15th International Congress on Acoustics (ICA'95), Trondheim, Norway, June 26-30, 1995

Title of the paper:

Direction-Dependent Physical Modeling of Musical Instruments

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SUMMARY

Modeling the directional behavior of musical instruments has several attractions both in research and application of sound synthesis and room acoustics. It is known that due to the directional properties the tone quality of the instrument can vary remarkably as a function of direction. To our knowledge, directivity has not been incorporated before in model-based sound synthesis of musical instruments. We have designed a simulation system using physical models of plucked string instruments and wind instruments. Both real-time and non-real-time simulation environments include radiational characteristics of these musical instruments. As an example, we have measured and modeled the directional properties of the trumpet. Several methods for incorporating radiation directivity in sound synthesis models are introduced.

MODELING OF MUSICAL INSTRUMENTS USING DIGITAL WAVEGUIDES

The term *physical modeling* is used for simulation of acoustic-mechanical principles found in musical instruments. By means of physical models it is possible to simulate quite detailed effects of sound generation. *Digital waveguide modeling* employs digital filter representation of wave propagation [1]. This allows for real-time synthesis on modern signal processors. The physical modeling approach may be extended to include the directional characteristics of the musical instrument. This is of great interest, e.g., in room simulation and virtual reality environments, where the sound source (the physical model) can be moved in an acoustic space [2].

Model for Plucked String Instruments

The main elements of a plucked string instrument are as shown in Fig. 1. Each string is a distributed subsystem that starts to vibrate when excited (e.g., plucked). The strings are coupled to the body and may also interact with each other (sympathetic vibrations). The body or a soundboard is a complicated resonator that is needed for acoustic amplification, sound radiation, and coloring of the sound.

The general solution of the wave equation for a string is composed of two independent transversal waves traveling in opposite directions (see, e.g., [3]). At the string terminations the waves reflect back with inverted polarity and form standing waves. The losses in the system damp the

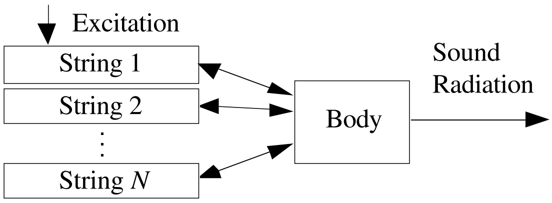

Fig. 1. *Model for a plucked string instrument.*

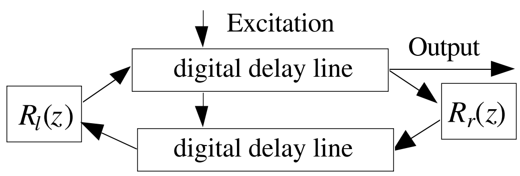

Fig. 2. *Digital waveguide string model.*

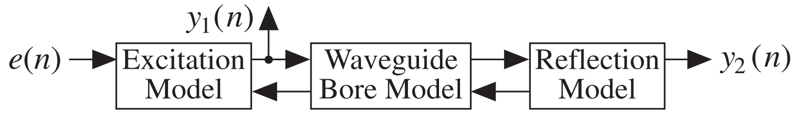

Fig. 3. *A waveguide model for a wind instrument.*

almost periodic vibration of the string. All losses and other linear non-idealities may be lumped to the termination and excitation or pickup points. The string itself is then described as an ideal lossless waveguide [1]. The system may be modeled using a pair of delay lines and a pair of termination filters as illustrated in Fig. 2.

A practical implementation is a digital waveguide with two digital filters which may often be combined into a single one—called the *loop filter*—and optional excitation and pickup filters. The lossless delay line in a waveguide filter can be implemented very efficiently by a circular buffer. The waveguide model for a plucked string instrument is a linear system consisting of the excitation, the string model, and a model for the body. Due to linearity, it is possible to change the order of the parts. In practice, we use a combined excitation that includes both the string excitation and the impulse response of the body [4] [5]. This method reduces the computational load by several orders of magnitude.

Model for Wind Instruments

A general waveguide model for wind instruments is illustrated in Fig. 3. It can be divided into linear and nonlinear parts. The linear part represents the bore of the instrument and the reflection from the open end of the bore or from the first open tone hole (in the case of woodwind instruments). The excitation model simulates the interaction of the pressure input and the wave that propagates in the bore. This part of the system includes a nonlinearity which is characteristic to each wind instrument family. The input signal $e(n)$ can be a white noise sequence or a DC signal. The model includes two outputs, $y_1(n)$ and $y_2(n)$. The former corresponds to the sound that radiates from the mouthpiece and the latter to that radiated from the end of the bore.

MODELING THE DIRECTIVITY OF MUSICAL INSTRUMENTS

Plucked string instruments exhibit complex sound radiation patterns due to various reasons. The resonant mode frequencies of the instrument body account for most of the sound radiation (see, e.g., [3]). Each mode frequency of the body has a directivity pattern such as monopole, dipole, quadrupole, or their combination. The sound radiated from the vibrating strings, however, is weak and can be neglected in the simulation.

In wind instruments, particularly in the flute, the radiation properties are dominated by outcoming sound from various parts of the instrument (the embouchure hole, the finger holes, the bell). Another noticeable factor in the modeling of directivity is masking and reflection caused by the player of the instrument. Masking plays an important role in virtual environments where the listener and sound sources are freely moving in a space.

Detailed computational modeling of directivity patterns of musical instrument sound radiation is out of the capacity of real-time DSP sound synthesis. It is therefore necessary to find simplified models that are efficient from the signal processing point of view and as good as possible from the perceptual point of view. We have considered three different strategies [2]: 1) directional filtering, 2) a set of elementary sources, and 3) a direction-dependent excitation.

Directional Filtering

A set of direction-dependent digital filters may be attached to the output of the physical model as illustrated in Fig. 4a. The output of each filter represents the response of the instrument to a particular direction. This method was studied for the acoustic guitar (see [2]) and the trumpet. The trumpet measurement was carried out by exciting the instrument by an impulse sound source and

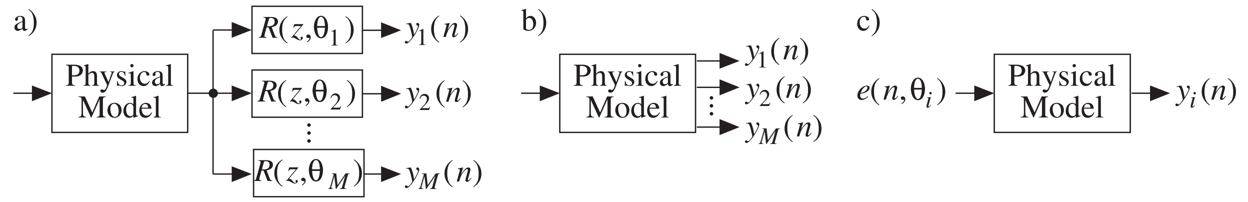

Fig. 4. *Three methods for incorporating directivity into physical models. a) Directional filtering, b) a set of elementary sources, and c) a direction-dependent excitation.*

by registering the reference response at 0° and the related response in various directions. The measured responses were fitted separately with first-order AR models: the transfer functions $H_{ref}(z)$ and $H_{dir}(z,\theta_i)$ were designed to match the frequency responses of the reference at 0° azimuth, and the directional response at azimuth angles θ_i (for i = 1, 2, 3, ..., M), respectively. Pole-zero directivity filters $R(z,\theta_i)$ were obtained by division of the transfer functions:

$$R(z,\theta_i) = H_{dir}(z,\theta_i) / H_{ref}(z), \quad i = 1,2,3,\ldots,M \tag{1}$$

Figure 5 depicts the modeling of direction-dependent radiation of the trumpet (in the horizontal plane) relative to the main axis radiation. Shown in the figure are magnitude responses of first-order IIR filters at azimuth angles 22.5°, 45°, 67.5°, 90°, 112.5°, 135°, 157.5° and 180°. The reference magnitude spectrum at 0° is assumed to be flat.

In Fig. 5, the lowpass characteristic of the filters is noticeably increased as the relative angle becomes greater. This result agrees well with the theory found in literature (e.g., [3], pp. 373–375). There are, however, some deviations from this trend. They can be caused by noise in the measurements or by nulls in the radiation pattern. Note that the model presented here includes the masking effect of the player. The reliability of the filter estimates may be increased by applying *auditory smoothing* to the responses before designing the filters. This is well motivated due to the critical band frequency resolution of the human hearing.

Set of Elementary Sources

The radiation pattern of a musical instrument may be approximated by a small number of elementary sources such as monopoles or dipoles. These sources are incorporated in the physical model and each of them produces an output signal $y_i(n)$ as illustrated in Fig. 4b. This approach is

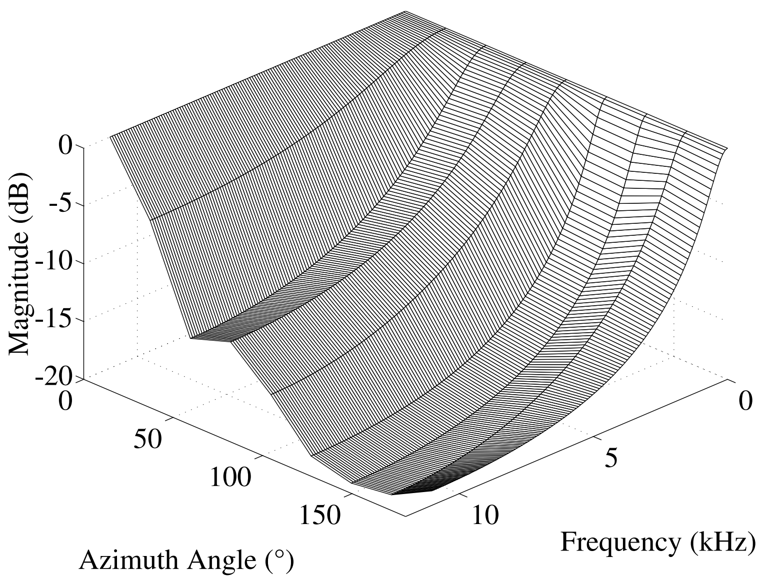

Fig. 5. *Magnitude responses of first-order digital filters that simulate the directional characteristics of the trumpet at different angles.*

particularly well suited to woodwind instruments, where there are inherently two point sources of sound radiation, the embouchure hole and the first open tone hole. We have applied this method to the modeling of the flute as shown in Fig. 3 (see [6]).

Direction-Dependent Excitation

The directivity filtering may be included in the combined excitation as shown in Fig 4c. The same approach has been suggested by Smith [7] for inclusion of the early room response in a physical model. This method is useful when it is desired to synthesize the sound of an instrument at one direction only. However, this approach is inefficient when sound radiation to several directions is simulated. This is because each modeled direction requires an additional physical model. The considerations above as well as our experiments have shown that the directional filtering technique is normally the most efficient one. A first or second-order filter approximation is often a satisfactory solution in a real-time implementation.

Application to Virtual Acoustic Reality

The methods presented above are applicable to virtual acoustic environments, where physical models are used as sound sources. Modern room simulation and auralization systems are capable of dynamic source and listener position changes. Moving and rotating sources can be modeled by changing the filter parameters of the paths in a proper way (e.g., the Leslie effect of a rotating loudspeaker can be simulated). Methods for designing virtual acoustic environments are discussed in a companion paper [8].

CONCLUSIONS

In this paper we have presented methods for incorporating directional characteristics of musical instrument sound radiation to model-based sound synthesis. This has been achieved by measuring and analyzing acoustical instruments, and using DSP techniques. We found three different methods for retaining the directional radiation information during spatial sound synthesis: 1) directional filtering, 2) a set of elementary sources, and 3) a direction-dependent excitation. The results are useful, e.g., in the design and implementation of room simulation and virtual reality environments for physical models of musical instruments [8].

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