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Velocity controlled sound field reproduction by non-uniformly spaced loudspeakers

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ABSTRACT

One approach to the reproduction of a sound field is to ensure the reproduction of the acoustic pressure on the surface bounding the volume within which reproduction is sought. However, this approach suffers from technical limitations when the loudspeakers used for the reproduction of the surface acoustic pressures are unevenly spaced. It is shown in this paper that sound field reproduction with a spatially non-uniform loudspeaker arrangement can be considerably improved by changing the physical quantity to be controlled on the bounding surface from pressure to particle velocity. One of the main advantages of the velocity control method is the simplicity with which the inverse problem can be regularized, irrespective of the direction of arrival of the sound to be reproduced. In addition, the velocity controlled sound field shows better reproduction of the time averaged intensity flow in the reproduction region which in turn appears to be closely linked with better human perception of sound localization. Furthermore, the proposed method results in smoother "panning functions" that describe the variation of the source outputs as a function of the angle of incidence of the sound to be reproduced. The performance of the velocity matching method has been evaluated by comparison to the conventional pressure matching method and through simulations with several non-uniform loudspeaker layouts. The simulated results were also verified with experiments and subjective tests.

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1. Introduction

Due to recently emerging interests in the production of virtual three-dimensional (3D) experiences, technologies for reproducing virtual 3D scenes have become one of the most important issues in the fields of entertainment, broadcasting and multi-media content. The rapid development of visual 3D technologies widely popularized in cinema and home theatre has led to the requirement for better aural 3D technologies in order to deliver immersive auditory experiences to consumers. A new generation of broadcasting service equipped with 3D spatial audio technology is fast becoming a real possibility.

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Binaural technology has proven to be an efficient and effective way for reproducing a 3D sound scene using relatively small numbers of loudspeakers with the clear limitation that a single binaural reproduction system cannot replicate the 3D sound image for multiple listeners over a wide area [1,2]. Several technical methods using multiple loudspeakers have been proposed for generating spatial audio experience for more people in a wider area. Wave Field Synthesis (WFS), which produces artificial wave fronts synthesized by multiple loudspeakers based on the Kirchhoff–Helmholtz integral, was developed in order to obtain the signal inputs to an array of multiple sound sources to reproduce the virtual sound field [3,4]. Ambisonics, which is another method used in multichannel audio (also referred to as a full-sphere surround sound technique), is based on a spherical harmonic analysis of the field to be reproduced, the spherical harmonics providing a means of describing a 3D sound field in terms of natural spatial basis functions [5,6]. The pressure matching technique using a least squares method [7,8] has also been applied to the problem of sound field reproduction. This method delivers the source inputs ensuring the reproduction of the target acoustic pressure on the surface that bounds the volume in which reproduction is desired. The approach has also been studied extensively in the context of the active control of sound and vibration.

These methods using multiple loudspeakers have been theoretically developed based on the assumption that the control area is surrounded by either continuously distributed sources, or at least uniformly distributed discrete sources in sufficient number to avoid the spatial aliasing determined by the high frequency limit to be controlled. Aside from the difficulties of positioning loudspeakers exactly, the ideal assumption of a uniform arrangement of multiple loudspeakers is clearly not met by the standard multi-channel formats such as 5.1, 7.1, 10.2 and 22.2 channel layouts proposed by international telecommunication union [9] although there have been several research studies that consider non-uniform standard layouts [10–13].

The objective of the research in this paper is to develop a control algorithm reproducing the target sound field in order to preserve the spatial perception of the virtual sources as a matter of the highest priority, regardless of loudspeaker arrangements. Dissimilar to other methods, even though the approach originates from the same assumption of continuous and discrete regular sources, the pressure matching technique using the least squares method provides a numerical approach to the solution of the “inverse problem” of determining the optimal source strengths and is not restricted to particular geometrical arrangements of sources or field points to be controlled. However, in non-uniform loudspeaker layouts, the pressure matching approach often yields results that require excessive source strength outputs. This in turn is detrimental to the perception of the location of the virtual source from which the field to be reproduced propagates. This is particularly the case when the sound field generated by the virtual source propagates from a direction from which there is either no, or a low density of loudspeakers able to render the reproduction. In order to overcome this limitation of the conventional pressure matching method, a modified method with the varying regularization parameter dependent on the direction of the field to be reproduced has been proposed. This is based on the pressure matching technique and has been applied in particular to the case of a 5 channel surround system [10]. However, it is found that this approach sacrifices the performance of the system when the direction of arrival of the field to be reproduced coincides with a sufficiently high density of sources to enable good reproduction without increased regularization. This approach also requires the magnitude of the regularization parameter to be dependent on each source arrangement, and this in turn sacrifices the system performance.

An alternative version of the least squares method for sound field reconstruction that overcomes the difficulties mentioned above has been proposed in this paper. The proposed method, the velocity matching technique, devotes the control effort to matching the particle velocities at the discrete control points on the bounding surface of the control region of the reproduced sound field with those of the target sound field. The proposed algorithm has been compared with the conventional pressure matching technique when the other conditions of control parameters applied in both methods are also comparable. Such control parameters include the regularization factor and the number and location of control points. Numerical simulations have been used to predict the performance of the new technique, which are also verified with experimental measurements. In addition, both pressure and velocity matching algorithms have been implemented in order to conduct subjective tests and assess the relative performance. These results confirm the superior capabilities of the velocity matching technique. The theory presented in this paper is based on that previously reported by the authors in a conference paper [14]. In this work, the original evaluation undertaken in the two-dimensional case [14] is extended to three dimensions with the verification of simulations, measurements and subjective tests with different designated control regions.

Section 2 defines the acoustical problem and introduces the theories of the pressure and velocity matching methods for the sound field reproduction. Simulation results including fields of pressure and time-averaged intensity, panning functions, and source input filters are analyzed in Section 3. Section 4 verifies the simulation results with the experimental data. Subjective test results are also presented in Section 5. Based on the results presented, discussions and conclusions follow.

2. Theory

The objective of sound field reproduction is to create a sound field with secondary sources (loudspeakers) that is as similar as possible to the original sound field observed at the locations of a number of control points. The input signals driving the multiple loudspeakers are obtained in order to reproduce the physical values matching the pre-observed

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