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# Discrete-Time Modeling of Acoustic Tubes Using Fractional Delay Filters

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Report 37
December 1995

Dissertation for the degree of Doctor of Technology to be presented with due permission for public examination and debate in Auditorium S4 at the Helsinki University of Technology (Espoo, Finland) on the 18th of December, 1995, at 12 noon.

ISBN 951–22–2880–7
ISSN 0356–083X

TKK Offset 1995

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## Abstract

This work deals with digital waveguide modeling of acoustic tubes, such as bores of musical woodwind instruments or the human vocal tract. The acoustic tube systems considered in this work are those consisting of a straight cylindrical or conical tube section or of a concatenation of several cylindrical or conical tube sections. Also, the junction of three tube sections is studied. Of special interest for our application are junctions where a side branch is connected to a cylindrical or conical tube since these are needed in the simulation of woodwind instrument bores.

Basic waveguide models are generalized by employing the concept of fractional delay, which means a fraction of the unit sample interval. A fractional delay is implemented using bandlimited interpolation. A novel discrete-time signal processing technique, deinterpolation, is defined. Applying fractional delay filtering techniques, a spatially discretized waveguide model is turned into a spatially continuous one. This implies that the length of the digital waveguide can be adjusted as accurately as required, and a change of the impedance of a waveguide may occur at any desired point between sampling points. This kind of a system is called a fractional delay waveguide filter (FDWF). It is a discrete-time structure but yet a spatially continuous model for a physical system.

The basic principles of digital waveguide modeling are first reviewed. Modeling techniques for cylindrical and conical acoustic tubes are described, as well as methods to simulate junctions of two or more of these sections. Different design methods for both FIR and IIR (allpass) fractional delay filters are reviewed and the theoretical foundations of FDWFs are studied. Fractional delay extensions for acoustic tube model structures are discussed and approximation errors due to fractional delay filters are analyzed. In addition, a new technique for eliminating transients due to time-varying filter coefficients in recursive filters is introduced.

The models described in this work are directly applicable to physical modeling and model-based sound synthesis of speech and wind instruments.

**Keywords:** digital signal processing, digital filter design, fractional delay, interpolation, acoustic tube, conical acoustic tube, vocal tract modeling, physical modeling, waveguide synthesis, time-varying digital filters