Physical modeling of the singing voice

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The singing voice is one of the most versatile musical instruments. In spite of the fact that singing can be learned by almost everybody, the physics of the singing voice are quite complex. This work presents a time-domain model for synthesis of sung vowels. The symmetric vocal fold model is based upon Titze's 16-mass model [1] but takes into account jet generation and vortex shedding. Two vocal tract models have been implemented: a reflection-type line analog and a fast multiconvolution algorithm. The combined vocal fold and vocal tract model includes aspiration noise generation and can be adjusted during phonation for vibrato and transitions, e.g. between voice registers. The results are compared to measured mouth impedances and pressure transfer functions that were obtained using novel measurement techniques. The model can be used as a tool for visual and aural verification of algorithms for voice or speech synthesis or as a didactical tool for therapeutic professionals as well as for interested patients.

INTRODUCTION

Human voice production is the result of complex functional interaction of the respiratory system, glottal vibration and vocal tract dynamics including specific characterization of sound radiation at the mouth. Many models exist to describe the phonatory components and their interaction. In this article, a tool written in MATLAB is presented that encloses time-domain models for the most important voice functions. Parameters being relevant for phonation can be interactively modified from a graphical user interface (GUI) and the degree of coupling can be varied. A comparison of simulations with measured results (frequency responses or impedance curves) can be done with the help of data acquisition modules that are integrated into the GUI showing the interaction of phonatory physiology and voice acoustics.

MODELS

Vocal Folds

The vocal fold model is a symmetric multiple mass model based upon the 16-mass model of Titze [1].

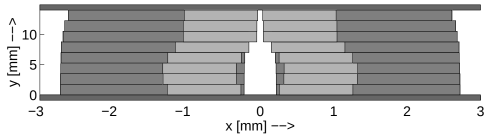

FIGURE 1. Shape of fold movement, top view.

A visualization of a higher order fold movement caused by a locally increased mass is shown in Fig. 1. The dark gray segments represent the vocalis muscle and the light gray segments indicate the mucosa membrane. Modifications of the model include jet generation and noise generation by vortex shedding [2]. Glottal parameters like mass distribution of mucosa and vocalis muscle or tissue stiffnesses can be changed during calculation.

Vocal Tract

The vocal tract is modeled with either a reflection-type analog or a multiconvolution algorithm [3] using area function data. The area function can be modified interactively and allows transitions between vowels. An example for an area function is given in Fig. 2.

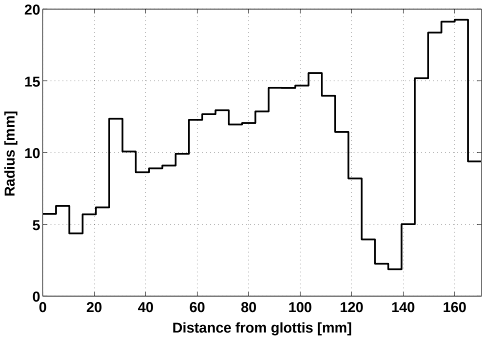

FIGURE 2. Area function of a vocal tract configured for an overtone at 1540 Hz.

Radiation

Radiation is modeled using a finite impulse response digital filter that represents an arbitrary complex radiation impedance. It is possible to use either an analytic impedance like that of a baffled piston or measured values [4].

Control

The modules can be combined in several ways. For modeling of a linear system without feedback vocal fold and vocal tract calculations are done seperately and results are convoluted. For an interactive calculation the modules are coupled by pressure and impedance at the junctions. Parameter changes during calculation can be executed using either the GUI or a script program.

APPLICATIONS

Apart from the visualization and auralization facilities that are basic features of a time-domain model, accurate physical voice models can be used to simulate pathologic voice functioning. As an example, fold nodules can be modeled by locally increased mass of e.g. the vocalis muscle (see Figure 1). Moreover, they can help to understand exceptional singing styles like overtone singing.

An example: overtone singing

One application for physical modeling of the singing voice is a comparison of simulations with measured signals of an overtone singer singing Khöömij style. By sonographic and impedance measurements at the mouth and comparison to MRI data [5] it was found that the strong amplification of the overtone is a result of a double resonance [6]. One resonator is a longitudinal resonator between glottis and a constriction of the tongue, as presented in Fig. 2. The other resonator is a Helmholtz resonator being formed by the cavity between the constriction and the lips.

Figure 3 represents a spectrum of a biphonic sound[1] that has been recorded in a distance of 10 cm in front of the mouth. The fundamental is near $c^{\#}$ (140 Hz) and the overtone is g (1540 Hz), 3.5 octaves above the fundamental.

Figure 4 represents the simulated spectrum using modal register at a higher frequency and the multiconvolution algorithm with modified area function data from Adachi [5]. No attempt has been made to add noise or vibrato to the synthesized signal. Perceptually, the overtone could be clearly identified.

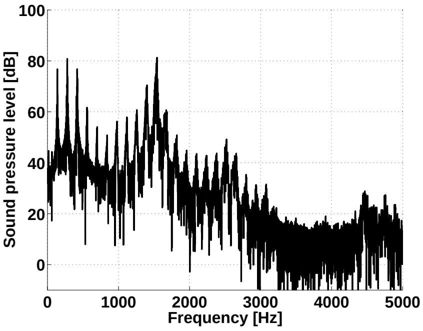

FIGURE 3. Spectrum of a Khöömij sound produced by an overtone singer.

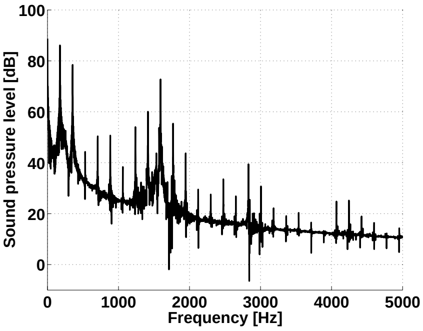

FIGURE 4. Spectrum of a simulated Khöömij sound.

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[1] Recordings and spectrograms of different overtone styles can be found on the Internet at http://www.akustik.rwth-aachen.de/~malte/overtone.