Violin Acoustic Radiation Synthesis:

A Source Model for Direct Sound Enhancement in Musical Acoustic Environments

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Reproducing sound in a listening space where all of the sound sources are correctly modeled in 3-dimensions and then projected via speaker to generate a desired listening experience, known as an immersive acoustic environment, has been an interest of acousticians, musicians and listeners alike for many years. Within the context of “musical telepresence,”—rendering musical sound and its associated spatial acoustic properties in a given room remotely via Internet-2 (commercially unavailable lines which have a larger bandwidth and less signal delay) for the purpose of real-time interactive musical performance—there are many factors that determine the nature of this musical experience. Of particular interest are the spatial properties of the radiated sound field emanating from a bowed violin whose far-field directivity patterns vary rapidly as a function of the fundamental frequency corresponding to the various notes played within the 1 – 5 kHz range.¹ We can identify an instrument “that sounds like a violin” without any spatial information. For example, spatial information may tell us where it is located in space or in which direction(s) the instrument prefers to send acoustic energy, as prescribed by the instrument’s physics. But it is spatial information which may determine how we experience sound in an immersive acoustic environment.

Scenario

With the goal of transmitting audio data (both the music and the spatial properties of the sound radiating from musical instruments) in real-time between two locations via Internet-2 (see Fig 1.2.1), all of the perceptually relevant information must be encoded properly. In order to circumvent the problems associated with processing, encoding, and transmitting multi-channel audio data via Internet-2, the directivity patterns are modeled using a multipole expansion (in the form of a cylindrical harmonic decomposition) as a function of frequency. The expansion coefficients are then stored in a dedicated processor at the speaker output destination which are indexed according to their multipole order and the fundamental frequencies of the notes played on the violin; coefficients can then be interpolated for notes whose fundamental frequencies lie between those whose multipole weights are calculated. With the proposed configuration in Fig. 1.2.1, the only data needed to be sent is the violin orientation (in this particular case the

front and back plates are considered to be parallel to the floor) and the sound radiated from the violin which is recorded by one microphone. In addition to the expansion coefficients, the location of the microphone relative to the violin in “Room 1” within the azimuthal plane is stored in the processor such that the amplitude of the recorded signal can be normalized accordingly. With this information, a horizontal sound imaging processor can calculate the correct driving signals for the speaker array (a circular array in this case) in the second room, such that the wave front (i.e. the directivity pattern) of the real violin can be reproduced in the form of a virtual source as predicted by Huygens’ principle for the outgoing waves.² A flowchart (Fig. 1.2.2) of the operations required to generate a synthesized version of the wave field is below.

Violin Directivity Measurements and Synthesis

Violin excitation and directivity measurements

A bowing machine was constructed by Wang for the purpose of exciting the violin over a range of pitches whose fundamental frequencies exist between 100 Hz and 5000 Hz. While exciting these pitches, an omnidirectional microphone circled around the violin on a boom at a radius of 2 m from its center (and thus in the far-field), and measured a 1.56 Hz narrow band spectrum in 5° increments from which the directivity patterns were generated.³ From these measurements, it is clear that the overall shape of the directivity patterns change drastically in the 1 – 5 kHz range when the note played only differs by a semitone. Furthermore, as fundamental playing frequency increases the directivity patterns become increasingly complex with many nulls and lobes varying as a function of angle around the violin. It should be noted that the radiation patterns vary minimally when the same note is played on different strings. This is a very important observation within the context of reproducing the radiation patterns over Internet-2: since the directivity patterns can be modeled independent of the string being played, the amount of data needed to be encoded and transferred is reduced by excluding string dependency as a potential parameter.

Theory and Methodology for Synthesis

A feasible approach for modeling the far-field directivity patterns of the violin is by way of a multipole expansion. This

mic position θ relative to violin and multipole expansion coefficients stored with WFS processing for speaker array

Multipole & Sound Field Processing

Outgoing waves from speaker array into listening area

Fig. 1.2.1: A representation of audio data transmission (both the music and the spatial properties of the sound radiating from musical instruments) in real-time between two locations via Internet-2.

scenario resembles that of an exterior domain problem,⁴ with the radiating violin body located at the center of the circle with a 2 m radius whose boundary is prescribed by the microphone array. Since the far-field microphone pressure measurements used here only correspond to the azimuthal plane, a cylindrical harmonic decomposition is used. This plane is of particular importance due to the fact that the listener's ears lay in this plane of direct sound propagation.

In order to extract the expansion coefficients for varying multipole order, the angular and radial dependence must be accounted for. Firstly, the angular dependence of the sound field must be removed using a circular Fourier transform:

$$P(k_\theta, \omega) = \frac{1}{2\pi} \int_0^{2\pi} p(\theta, \omega) e^{-jk_\theta \theta} d\theta \quad (1)$$

where p corresponds to the microphone pressure measurement at angular position θ and frequency ω , and P corresponds to the angular spectrum as a function of multipole order k_θ and frequency.⁵ In order to extract the multipole coefficients from P , we must remove the radial dependence pertaining to the outgoing waves:

$$M^{(2)}(k_\theta, \omega) = \frac{P(k_\theta, \omega)}{H_{k_\theta}^{(2)}(kR)} \quad (2)$$

where $M^{(2)}$ corresponds to the desired coefficients of varying multipole order, and $H_{k_\theta}^{(2)}$ corresponds to the Hankel function (Blackstock, 2000 for an explanation of Hankel functions) with k equaling the wave number and R equaling a radius of 2 meters (the superscript "2" refers to outgoing waves as opposed to incoming).⁶ The synthesis equation is as follows:

$$p(r, \theta, \omega) = \sum_{k_\theta} M^{(2)}(k_\theta, \omega) e^{jk_\theta \theta} H_{k_\theta}^{(2)}(kr) \quad (3)$$

Although the synthesized pressure values can be calculated at any distance r from the violin, the distance of $r = R = 2$

meters is the value used for synthesizing the directivity patterns here.

Matlab Synthesis, Results and Analysis

In the technical computing platform of Matlab, equation (1) was modified in the form of a Discrete Fourier Transform, given that the pressure measurements were spaced evenly in 5 degree increments along a circle and additional values were interpolated between measurements in order to generate a vector of 360 points. After extracting the multipole expansion coefficients using equation (2) the directivity patterns were synthesized up to 8th, 16th, and 32nd order multipole reconstruction for the purpose of comparison. Measured directivity patterns (Fig. 1.2.1 for violin orientation with respect to directivity pattern) along with their synthesized versions (red line = measured directivity and blue line = synthesized directivity) are shown in Figs. 2.3.1-2.3.3 for various notes whose fundamental frequency corresponds to the frequency listed in the caption:

From Fig. 2.3.1 it is evident that the spatial harmonics present in the measured pattern require only a few multipole orders for accurate reconstruction. However, Figures 2.3.2 and Figures 2.3.3 suggest that as the fundamental frequency of the note played increases we find the radiation patterns to be very complex, with many large nulls and lobes, thus requiring higher multipole orders for reconstruction. Figure 2.3.4 hints at a possible psychoacoustic consequence of rendering an acoustic field without accounting for high spatial harmonics (the listener's head is assumed to be located approximately 10 ft from the source and thus subtending an angle of approximately 6 degrees). Synthesizing a sound field with incorrect values of the acoustic pressure at each of the listener's ears will most likely affect the listener's ability to localize the sound (for explanations of "inter-aural level difference", i.e. the magnitude difference between the signals in each ear, see Blauert, 1997) and/or affect their perception of directional tone color.⁷

Fig. 2.3.1 The measured (thick line) and synthesized (thin line) directivity patterns at 1177 Hz, for a) 8th order b) 16th order c) 32nd order reconstruction.

Fig. 2.3.2 The measured (thick line) and synthesized (thin line) directivity patterns at 1733 Hz, for a) 8th order b) 16th order c) 32nd order reconstruction.

Fig. 2.3.3 The measured (thick line) and synthesized (thin line) directivity patterns at 2658 Hz, for a) 8th order b) 16th order c) 32nd order reconstruction.

Fig. 1.2.2: A simplified flowchart of the operations required to generate a synthesized version of the wave field.

Fig. 2.3.4 The magnitude values of the sound field in each ear for the synthesized pattern (circles) and measured pattern (squares) with the head subtending a 6 degree angle with respect to the source. (This is a magnified area of Fig 2.3.3.a)

In the case of a cylindrical harmonic decomposition is important to note that the number of loudspeakers required to reproduce a field of order k_0 equals $(2k_0 + 1)$, thus bearing a strong resemblance to High Order Ambisonics (HOA).⁸ In this instance however, the speaker array is pointing outward, thus providing the counterpart to HOA (Daniel, 2003 mentions that HOA assumes a “centered point view” and therefore prescribing the listening area to be inside the circular array in a “surround sound” type setup as opposed to the configuration proposed here) which can also be realized in the form of Wave Field Synthesis (WFS). Although originally thought of as two different methods of sound reproduction, we find that both HOA and WFS are in fact equivalent since they can both be derived from the Kirchoff-Helmholtz integral which describes the physical phenomena illustrated by Huygens’ principle.⁹

Conclusions and Further Research

Clearly, listening tests must be performed in order to gain a more comprehensive understanding of the perceptual effects associated with synthesizing a violin’s directivity pattern. A feasible test might be to systematically vary the multipole reconstruction order as a means of pinpointing the human tolerance for error. The results of the listening tests may be a function not only of angle but also of distance from the perceived source. Furthermore, the data used to model the directivity patterns only give us an understanding of these patterns at steady state, and not the change in directivity between notes, which may greatly affect our perception of the instrument’s spatial acoustic properties.

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Jacob (Cobi) Waxman '05, a Mechanical Engineering major and Electrical Engineering minor, presented this research at a special session on the “Integration of Synthesis Techniques and ‘Acoustic’ Music” at the 148th meeting of the Acoustical Society of America in San Diego in November 2004. As a musician, ethnomusicologist and scientist, Cobi will continue to explore the nature of musical sound and its relevance within the context of human life.