Influence of vocal fold stiffness on phonation characteristics at onset in a body-cover vocal fold model

Zhaoyan Zhang, Juergen Neubauer

School of Medicine, University of California
Los Angeles, CA, USA

July 3, 2008
Acoustics 08, Paris, France

Acknowledgment:
Research supported by NIH R01-DC009229
Motivation/Objective

• An ultimate goal of voice production research is to predict the acoustic consequences of laryngeal adjustments and pathological variations.
  – How would such adjustments and variations affect biomechanical properties of the vocal folds?
  – How would these changes in biomechanical properties of the vocal folds affect vocal fold vibration and voice quality
Previous Work

Not a complete list:

• Titze, Jiang, and Drucker (1988) – pitch control mechanisms
  – Pitch control mechanism through contraction of the cricothyroid (CT) and thyroarytenoid (TA) muscles
  – Contraction of CT increasing phonation frequency
  – Contraction of TA may increase or decrease phonation frequency

• Story and Titze (1995) – vocal fold vibration pattern under different conditions
  – Increasing body stiffness leads to lower amplitude for the body layer motion and higher pitches
  – Primary mechanism for energy transfer

• Tokuda, Horacek, Svec, and Herzel (2007) – mechanisms of register change
  – Variation of vocal fold stiffness may cause abrupt transition in dominance between different eigenmodes of the vocal folds, leading to chest-falsetto-like register change.

Limitations of Lumped-mass models
  – May have oversimplified the underlying physics
  – Difficult to relate the model parameters to realistic parameters of the vocal system
In This Study

• Continuum aeroelastic phonation model, which gives a better representation of:
  – Vocal fold structure and geometry
  – Vocal fold mechanics
  – Fluid-structure interaction

• Investigate how vocal fold biomechanics affect phonation onset
  – Phonation threshold pressure
  – Phonation onset frequency
  – Vocal fold vibration pattern at onset
  – Sound production efficiency.
Body-cover Vocal Fold Model

Plane-strain isotropic for each layer

Control Parameters:
- Thickness: $T$
- Divergent angle: $\alpha$
- Depths: $D_b$ and $D_c$
- Young’s moduli: $E_b$ and $E_c$
- Minimum glottal half width at rest: $g_0$
- Glottal entrance angles
- Glottal exit angles

$r = T/10$
$t = T/15$
$\alpha_{1b} = 83^\circ$
$\alpha_{1c} = 85^\circ$
$\alpha_{2b} = 50^\circ$
$\alpha_{2c} = 52^\circ$
Glottal Flow

- One-dimensional potential flow up to the point of flow separation;
- Flow separation was assumed to occur at a point as determined by a separation constant $H_s/H_{min} = 1.2$
  - At a point downstream of the minimum glottal constriction with a glottal width equal to 1.2 times the minimum glottal width.
- Zero pressure recovery for the flow downstream the flow separation point, and no vocal tract
  - zero pressure fluctuation boundary condition at the vocal fold outlet;
- Constant flow rate at the vocal fold inlet
  - zero velocity fluctuation.
Simulation Procedure

- Two-step procedure:
  - 1. Solve for steady state for a given flow rate at glottal entrance
  - 2. Solve the eigenvalue problem, checking for phonation onset. If no onset, increase flow rate, and repeat steps 1 and 2. If onset, stop.
Simulation Procedure – Two Steps

• Step 1: Solve for static deformation of the vocal fold for a given flow rate at glottal entrance

Vocal fold geometry:
Red: deformed
Blue: at rest
Simulation Procedure – Two Steps

- Step 2: linear stability analysis (Zhang et al., 2007)
  - Linearize system equations around the mean deformed state
  - Control equations derived from Langrange’s equations
  - Solve the eigenvalue problem, checking for phonation onset.

\[(M - Q_2)\ddot{q} + (C - Q_1)\dot{q} + (K - Q_0)q = 0\]

Structure
Mass: \(M\); Stiffness: \(K\)
Damping: \(C = \sigma \omega M\)

Flow: \(Q = Q_2 \ddot{q} + Q_1 \dot{q} + Q_0 q\)

- Onset occurs when the growth rate of one of the eigenvalues first becomes positive.
- If no onset, increase flow rate, and repeat steps 1 and 2, until onset.
Non-dimensional Formulation

- Length: vocal fold thickness $T$
- Density: vocal fold density $\rho$
- Pressure: Young’s modulus of the vocal fold cover layer: $E_c$
- Velocity: wave velocity of the vocal fold structure $\sqrt{\frac{E}{\rho_{sf}}}$
- Time: $\frac{1}{T} \sqrt{\frac{E}{\rho_{sf}}}$
- Frequency: $T \sqrt{\frac{\rho_{sf}}{E}}$
## Model Parameters Used

<table>
<thead>
<tr>
<th></th>
<th>Non-dimensional values</th>
<th>Physical value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural Damping Loss factor</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>VF Thickness T</td>
<td>1</td>
<td>3 mm</td>
</tr>
<tr>
<td>VF Cover Depth</td>
<td>0.333</td>
<td>1 mm</td>
</tr>
<tr>
<td>VF Body Depth</td>
<td>2</td>
<td>6 mm</td>
</tr>
<tr>
<td>Glottal Channel Gap</td>
<td>0.03</td>
<td>0.09 mm</td>
</tr>
<tr>
<td>VF Density</td>
<td>1</td>
<td>1030 kg/m³</td>
</tr>
<tr>
<td>Flow Density</td>
<td>0.0012</td>
<td>1.2 kg/m³</td>
</tr>
</tbody>
</table>
Results

• Phonation threshold pressure
• Phonation onset frequency
• Vocal fold vibration pattern
• Sound production efficiency
Straight Glottis

- Phonation threshold pressure
  - $P_{th}$ vs. $E_b$ (Body stiffness)

- Phonation onset frequency
  - $F_0$ vs. $E_b$ (Body stiffness)

- Prephonatory minimum glottal half-width
  - $g$ vs. $E_b$ (Body stiffness)

- Radiated sound pressure
  - $p_a$ vs. $E_b$ (Body stiffness)
Vocal Fold Vibration

\[ \frac{E_b}{E_c} = 1 \quad \frac{E_b}{E_c} = 100 \]

Increasing body stiffness restricts motion to the cover layer and the medial surface.
Increasing body stiffness restricts motion to the cover layer and the medial surface.

\[ \frac{E_b}{E_c} = 1 \]
Increasing body stiffness restricts motion to the cover layer and the medial surface.
Restriction of motion to the medial surface

• Each FSI eigenmode at onset was normalized so that, for each eigenmode, the kinetic (vibrational) energy of the vocal fold structure equals one.
  
  – Vocal fold structure has the same vibrational energy no matter at which eigenmode it vibrates
Vocal Fold Surface Displacement

**dark lines:** $E_b/E_c=100$

**gray lines:** $E_b/E_c=1$

**Red lines:** vocal fold surface

**Solid lines:** medial-lateral
**Dashed lines:** inferior-superior

Reduced body movement allows more energy to be spent for motion along the vocal fold surface.
Acoustic Consequence: Radiated Acoustic Pressure to an infinitely long vocal tract

• Zhang et al. (2002)

\[ P_a = -\frac{1}{2H_{in}} \int_S pn_z \cdot dS - \frac{1}{2H_{in}} \int_S \rho_f c \dot{w} \cdot ndS \]

\( P \): flow pressure along the vocal fold surface
\( W \): vocal fold displacement
\( S \): vocal fold surface
\( H_{in} \): glottal width at glottal entrance
• Since the FSI eigenmodes are normalized to have the same vibrational energy, the amplitude of the radiated sound pressure quantifies sound production efficiency – How efficient vibrational energy is converted into sound energy.
Increasing body stiffness increases sound production efficiency.

Increasing body stiffness →
Large amplitude at the medial surface →
More effective flow modulation →
Higher sound production efficiency.

\[ \text{Increasing body stiffness} \rightarrow \]
\[ \text{Large amplitude at the medial surface} \rightarrow \]
\[ \text{More effective flow modulation} \rightarrow \]
\[ \text{Higher sound production efficiency}. \]
Convergent and Divergent Glottis
\( P_{th} \) vs. \( E_b \) (Body stiffness)

\[ \begin{align*}
E_b & \quad P_{th} \\
10 & \quad 0.01 \\
100 & \quad 0.1 \\
1000 & \quad 0.5 \\
10000 & \quad 2.0 \\
\end{align*} \]

\( F_0 \) vs. \( E_b \) (Body stiffness)

\[ \begin{align*}
E_b & \quad F_0 \\
10 & \quad 0.025 \\
100 & \quad 0.5 \\
1000 & \quad 3.0 \\
10000 & \quad 15.0 \\
\end{align*} \]

\( P_a \) vs. \( E_b \) (Body stiffness)

\[ \begin{align*}
E_b & \quad P_a \\
10 & \quad 500 \\
100 & \quad 1500 \\
1000 & \quad 3000 \\
\end{align*} \]

- **\( \alpha \):**
  - ◇ -10 convergent
  - □ -5 convergent
  - ▼ 10 divergent
  - △ 5 divergent
  - ○ 0 straight
Red: divergent
Blue: convergent
Black: straight

Phonation threshold pressure

Phonation onset frequency

Phonation threshold pressure vs. Body stiffness

Phonation onset frequency vs. Body stiffness
Change in eigenmode-synchronization pattern

$E_b = 6$

$E_b = 7$

Change in eigenmode-synchronization pattern
Vocal Fold Vibration

\[ \frac{E_b}{E_c} = 6 \]
\[ \alpha = -5 \]

\[ \frac{E_b}{E_c} = 7 \]
\[ \alpha = -5 \]

Oscillation at a higher-order mode exhibits a more wave-like motion (smaller wavelengths).
Vibrating at a higher-order mode led to reduced superior-inferior motion and a smaller wavelength and therefore a wave-like motion.
Vocal Fold Vibration

\[ E_b/E_c = 7 \]

Vibrating at a higher-order mode led to reduced superior-inferior motion and a smaller wavelength and therefore a wave-like motion.
Vocal fold Surface Displacement

**dark lines:**
\[ E_b/E_c = 7 \]

**gray lines:**
\[ E_b/E_c = 6 \]

**Red lines:**
Vocal fold surface

**Solid lines:** medial-lateral
**Dashed lines:** inferior-superior

Vibrating at a higher-order mode led to:
1. reduced superior-inferior motion and
2. Large medial-lateral motion around the superior edge of the medial surface.
Zibrating at a higher-order mode leads to consistently higher sound production efficiency
Effective pitch control mechanism:

For large stiffness ratio: varying cover stiffness

For small stiffness ratio: varying body stiffness
Summary

- Increasing body-cover stiffness ratio
  - restricts vocal fold motion to the cover layer and the medial surface
  - Increases sound production efficiency
- Vibrating at higher-order modes generally leads to higher sound production efficiency
- A mucosal wave is NOT a necessary component to achieve self-sustained oscillation, but may be preferred to achieve better sound production efficiency.
- A sudden change in $F_0$ and vocal fold vibration can be induced by a slight and continuous change in body/cover stiffness or vocal fold geometry
  - Due to a change in the eigenmode-synchronization pattern.
  - A similar mechanism may also play a role in register change for finite-amplitude oscillations
For more …

Zhang, Z., “Characteristics of phonation onset in a two-layer vocal fold model,” under review, JASA.

References: