Structure-Borne Sound and Aurally Active Spaces

Otso Lähdeoja
University of the Arts,
Sibelius Academy
Centre for Music and Technology
PL 30, FI 00097 Taideyliopisto,
Helsinki, Finland
otso.lahdeoja@free.fr

ABSTRACT
This paper provides a report of a research effort to transform architectural and scenographic surfaces into sound sources and use them in artistic creation. Structure-borne sound drivers are employed to induce sound into the solid surfaces, making them vibrate and emit sound. The sound waves can be perceived both via the aural (airborne diffusion) as well as the tactile (structure-borne diffusion) senses. The paper describes the main challenges encountered in the use of structure-borne sound technology, as well as the current results in overcoming them. Two completed artistic projects are presented in order to illustrate the creative possibilities enabled by the research.

Keywords
Structure-Borne Sound, Aural Architecture, Sound Spatialization, Augmented Instrument

1. INTRODUCTION
This paper presents the results of an ongoing investigation for transforming architectural and scenographic elements into a macro-scale electro-acoustic instrument. The project is based on the use of structure-borne sound driven into a variety of surfaces, making them vibrate and emit sound.

The term “structure-borne sound” is used to signify sound waves induced into solid elements via acoustic transducers (electromagnetic structure-borne sound drivers). The resulting vibrating solids act as loudspeakers, giving rise to air-borne sound diffusion via the structures of the performance space (e.g. walls, seats, windows, scenographic elements), as well as to audiotactile perception when these elements are brought in direct physical contact with the spectators.

The research builds on an allegory of instrument augmentation, toying with a more literal interpretation of the term. An "augmented instrument" could stand for the extension of the idea of an instrument into the very structures of the performance space. Just as if one would zoom into the body of an acoustic instrument, the walls of the space becoming a large-scale resonant chamber. We aim to create architectural and/or scenographic spaces that are capable of delivering high quality full-spectrum audio output. Together, the vibrating surfaces constitute a set of spatially distributed sound sources of various sizes and materials, forming a complex 3-dimensional acoustic space termed here as an *aurally active space*.

The research merges design and implementation issues in the fields of physical materials, audio hardware and software, human-computer-hardware interaction, as well as spatial sound perception. The present article will overview existing work on the subject, discuss the main challenges encountered so far during the work, and present the results via two artistic projects exploring creative applications enabled by the research.

2. PREVIOUS WORK
Structure-borne sound is a widely studied phenomenon in industrial design and the acoustics of vibrating solids are well understood. However, the existing corpus of engineering-related research is primarily concerned about the reduction of structural vibration, for example in order to attenuate machine-related noise levels. However, some studies point towards the actual use of vibrating solids in the domain of music and sound arts. For instance, Panel-type loudspeaker acoustics and equalization have been studied [5], and methods for enhancing the sound output via signal processing in plane-wave producing dipole speakers have been proposed [4]. A full audio range glass speaker has been developed, but not commercialized [8]. A wooden speaker has been studied in order to enhance room acoustics by adding reverberation with an aurally active panel [2]. Cinema has been the main area of development for the use of structure-borne sound in a sonic context. Enhanced realism and spectator immersion have been achieved with audio bass frequencies conducted into the public seating. Also, some recent flatpanel-speaker public address systems are based on audio driven into solid surfaces (ex. the "whispering window" trademark) [12]. Structural vibration has stirred interest in the artistic domain, in the footsteps of the pioneering piece "Rainforest" by David Tudor [11]. More recent pieces include, for example, sound conducted into the bone structure of the body in order to create new sonic percepts [10]. In the music domain, recent psychoacoustic experiments have showed that the subjective quality of the listening experience is enhanced with the pairing of structural vibration with air-borne sound diffusion [1]. The work resented in this article is aimed to be a technological development as well as an artistic application for the use of structural vibration in the music and sound art context.

3. ARCHITECTURAL AND SCENOGRAPHIC INSTRUMENTS
The present research stems from a previous work in the field of instruments augmentation with sensors and software. Gaining knowledge about the possibilities of structure-borne sound, the author started toying with the idea of an "acoustical augmentation" of an instrument. What if the sound of a traditional instrument would be expanded to the structures of the concert hall, producing a zoom-in effect of being inside the instrument itself? In a broader sense, the ability to transform a broad range of surfaces into sound-emitting objects opens new perspectives for creating spatial, architectural instruments.

The aurally active spaces developed through this line of research extend the gesture of spatial composition from traditional loudspeaker arrays to a set of elements distributed in a 3D space. It is thus possible to conceive an aural design - or a sonic topology - for a given space. The sound can radiate from instruments and loudspeaker arrays, but also from the walls, furniture and specific scenographic elements. The performance space becomes inhabited with sound, allowing for new compositional and performative strategies for music and sound design. Possible applications have been identified in electroacoustic music performance, set design for the performing arts, intermedia installations and in aural design for public spaces.

The present work fundamentally explores spatial sound perception, and is aimed at producing new spatial and timbral percepts to be used in an artistic context. As physical structures in architectural space are augmented to become sonic, complex sound localizations can be created in the 3D space, as well as novel effects of sound movement, space and presence. A topology of sound opens a fertile ground for creating sound- and space-related meanings and poetics.

3.1 Turning surfaces into sound sources

Structure-borne sound technology is a variation of the classic electromagnetic loudspeaker design. Instead of an air moved by the speaker cone, the audio-rate vibration is transferred into a solid object or surface by a vibrating mass i.e. a "shaker". As the surface shakes, it produces both airborne and structure-borne audio waves. The structure-borne audio technology thus offers two modes of sound perception: aural and tactile. In recent studies, these modes have been found to be complementary; the tactile audio perception enhances the overall perception of sound [1]. The two modes can also be used independently, or combined in various ways, offering a wide a creative space for future experimentation.

The main inhibition for the use of structure-borne sound in music is the issue of sound quality. An audio wave induced into a solid object is affected by the acoustic properties of the material as well as its physical dimensions. The material acts as a physical object filter according to its resonant modes. As a result the sound quality (both spectral perception and reproduction of dynamics) is heavily affected.

Past efforts to produce flatpanel loudspeakers suited for the needs of consumer-market audio applications have failed to address this problem. It has not been possible to build full-spectrum flatpanel speakers that would equal the cone speakers in spectral and dynamic reproduction. However, our point of view is entirely different from an optimized everyday-use multipurpose speaker design. We aim to build sets of numerous spatial sound sources capable of creating together the entire audible spectrum (and also infrabass audiotactile vibrations). Moreover, the acoustically active elements offer exciting possibilities for the creative use of sound in many different fields from purely "musical" contexts to interactive audio environments and consumer applications.

3.2 Enhancing sound quality

In order to overcome the sound-quality issue related to the use of structure-borne sound, we have investigated a method of inverse Impulse Response (IR) filtering. Our method relies on the measurement of the object's IR and the application of an inverse IR convolution filter to the audio signal prior to the structure-borne sound driver in the signal chain. Theoretically, the digital filter would cancel the object's resonant modes and produce a balanced IR.

A Max/MSP patch has been implemented using the Impulse Response measurement and correction tools made available by the Huddersfield University HISS Tools project [3]. The patch measures the object's IR and creates a smoothed inverse convolution filter. The figures 1 to 3 illustrate the process: the IR of a HiWave HIAX32C30-4/B transducer on a 60cm/60cm glass sheet is measured (fig. 1), a smoothed-out inverse IR is calculated (fig. 2) and applied to a convolution filter, producing a new balanced FR (fig. 3). The results show a significant enhancement of the Impulse Response curve, accredited perceptually by an improvement in audio quality.

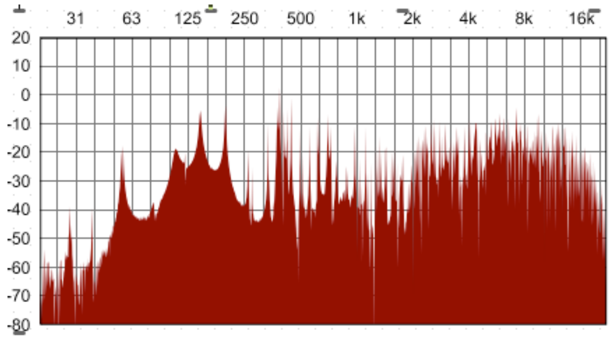

Figure 1. Frequency Response curve for a HiWave HIAX32C30-4/B transducer mounted on a 60cm x 60cm sheet of plain glass.

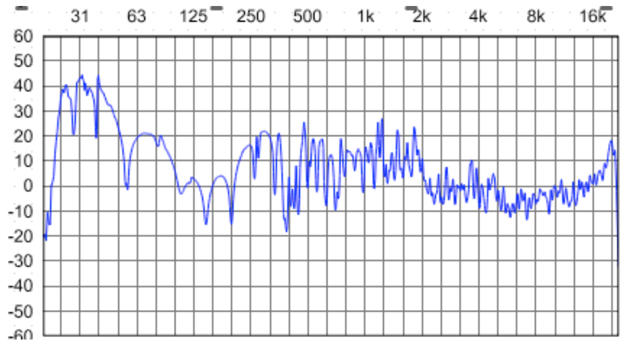

Figure 2. Inversion of the Frequency Response curve presented in Figure 1., with a slight smoothing applied (iraverage~ *smoothamount* 0.02).

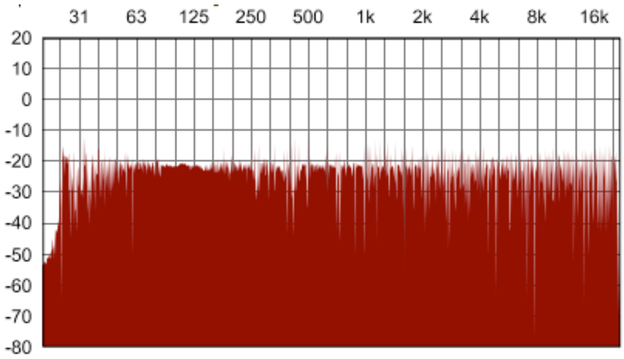

Figure 3. The final Frequency Response curve obtained by the application of the Figure 2 curve on the signal chain of Figure 1 via convolution filtering.

However, the rather flat curve of Fig 3. does not tell the whole truth: the whole process of IR measurement and inversion applies to only to the sole point in space where the measurement microphone is placed. Vibrating surfaces present a 360 degree sound radiation pattern, and significant changes in the Frequency Response can be observed according to the angle. A method for producing an optimal mean filtering taking into account the angular variations of the IR is currently the center of our research effort. Also, it should be noted that the dynamic properties of vibrating surfaces compared to cone-based loudspeakers are more limited. Sudden bursts of sound tend to overexcite the harmonic modes of the surface, producing distortion, whereas quiet sounds lack definition and presence. In our projects we tend to employ heavy dynamic compression to overcome this limitation.

3.3 Acoustically active surfaces in use

In our experience, the sonic quality of structure-borne sound presents the foremost challenge to its widespread use, but we have already used it in numerous projects in very effective and aesthetically convincing ways. Beyond the sound quality issues, one is faced with further issues related to the actual praxis of a complex multichannel 3D aural environment.

Interfacing with a multichannel, spatially unevenly distributed, timbrally non-standard instrument presents a major challenge. Due to their custom-made and site-specific nature, the cardinal sound spatialization algorithms such as Ambisonics or VBAP cannot be applied to the acoustically active surfaces of this project[1]. Rather, one needs an adaptable tool for sound distribution and movement in an irregular and non-normalized set of sound sources.

An existing tool providing such a possibility is the Distance-Based Amplitude Panning algorithm (DBAP) [7], which allows for sound spatialisation with irregular distribution of sound sources. Nevertheless, for the moment creating complex spatial polyphonies and sound movements remains laborious and out of reach for real-time control. Also, there is an urgent need for tools designed for the detailed composition of sound trajectories in a time/space continuum, such as the Holophon project which is unfortunately not available for public distribution for the moment[2]. We are currently actively researching an optimized framework for controlling sound in an irregular 3D space.

Another challenge presented by the use of vibrating surfaces is related to sound perception. For the moment, there is little data on the sonic characteristics of flatpanel speakers, such as radiation patterns (frequency as a function of angle), sound propagation (plane wave vs. spherical wave), and sonic percepts related to the size of the vibrating surface. For the moment, we are proceeding with a perceptual methodology of working with structure-borne sound-related projects, and gaining insight into the psychoacoustic effects enabled by the technology. We have been mainly working with sound localization, testing localization accuracy as a function of frequency, type of sound (percussive vs. drone) and surface size. The results point to the ability to create precisely located sonic events in a 3D space with percussive, high-frequency sounds driven into small objects. Large panels with lower frequencies and longer sounds are more difficult to situate in space, and very large surfaces can be used to intentionally blur the sense of the sound's origin.

4. ARTISTIC PROJECTS

In this section, two completed artistic projects using structure-borne sound in distinct ways are presented.

[1] Both Ambisonics and VBAP algorithms presuppose a circular array of loudspeakers

[2] See the GMEM website http://dvlpt.gmem.free.fr/ for details about the Holophon project

4.1 "Full Contact" - a spatially augmented instrument

"Full Contact" is a composition for solo cello and an aurally active space [6]. The piece is based on live-processing of the cello sound and on the spatial distribution of the processed sound. The piece is written for a cellist and an electronic musician performing live processing of the cello sound as well as spatialization. Twelve structure-borne sound drivers are distributed on the walls, windows and ceiling of the performance space. The sound of the cello expands into the room itself, and the space acts as a sonic prolongation of the cello as well as a counterpart of a musical dialog. It is an investigation that ultimately dreams of melding architecture, space and instruments into one sonic tool for expression.

The piece uses a mix of prewritten spatialization trajectories and gesture-based live control of the sound's localization. An Interface-Z 2-axis tilt sensor is used for the live spatialization, controlling a Max/MSP DBAP module.

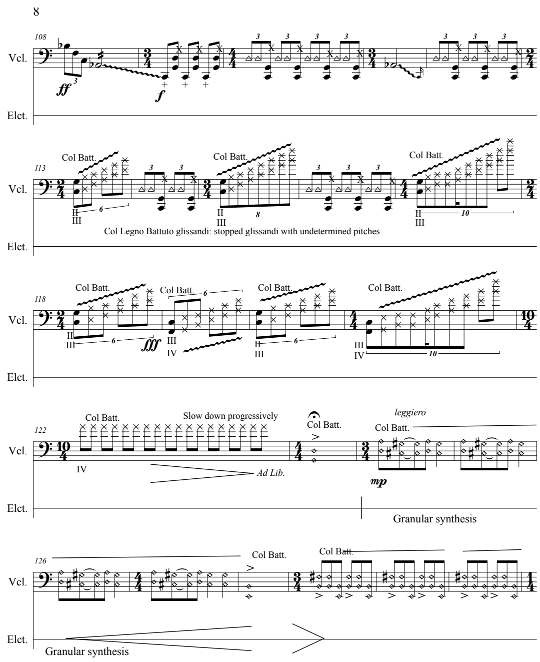

Figure 4. A page from the "Full Contact" score

Figure 5. Emilie Girard-Charest performing "Full Contact"

The overall perceptual characteristic of the piece's electronic soundscape is the "elusive" sound signature of the vibrating walls, windows and ceiling. Compared to loudspeaker arrays, the vibrating surfaces produce a more distant, spacious sonic percept. As one audience member put it: "loudspeakers sound like a person talking to you, the vibrating surfaces more like ambient soundscape".

4.2 "O V A L" - an interactive scenographic instrument

The audiovisual installation O V A L was created at the Hexagram, Centre for Research-Creation in Media Arts and Technologies, Montreal, Canada, by Lenka Novakova and the author. The installation is composed of 10 large sheets of glass are hanging in a dark room, forming a large (7m x 3m) oval, each equipped with a structure-borne sound driver making the glass sheets vibrate and emit sound. Video footage of the spectators themselves is projected on the glass sheets, creating a maze of self-portrait reflections and transparencies. The spectator is immersed into a chimerical space of sonic and visual illusions.

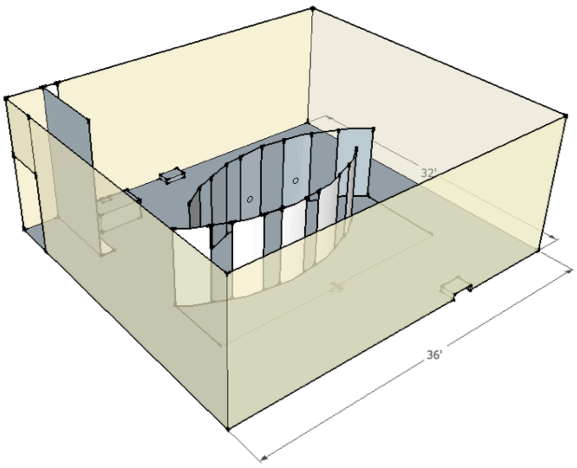

Figure 6. The floor plan of "O V A L"

The installation is interactive: a ceiling-mounted video camera tracks the position of the visitors in the installation space. The tracking data is used to discriminate between two stages of the piece's soundscape. The first one corresponds to the spectators being outside the oval of glass sheets, the second to having at least one person inside.

The audio composition of the piece is based on a spatial polyphony of aurally active glass sheets designed to warp one's perception of sound in space. The soundscape perceived being outside the oval is balanced to tease the visitor's threshold of sound perception. The sound is diffused at low decibel elvel, being "almost there" to be perceptually grasped. There is an evanescent, phantomatic quality to the sonic experience. When passing inside, the sonic oval suddenly becomes alive, surrounding the visitor with quickly moving powerful sonic events. The sensation is close to being in a real-life 3D space filled with moving sound sources.

Figure 7. Spectators immersed in the "O V A L" installation

5. ACKNOWLEDGMENTS

The author would like to thank the Emil Aaltonen Foundation (Finland) for its generous support towards the present research project.

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