Synthesis of breathy, normal, and pressed phonation using a two-mass model with a triangular glottis

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Abstract

Two-mass models of the vocal folds and their variants are valuable tools for voice synthesis and analysis, but are not able to produce breathy voice qualities. The produced voice qualities usually lie between normal and pressed. The reason for this property is that the mass elements are aligned parallel to the dorso-ventral axis. Thereby, the glottis always closes simultaneously along the entire length of the vocal folds. For breathy phonation, however, the closure happens rather gradual. This article introduces a modified two-mass model with mass elements that are inclined with respect to the dorso-ventral axis as a function of the degree of abduction. In this way, the closing phase of the glottis becomes progressively more gradual when the degree of abduction is increased. This model is able to produce the continuum of voice qualities from pressed over normal to breathy voices.

Index Terms: Vocal fold model, triangular glottis, voice quality

1. Introduction

Low-dimensional lumped-mass models of the vocal folds (e.g. [1, 2, 3]) are able to reproduce many properties of phonation, like self-sustained oscillations over a wide frequency range, different voice registers, and the phase differences between the upper and lower margins of the vocal folds. However, the simulation of breathy voice qualities was recognized as problematic with this class of models [4]. During breathy phonation, the vocal folds open and close more gradually than during modal phonation, however, the closure happens rather gradual. This article introduces a modified two-mass model with mass elements that are inclined with respect to the dorso-ventral axis as a function of the degree of abduction. In this way, the closing phase of the glottis becomes progressively more gradual when the degree of abduction is increased. This model is able to produce the continuum of voice qualities from pressed over normal to breathy voices.

2. Proposed two-mass model

2.1. Mechanics

Each vocal fold is represented by two mass elements that are connected to a fixed reference frame with springs $k_i$ and dampers $r_i$ ($i = 1, 2$) and coupled to each other with an additional spring $k_o$ (Fig. 1). We assume symmetry with respect to the midsagittal plane. In the pre-phonatory rest position, the displacements of the masses at the posterior end (at $z = 0$) are given by $x_{rest1}(0)$ and $x_{rest2}(0)$. When $x_{rest1}(0) \geq 0$, the displacements decrease linearly towards zero at the anterior commissure, so that the pre-phonatory shape of the glottis becomes triangular, i.e. $x_{rest}(z) = x_{rest1}(0)(1 - z/l)$ for $z > 0$, where $l$ is the length of the vocal folds. In the following, we use the shorthand notation $x_{rest} \equiv x_{rest1}$. Let $x_1$ and $x_2$ denote the time-varying horizontal displacements of the masses. Then, the half-width of the glottis along the dorso-ventral $z$-axis is given by $w(z) = \max\{0, x_{rest1}(1 - z/l) + x_1\}$ and the glottal areas between the lower and upper mass pairs are 

$A_1 = 2 \int_{z=0}^{z_{rest1}} w_1(z) dz$. Figure 1b and c) illustrate the shape of the glottis for different time-varying displacements but the same pre-phonatory rest displacements. When the rest displacement $x_{rest1} < 0$, i.e. when the vocal folds are strongly adducted, then 

$A_1 = \max\{0, 2\{x_{rest1} + x_1\}\}$, as in the classical TMM.

The equations of motion for each of the masses are

$$F_1 = m_1 x_1 + r_1 x_1 + k_1 x_1 + k_{col1} \alpha_1 (x_1 + x_{rest1}) + k_c (x_1 - x_2) \tag{1}$$

$$F_2 = m_2 x_2 + r_2 x_2 + k_2 x_2 + k_{col2} \alpha_2 (x_2 + x_{rest2}) + k_c (x_2 - x_1), \tag{2}$$

where $\alpha_i$ are the time-varying relative portions of the length $l$, where the left and right masses are in contact ($0 \leq \alpha_i \leq 1$, cf. Fig. 1b and c), and $x_{rest1}$ and $x_{rest2}$ are the rest displacements in the middle of these portions along the $z$-axis (at $z^*_1$ and $z^*_2$ in Fig. 1c). $k_{col1}$ and $k_{col2}$ are the spring constants of the additional springs that repel the left and right vocal folds during
collision. For simplicity, we use linear springs in our model, because the nonlinear spring characteristics of the classical model have a relatively little effect on the oscillations according to [10, p. 916]. The external forces are

\[ F_1 = P_{sub} d_{in1} + 0.25 \cdot (P_{sub} + P_1) d_{in1} \]
\[ F_2 = P_{sub} d_{in2} + 0.25 \cdot (P_2 + P_{supra}) d_{out1}, \]

where \( d_{in1} \) and \( d_{in2} \) are the lengths of the open partitions between the upper and lower mass pairs (0 \( \leq \) \( d_{in1} \) \( \leq \) 1), i.e. the partitions where the masses are not in contact. \( d_1, d_2, d_{in}, \) and \( d_{out} \) are explained in Tab. 1. \( P_{sub}, P_1, P_2, \) and \( P_{supra} \) denote the subglottal pressure, the pressures between the lower and upper masses, and the supraglottal pressure, respectively.

The second terms on the right-hand side of Eqs. 3 and 4 are the hinge moments on the lower and upper masses due to the mean pressures in the inlet and outlet regions. The classical TMM neglects these forces, but we consider it as more realistic to include them like e.g. [2].

Table 1: Mechanical parameters of the two-mass model. Refer to the main text for \( q, \alpha_1, \) and \( \alpha_2. \)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vocal fold length</td>
<td>( l )</td>
<td>1.3 ( \cdot \sqrt{q} )</td>
<td>cm</td>
</tr>
<tr>
<td>Lower mass thickness</td>
<td>( d_1 )</td>
<td>0.25/( \sqrt{q} )</td>
<td>cm</td>
</tr>
<tr>
<td>Upper mass thickness</td>
<td>( d_2 )</td>
<td>0.05/( \sqrt{q} )</td>
<td>cm</td>
</tr>
<tr>
<td>Lower mass</td>
<td>( m_1 )</td>
<td>0.125/q</td>
<td>g</td>
</tr>
<tr>
<td>Upper mass</td>
<td>( m_2 )</td>
<td>0.025/q</td>
<td>g</td>
</tr>
<tr>
<td>Lower spring constant</td>
<td>( k_1 )</td>
<td>80 ( \cdot q )</td>
<td>N/m</td>
</tr>
<tr>
<td>Upper spring constant</td>
<td>( k_2 )</td>
<td>8 ( \cdot q )</td>
<td>N/m</td>
</tr>
<tr>
<td>Coupling spring cons.</td>
<td>( k_{cou} )</td>
<td>25 ( \cdot q^2 )</td>
<td>N/m</td>
</tr>
<tr>
<td>Lower collision spring cons.</td>
<td>( k_{col} )</td>
<td>240 ( \cdot q )</td>
<td>N/m</td>
</tr>
<tr>
<td>Upper collision spring cons.</td>
<td>( k_{col} )</td>
<td>24 ( \cdot q )</td>
<td>N/m</td>
</tr>
<tr>
<td>Lower damping ratio</td>
<td>( \zeta_1 )</td>
<td>0.1 + ( \alpha_1 )</td>
<td>-</td>
</tr>
<tr>
<td>Upper damping ratio</td>
<td>( \zeta_2 )</td>
<td>0.6 + ( \alpha_2 )</td>
<td>-</td>
</tr>
<tr>
<td>Inlet region length</td>
<td>( d_{in} )</td>
<td>4.0</td>
<td>mm</td>
</tr>
<tr>
<td>Outlet region length</td>
<td>( d_{out} )</td>
<td>1.0</td>
<td>mm</td>
</tr>
</tbody>
</table>

Figure 1: (a) Pseudo-3D view of the model. (b,c) Top view of the model for a wide open and a partly closed glottis during an oscillation cycle with the same pre-phonatory rest displacements. The dotted lines show the vocal fold margins in the rest position, i.e. \( x_{rest1,2}(z) \).

For the digital simulations, Eqs. 1 and 2 were approximated by a finite difference scheme analog to [1] to obtain \( x_1 \) and \( x_2 \) at a rate of 44100 Hz.

2.2. Aerodynamic-acoustic model

The model of the vocal folds was implemented in the framework of the articulatory speech synthesizer VocalTractLab (www.vocaltractlab.de). The synthesizer approximates the trachea, the glottis, and the vocal tract as a series of abutting cylindrical tube sections with variable lengths. Two tube sections with the time-varying lengths \( d_1 \) and \( d_2 \) and areas \( A_1 \) and \( A_2 \) represent the glottis. The aerodynamic-acoustic simulation is based on a transmission-line representation of the tube system [11, 12]. The simulation assumes a Bernoulli-type flow from the subglottal region to the glottis section with the minimum diameter and flow detachment without dynamic pressure recovery at the exit of this section. This differs from the original assumptions by Ishizaka and Flanagan [1] and conforms with more recent findings about the pressure distribution in the glottis [13]. A dipole noise source injects white noise with an amplitude proportional to the squared Reynolds number of the glottal flow right above the glottis to simulate aspiration noise.

3. Simulation experiments

At the physiological level, pressed, normal, and breathy voice qualities mainly differ in terms of the degree of glottal abduction (and hence glottal rest area), which is greatest for breathy voice, least for pressed voice, and somewhere in between for normal voice. We examined for both the classical TMM and the new TMM to what extent these models can reproduce this relationship between voice qualities and degrees of abduction by synthesizing the vowel /a/. The classical TMM was implemented along with the new model in VocalTractLab. With respect to the aerodynamic-acoustic part, it was simulated analogous to the new model.

Firstly, we determined for each model the range of rest displacements, for which a self-sustained oscillation was possible at a subglottal pressure of 1 kPa and \( F_0 = 120 \) Hz. These ranges were then sub-divided in 10 or 11 equally spaced values. For the classical TMM, the displacement \( x_{rest1,2} \) was varied from -0.15 to 0.35 mm in steps of 0.05 mm. For the new
model, $x_{\text{rest}1,2}$ was varied between -0.2 and 0.7 mm in steps of 0.1 mm. For all these degrees of abduction ($x_{\text{rest}1}$ and $x_{\text{rest}2}$ were set equal in all cases) we synthesized the vowel /a/ using a subglottal pressure of 1 kPa. The tension factor $q$ was adjusted for $F_0 = 120$ Hz.

There are several acoustic measures known to correlate with the degree of abduction and the perceived voice quality [15]. Some of these measures were selected to assess the ability of the two models to simulate the continuum of voice qualities. With regard to the acoustic performance of the models we calculated the mean open quotient $OQ$, speed quotient $SQ$, and closing quotient $CQ$ of the simulated glottal flow waveforms of five periods in the middle of each item, the harmonic richness factor $HBF$, and $H^* = H - H_2$. $OQ$ is defined as pulse width divided by fundamental period, $SQ$ as rise time divided by fall time, and $CQ$ as fall time divided by fundamental period [16]. $HBF$ was calculated according to [16] and $H^* = H_2$ according to [5]. Furthermore, the models were evaluated at the kinematic level using the $OQ$, $SQ$, and $CQ$ of the projected glottal area waveform, i.e. $\min\{A_1(t), A_2(t)\}$. Finally, the models were evaluated perceptually. Ten listeners were asked to rate the voice quality of each item on a discrete scale from 1 (very pressed) to 5 (very breathy). All vowel stimuli of both models were presented over earphones to one subject after the other in a different randomized order for each subject. Each stimulus could be repeated once on request. The subjects were not trained before the task but asked to judge the stimuli according to their associations with the according voice qualities.

### 4. Results and discussion

The results are shown in Figures 2, 3, and 4. For both the classical and the new model, all kinematic and acoustic data change into the expected direction when the degree of abduction is increased. However, the amount of change varies for most parameters between the two models. The arrows at the left and the right side of the upper two panels in Fig. 4 show exemplarily the values measured for male subject 1 in [14] for pressed and breathy phonation, respectively. They indicate that the new model generates glottal area and flow waveforms for breathy phonation that come closer to these real values than the classi-
Glottal flow spectrum parameters

Figure 4: Glottal area and flow waveform time parameters (open quotient \(OQ\), closing quotient \(CQ\), speed quotient \(SQ\)) and glottal flow spectrum parameters (\(H1^* - H2^*\) and \(HRF\)) as a function of the relative degree of abduction for the classical model (dashed lines) and the new model (solid lines). The arrows on the left and right side of the graphs indicate the measured values for \(OQ\), \(SQ\), and \(CQ\) of subject 1 in [14] for pressed and breathy voice, respectively.

5. References


