Recent Developments in Woodwind Instrument Physical Modeling

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This paper briefly reviews several recent developments in physical modeling of woodwind musical instruments. In particular, issues with regard to real-time synthesis of toneholes, the single-reed excitation mechanism, and conical air columns are discussed. A programming environment appropriate for real-time physical modeling synthesis is presented, as well as issues of control demanded by recent increases in model complexity. Psychoacoustic studies have begun to exploit the parametric flexibility of physical models to study complex auditory perception. One recent study addressing auditory learning and memory is described.

MODEL DEVELOPMENTS

This paper addresses time-domain models of woodwind musical instruments which can be used for real-time sound synthesis. In particular, digital waveguide techniques are employed to efficiently model wave propagation within the instrument air column.

Toneholes

Keefe (1981) presents a rigorous study of woodwind instrument tonehole acoustics and provides frequency-domain results calibrated in part through experimental measurements. Scavone (1997) and Smith and Scavone (1997) translate these results for efficient implementation in time-domain digital waveguide models. Keefe's approach provides two distinct models for the open and closed tonehole states. Scavone and Cook (1998) present a single tonehole model capable of dynamic state changes from fully open through fully closed which shows good agreement with the Keefe model. An alternate approach using wave digital filter techniques resolves a limitation on the minimum tonehole height inherent in the earlier model (van Walstijn and Scavone, 2000).

The Single-Reed Excitation

The reed mechanism of woodwind instruments is traditionally modeled as a second-order oscillator and a nonlinear volume flow characteristic. For clarinet-like systems, the reed behavior is dominated by stiffness. Under this assumption, it is common to neglect the reed mass to produce a simplified, memory-less model. Recent work has concentrated on efficient numerical techniques to solve the simultaneous reed/bore and nonlinear flow equations (Borin *et al.*, 2000; Avanzini, 2000).

Conical Waveguide Issues

Ayers *et al.* (1985) provides a detailed study of conical air column acoustics. While a complete cone can support harmonically-aligned partials, the resonances of a truncated and stopped conic frustrum are "warped" in proportion to the length of the truncated section. When an appropriately designed digital waveguide structure is used to model a truncated cone, the resulting inharmonicity of the air column can complicate the production of a stable "regime of oscillation". Several approaches have been investigated to yield stable "conical" air column behavior.

REAL-TIME SYNTHESIS

Digital waveguide techniques have been used to implement real-time woodwind instrument synthesis models on computer host processors since the mid-1990s (and on special purpose digital signal processing hardware since the late-1980s). Continuing advances in desktop computing power are allowing ever greater model complexity. The digital waveguide technique computes the air column reflection function in real time (as opposed to the use of a fixed reflection function stored in memory). This allows smooth modification of the air column parameters, such as the opening and closing of toneholes or muting of a brass instrument bell. A cross-platform synthesis environment has been written in the C++ programming language to aid in the prototyping and testing of the models discussed above.

The Synthesis ToolKit (STK) in C++

The Synthesis ToolKit (Cook and Scavone, 1999) provides an object-oriented, C++ framework for the programming of audio signal processing algorithms. Specific design goals have included cross-platform functionality, ease of use, real-time synthesis and control, and user extensibility. STK provides "unit generator" classes for a variety of filter and synthesis algorithms, as well as input/output functionality for internet streaming, realtime computer audio hardware, and .wav, .snd, .aif, and .mat (Matlab MAT-file) formatted files. The ToolKit currently runs with realtime support (audio and MIDI) on Linux, SGI (Irix), and Windows computer platforms. Generic, non-realtime support has been tested under NeXTStep, but should work with any standard C++ compiler.

Realtime Control

One advantage of physical models is parametric control of instrument features. The complex parameter space which often results, however, can prove to be nearly as difficult to master as that of real musical instruments. This has stimulated research and development in human-computer interface technologies, a rapidly growing field of study. While commercially available MIDI wind controllers provide a more appropriate interface to woodwind instrument models, these devices remain limited in their functionality, in part because of limitations in commercial synthesizers. Extensions have been proposed and implemented to address the control of dynamic tonehole models as discussed above (Scavone and Cook, 1998).

PSYCHOACOUSTIC STUDIES

The parametric flexibility of physical models offers new opportunities for the study of complex auditory perception. Recent experiments were conducted to test listeners' ability to attend selectively to the properties of a physical model comprising collisions between multiple independent sound-producing objects (Lakatos *et al.*, 2000). Percussion instrument sounds were synthesized using physically informed sonic modeling (PhISM) techniques (Cook, 1997). Results showed that listeners are able to correlate some common physical properties across different target and cue object types.

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