THREE-DIMENSIONAL NUMERICAL ANALYSIS OF CZECH VOWEL PRODUCTION

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Fluid-structure-acoustic interactions during phonation are directly linked to spatial physical effects. Can spatial model reveal new relationships between these phenomena?
Computational Model

Fluid Geometry

Vocal tract for vowel [oː], [1]

Idealized trachea

3D model

Trachea

Vocal folds

272 mm

187 mm

19 mm

85 mm
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Computational Model

Solid Geometry

3D model

Vocal tract for vowel [o] 272 mm

Vocal folds

Trachea

M5 shaped vocal fold [2], front view

M5 shaped vocal fold [2], oblique view

11 mm

9 mm

12 mm
### Computational Model

#### Material

<table>
<thead>
<tr>
<th>Vocal folds</th>
<th>E [Pa]</th>
<th>μ [−]</th>
<th>ρ [kg·m(^{-3})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epithelium</td>
<td>25000</td>
<td>0.49</td>
<td>1040</td>
</tr>
<tr>
<td>SLP</td>
<td>2000</td>
<td>0.49</td>
<td>1040</td>
</tr>
<tr>
<td>Ligament</td>
<td>8000</td>
<td>0.49</td>
<td>1040</td>
</tr>
<tr>
<td>Muscle</td>
<td>65000</td>
<td>0.40</td>
<td>1040</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Structural damping</th>
<th>α [s(^{-1})]</th>
<th>β [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>All layers</td>
<td>116.5279</td>
<td>0.0003</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Vocal tract</th>
<th>c(_{\text{air}}) [m·s(^{-1})]</th>
<th>η [Pa·s]</th>
<th>ρ [kg·m(^{-3})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air (36 °C)</td>
<td>353</td>
<td>1.81351·10(^{-5})</td>
<td>1.205</td>
</tr>
</tbody>
</table>

Four-layered M5 vocal fold [2], oblique view
### Computational Model

- **Vocal tract for vowel [o]:**
  - Open lips: Zero pressure
  - Walls: Zero flow velocity, absolute reflectivity
  - Lung pressure: $p_L = 165$ Pa

### Boundary Conditions

- Trachea
- Vocal folds
- Four-layered M5 vocal fold [2], oblique view

**Fixed displacement**

- Fixed displacement
Model features:

- Vocal tract for **Czech vowel** [o:]
- **Fluid-structure-acoustic interaction**
- **Structural model**: large deformations and proportional damping
- **Flow model**: unsteady, compressible, viscous air for 36 °C
- **Acoustics**: obtained from solution of Navier-Stokes equations
- Vocal folds **contact** and **fluid flow separation** in glottis region
- 3D finite element model: 324650 nodes, 305664 elements

Algorithm:

1. Pushing vocal folds into the **contact** (adduction)
2. **Fluid solution**: excitation by the lung pressure $p_L$
3. **Structure solution**: motion of the vocal folds
4. **Deformation** of the fluid mesh

**Iterations**: transient solution in the time domain with increment of $1.5 \cdot 10^{-4} \text{ s.}$
Three-dimensional Numerical Analysis of Czech Vowel Production

**Computational Model**

**Evaluation Points**

- **Point m**: Near the lips
- **Point s**: Subglottal
- **Point e**: Epiglottal
- **Point g**: Glottal

Structural results evaluated on the level of point $g$ are marked by $V_{F_L}$ & $V_{F_R}$

Structural results evaluated in minimal glottal width are marked by $V_{F_L}^{\text{min}}$ & $V_{F_R}^{\text{min}}$
Structural Results

Motion of Vocal Folds

1. \( t = 0.13755 \text{ s} \)
   convergent shape
   (just before opening)

2. \( t = 0.13920 \text{ s} \)
   collateral shape
   (during opening phase)

3. \( t = 0.14010 \text{ s} \)
   divergent shape
   (during closing phase)

4. \( t = 0.14175 \text{ s} \)
   closed phase
   (immediately after closing)

Total displacements of the vocal folds in middle frontal section
Structural Results

Motion of Vocal Folds

1. t = 0.13755 s, convergent shape
2. t = 0.13920 s, collateral shape
3. t = 0.14010 s, divergent shape
4. t = 0.14175 s, closed phase

Total displacements of the vocal folds in top view
### Structural Results

#### Vocal Folds Vibration

Displacements in $x$ direction from facing VF nodes in minimal glottal gap

<table>
<thead>
<tr>
<th>Vibration characteristics</th>
<th>$\text{WG}_{\text{max}}$ [mm]</th>
<th>OQ [-]</th>
<th>$f_0$ [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.31</td>
<td>0.49</td>
<td>180</td>
</tr>
</tbody>
</table>

$\text{WG}_{\text{max}}$ – maximal width of glottis

OQ – open quotient (duration of open phase divided by cycle duration)

$f_0$ – fundamental oscillation frequency

(CHARACTERISTICS ARE EVALUATED FROM LAST TWO PERIODS)
Comparison of displacements in $x$ direction:
- **dashed** – facing VF nodes in minimal glottal gap,
- **solid** – facing VF nodes evaluated on the level of point $g$

Structural results evaluated in point $g$ are marked by $VF_L$ & $VF_R$

Structural results evaluated in minimal glottal width are marked by $VF_{L\text{min}}$ & $VF_{R\text{max}}$.
Fluid Results

1. Convergent shape (just before opening)  
   - $t = 0.13755 \text{ s}$

2. Collateral shape (during opening phase)  
   - $t = 0.13920 \text{ s}$

3. Divergent shape (during closing phase)  
   - $t = 0.14010 \text{ s}$

4. Closed phase (immediately after closing)  
   - $t = 0.14175 \text{ s}$

Fluid Flow

Flow velocity in vocal tract

Total displacements of vocal folds

Flow results
Fluid Results

Subglottal pressure $p_s$, glottal pressure $p_g$ and epiglottal pressure $p_e$ (Pressure behaviors are very similar due to incomplete glottal closure)

Pressure $p_m$ just below the lips
Fluid Results

Velocities & Glottal Flow

Subglottal velocity $v_s$, glottal velocity $v_g$ and epiglottal velocity $v_e$

Velocity $v_m$ just below the lips

Glottal flow rate in point g
Fluid Results

Displacement in $x$ from minimal dist.

Pressures $p_s$, $p_g$ & $p_e$

Velocities $v_s$, $v_g$ & $v_e$

Phases

These are last four periods from abovementioned graphs
Acoustic Results

Vowel Spectrum

Power spectral density evaluated just below the lips, green $F_1$ & $F_2$ from [3]
### Acoustic Results

#### Natural Frequencies

<table>
<thead>
<tr>
<th>Natural frequency</th>
<th>Frequency [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>517.63</td>
</tr>
<tr>
<td>2.</td>
<td>928.68</td>
</tr>
<tr>
<td>3.</td>
<td>2223.80</td>
</tr>
</tbody>
</table>

#### First pressure mode

#### Second pressure mode

#### Third pressure mode
Conclusion

Structural Results

- Oscillations of the vocal folds were stabilized after 0.05 s.
- The fundamental frequency of the vocal fold oscillation of 180 Hz corresponded to a slightly raised male or female comfortable voice [4].
- Open quotient of 0.49 fell within an interval measured on healthy subjects [5].
- Incomplete glottal closure occurred during oscillation of the vocal folds.
Conclusion

Fluid Results

- Glottal flow rate reached maxima around $0.45 \cdot 10^{-5} \text{ m}^3\cdot\text{s}^{-1}$.
- Incomplete glottal closure made behavior of subglottal, glottal & epiglottal pressures very similar.
- Maxima of glottal velocity did not exceed $20 \text{ m}\cdot\text{s}^{-1}$.
Acoustic Results

• First two natural frequencies of vocal tract were within the range of formant frequencies for the Czech vowel [o:] measured in [3].
• Frequencies of the dominant harmonic peaks were lower compared to the measured formants, probably because of the vocal fold-vocal tract interactions [6].
Future Work

• Spatial model of the fluid-structure-acoustic interaction with acoustic analogy.
• Application of a kinematic model of the vocal fold motion to the fluid-structure-acoustic interaction.
Thank you for your attention.

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References


