conductor: Pedro Neves. Photo: Cristina Costa.

Figure 4. Rehearsals in the same concert. PLA operator: Joana Guerra; electronics: Jaime Reis.

In this piece, the electronics have three fundamental grounds:

1) generate *large architectural spaces* through the hi-hat amplification, using very close miking (less than 1 cm, using a condenser microphone) of the hi-hat, combined with timbre transformations and spatialization of the signal trough the six regular loudspeakers and the PLA; with such close miking, there are significant changes in the hi-hat timbre, in order to create the idea of playing a huge non pitched gong that it should sound as if it was in a big *pyramid*; different areas of the spectra are distributed in space using both the regular loudspeakers (generally using low and mid frequency, whose range usually changes gradually) and the PLA (dedicated to higher frequencies and distributed in the room in reflective surfaces such as walls, ceiling and floor); resonators were also applied to such timbres that have common pitches with the instrumental textures;

2) *new dimensions* in instrumental spatialization, using the PLA as an extension of instrumental melodic lines, besides punctual diffusion in the regular loudspeakers; the combined use of a timbre and pitch in acoustic instruments, regular loudspeakers and PLA generates very peculiar perceptions of location and source identification;

3) a semantic approach to unveil *hidden messages* that are sung live and in the electronics (mainly in the PLA); the poem to be sung is polysemic and its different meanings are suggested in the prosody, mainly differentiated in this piece by rhythm; the use of the so-called *hidden messages* appear as a reinforcement for the intended meaning, punctually completely revealed by the singers in spoken text; due to the high degree of directivity, such passages should be pointed directly at the audience, making it possible that only specific parts of the audience will listen to those exact passages; more than the usual problem of a member of the audience staying outside of the *sweet spot* and not being able to listen to the spatialization in the same way (as often occurs in acousmatic music), here the purpose is to make each performance unique and somehow personalized, in the sense that the PLA operator may direct sound just for one person or a group of people (that I call *direct operations*); this is different from the *reflective operations* of the PLA (in both figures 5 and 6), constituted by the moments when the PLA is pointed at a surface and the sounds are diffused in the room.

The use of the PLA was integrated from the beginning in the piece's structure and it isn't possible to play the piece without such technology.

Other piece that requires PLA is the 2015 acousmatic work "Jeux de l'Espace", for eight regular loudspeakers, equidistant around the audience (such as in a regular octophonic system) and one directional PLA loudspeaker (to be operated during performance either in the center of the octophony or in front of the audience).

Figure 5. Premiere of the piece “Jeux de l'Espace” in Festival Monaco Électroacoustique, 30th May 2015; playing the PLA in the center of Théâtre des Variétés, using Michel Pascal’s (on the left) and Gaël Navard’s *Acousmonium* du CNRR de *Nice. Photo:* [43].

Although the PLA movements also have to be precise for each moment of the composition (requiring adaptations to the performance architectural space), there were other principles involved for this composition. It was inspired in *space* as a musical parameter and as the cosmos, integrating sounds derived from processes of sonification from NASA and ESA. The intention is to create an imaginary of a *cosmic momentum* were space is experienced in a tridimensional octophonic sound system with an additional spatial dimension of sound created by the PLA.

In this piece, the main principles of working *space* as a musical parameter are:

1) working on the limits of perception of spatial movements, for example, varying the speed of rotations, based on my own perception of what is heard as a rotation or, if too fast, as a texture of points whose movements in space cannot be perceived in their directionality;

2) create spatial movements that are similar, meaning, identifiable as being connected, like identical paths, or in opposite direction, or symmetric; where the used sounds change in envelope, timbre, rhythm and pitch in order to make such paths more or less identifiable, such as in a gradual scale of levels of identification that is used to make such paths more clear in some situations than in others;

3) compose moments of *hybrid* spatialization using the octophonic system and the PLA in *indistinguishable* ways were the fusion between PLA sound and the regular loudspeakers sound doesn’t allow a precise perception of the sound source; this is usually achieved by using *reflective operations* of the PLA simultaneously with the use of the octophonic system as an extension of the PLA (or PLA as an extension of the octophony), and connecting both in timbre and *gestures*;

4) compose moments of *independent* spatialization of both systems; such as PLA *solos* than can be arranged in different ways with different degrees of elucidating the listener to the on going spatial processes: to play the PLA as a *soloist* (as if it was an instrument playing with an orchestra) with *direct operations* while operating the octophony in a more detached way from the PLA; use PLA *solos* (without octophony) using mainly *reflective operations* and punctually *direct operations.*

Figure 6. Performance of the piece “Jeux de l'Espace” in Santa Cruz airfield (Aeroclube de Torres Vedras); 25th June 2015; schema exemplifying *reflective operations*, in this case, pointing the PLA to the floor. Photo: [44]

I have only read about the works and research of Darren Copeland, Miha Ciglar, Juan Pampin and others recently, years after starting using such technology. Even so, it was interesting to note that many aspects that I have mentioned are similar to other composers, namely some of the spatialization techniques used by Copland [38]. Other elements about the construction of sounds, form and other compositional elements could be discussed, but will be left for further discussions and at the light of new research in this field.

5. Conclusions

By the its name, the concept of a “4th dimension” could be expressed in the sound system *4DSound* [45], [46]. The creators of this system decided to refer to the idea of a fourth dimensional sound not by using *superdirectional sound beams*, but using omnidirectional loudspeakers, with experiments in different fields, one of the most significant being from one of it's designers, Paul Oomen, in his opera “Nikola” [47].

However, the title of this presentation wasn’t taken from *4DSound*, but from a reflection based on my experience with PLA technology. To answer to the proper application of the concept of a fourth dimension in (electronic) music isn’t simple. In modern physics, space and time are unified in a four-dimensional Minkowski continuum called *spacetime*, whose metric treats the time dimension differently from the three spatial dimensions. Since a fourth dimension is considered the *spacetime continuum* and sound waves exist *within* it in the way such *continuum* has in itself three dimensional material space which is where sound waves exist, one could argue if such dimension could exist in sound by questioning *where* and *when* such dimension could be found.

Considering this, one could question if PLA can be considered a fourth dimension of space in electronic music? I would have to answer: no, because I don't think the concept of a fourth dimension is applied to sound simply by using PLA technology. However, I do believe that such use implies indeed a *new dimension* in space and in our perception of it, making a new parameter to consider while composing or working with sound. And, if not, one could ask why even to consider such concept as a main question. The answer to that is merely empirical, because in the last five years that I have worked with PLA technology and presented it in my tours in Europe, America and Asia, this question would very often come from people in audiences of concerts and conferences: *is it like a fourth dimension of sound?* So, it seemed to be a good question to reflect.

The use of PLA is in expansion in many fields. The novelty doesn't appear to be in the technology itself (since it’s around for decades), but on the way it's being used. The *how* and *whys* for each creator or group of creators are to be intensively developed and studied.

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Extended Convolution Techniques for Cross-Synthesis

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ABSTRACT

Cross-synthesis, a family of techniques for blending the timbral characteristics of two sounds, is an alluring musical idea. Discrete convolution is perhaps the most generalized technique for performing cross-synthesis without assumptions about the input spectra. When using convolution for cross-synthesis, one of the two sounds is interpreted as a finite impulse response filter and applied to the other. While the resultant hybrid sound bears some sonic resemblance to the inputs, the process is inflexible and gives the musician no control over the outcome. We introduce novel extensions to the discrete convolution operation to give musicians more control over the process. We also analyze the implications of discrete convolution and our extensions on acoustic features using a curated dataset of heterogeneous sounds.

1. INTRODUCTION

Discrete convolution (referred to hereafter as *convolution* and represented by $*$) is the process by which a discrete signal f is subjected to a finite impulse response (FIR) filter g to produce a new signal $f * g$. If f has a domain of $[0, N)$ and is 0 otherwise and g has a domain of $[0, M)$, then $f * g$ has a domain of $[0, N + M - 1)$. We define convolution as Eq. (1).

$$(f * g)[n] = \sum_{m=0}^{M-1} f[n-m]\, g[m] \tag{1}$$

The convolution theorem states that the Fourier transform of the result of convolution is equal to the point-wise multiplication of the Fourier transforms of the sources. Let $\mathcal{F}$ denote the discrete Fourier transform operator and $\cdot$ represent point-wise multiplication. An equivalent definition for convolution employing this theorem is stated in Eq. (2) and is often referred to as *fast convolution*.

$$\begin{aligned} \mathcal{F}(f * g) &= \mathcal{F}(f) \cdot \mathcal{F}(g) \\ &= \|\mathcal{F}(f * g)\|\, e^{\mathrm{i}\,\angle\mathcal{F}(f*g)} \\ \text{where } \|\mathcal{F}(f * g)\| &= \|\mathcal{F}(f)\| \cdot \|\mathcal{F}(g)\|\,, \\ \angle\mathcal{F}(f * g) &= \angle\mathcal{F}(f) + \angle\mathcal{F}(g) \end{aligned} \tag{2}$$

When employing convolution for cross-synthesis, one of the two sounds is interpreted as an FIR filter and applied to the other. There are several issues with convolutional cross-synthesis that restrain its musical usefulness.

Treating one of the sounds as an FIR filter essentially interprets it as a *generalized resonator* [1]. However, because convolution is a commutative operation the process is akin to coupling two resonators. The results of convolutional cross-synthesis are often consequently unpredictable and ambiguous. Additionally, there is no way to skew the influence over the hybrid result more towards one source or the other.

Another issue with convolutional cross-synthesis is that the frequency spectra of naturally-produced sounds is likely to decrease in amplitude as frequency increases [2]. The convolution of two such sounds will result in strong attenuation of high frequencies which has the perceived effect of diminishing the "brightness" of the result.

Early attempts to remedy the brightness issue, especially with regard to the cross-synthesis of voice with other sounds (vocoding), involved a preprocessing procedure. A "carrier" sound would be whitened to bring its spectral components up to a uniform level to more effectively impress the spectral envelope of a "modulator" sound onto it [3]. While effective at increasing the intelligibility of the modulator, preprocessing still leaves the musician with limited control over the cross-synthesis procedure and is not particularly generalized.

We introduce an extended form of convolution for the purpose of cross-synthesis represented by $\hat{*}$. This formulation allows a musician to navigate a parameter space where both the perceived brightness of the result as well as the amount of influence of each source can be manipulated. We define extended convolution in its full form as Eq. (3). We will present our justification of these extensions from the ground up in Section 2 and analyze their effect on acoustic features in Section 3.

$$\begin{aligned} \mathcal{F}(f \hat{*} g) &= \|\mathcal{F}(f \hat{*} g)\|\; e^{\mathrm{i}\,\angle\mathcal{F}(f \hat{*} g)} \\ \text{where } \|\mathcal{F}(f \hat{*} g)\| &= (\|\mathcal{F}(f)\|^{p} \cdot \|\mathcal{F}(g)\|^{1-p})^{2\,q}, \\ \angle\mathcal{F}(f \hat{*} g) &= 2\,s\,(r\,\angle\mathcal{F}(f) + (1-r)\,\angle\mathcal{F}(g)) \end{aligned} \tag{3}$$

2. EXTENDING CONVOLUTION

In this section we will expand on our extensions to convolution based on the two criteria we have identified: control over the brightness and source influence over the outcome.

2.1 Brightness

Convolution of arbitrary sounds has a tendency to exaggerate low frequencies and understate high frequencies. One way to interpret the cause of this phenomenon is that the