Experimental study of the airflow through in-vitro models of vocal-folds


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Grants: International cooperation CNRS /NWO, van Gogh project, Eurodoc.
Production of voiced sound

- Mechanical System
- Fluid
- Vocal-fold Tissues
- Airflow coming from the Lungs

Flutter = Voiced Sound
Speech Modelling

The Lungs

Energy source

Vocal folds

The Vocal Tract

Acoustical Filter

Vocal folds
Speech Modelling

The vocal folds

Cross section of a fold

Vocal Folds

Length ≈ 15 mm

Opening during speech ≈ 1 mm

Height ≈ 4 mm

The source of sound

EFMC-2000
Oscillation of the vocal folds

Volume, Flow

Opened phase

Closed phase

Converging shape

Diverging shape

Flow

time

1 2 3 4 5 6 7 8
Why Modelling Voiced Sounds?

Normal Voice

Pathological Voice (Cyst, Paralysis)

Examples of Applications

Speech Data transmission

Help for diagnostics of pathology
Model of Voiced Sounds Production

Mechanics

Caricatural model of vocal folds:
The two-mass model

2 degrees of freedom needed for flutter.

Fluids

Need for a model of fluid that predicts self-sustained oscillations

We focus on it!
Characterization of the flow in the glottis

<table>
<thead>
<tr>
<th>Glottis opening</th>
<th>1 mm</th>
<th>≈ 6 \times 10^{-2}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of the vocal folds</td>
<td>15 mm</td>
<td></td>
</tr>
</tbody>
</table>

| \frac{\lambda}{L} | ≈ \frac{30 \text{ cm}}{3 \text{ mm}} | ≈ 10^2 |

<table>
<thead>
<tr>
<th>Quasi-steady Flow.</th>
</tr>
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<th>Compact source, fluid locally incompressible.</th>
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</table>

| Strouhal Number | Sr = \frac{f \times L}{U} | ≈ \frac{100 \text{ Hz} \times 3 \text{ mm}}{30 \text{ m/s}} | ≈ 10^{-2} |

<table>
<thead>
<tr>
<th>High Re laminar Flow.</th>
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</table>

| Reynolds Number | Re = \frac{U \times L}{\nu} | ≈ \frac{30 \text{ m/s} \times 3 \text{ mm}}{1.5 \times 10^{-5} \text{ m}^2/\text{s}} | ≈ 6 \times 10^3 |

\[ \begin{align*}
\text{Ma} &= \frac{U}{c} \approx \frac{30 \text{ m/s}}{340 \text{ m/s}} \approx 10^{-1} \\
\text{Strouhal Number} &\approx \frac{100 \text{ Hz} \times 3 \text{ mm}}{30 \text{ m/s}} \approx 10^{-2} \\
\text{Reynolds Number} &\approx \frac{30 \text{ m/s} \times 3 \text{ mm}}{1.5 \times 10^{-5} \text{ m}^2/\text{s}} \approx 6 \times 10^3
\end{align*} \]
Theoretical model

- 2D
- Incompressible
- Quasi-steady
- Laminar

Boundary Layer Theory

Prandtl Equations

Integral Method

Von Karman Equation

Simplified Solution

Thwaites Equation
Thwaites Equations

**Momentum Conservation Equation**

\[ u_e^6(x) \cdot \theta^2(x) - u_e^6(0) \cdot \theta^2(0) = 0.45 \cdot v \cdot \int_0^x u_e^5(x')dx' \]

- Flow velocity outside the boundary layer
- Momentum thickness
- Displacement thickness

**Mass Conservation**

\[ u_e(x) \cdot (h(x) - 2 \cdot \delta_1(x)) = Cste \]

- Height of the channel

**Relation between \( \delta_1 \) and \( \theta \):**

\[ \delta_1 = H(\lambda) \cdot \theta \]

where \( \lambda = \frac{\theta^2}{v} \cdot \frac{du}{dx} \) → criterion for flow separation

and \( H(\lambda) \) is a **tabulated function**
Experimental study

In Vitro rigid models

Diverging Channel

• 2-mass model shape
  • Up-scaling factor = 3

Lip model shape
  • Up-scaling factor = 1

Incoming Airflow:
  • Steady
  • Accelerated
  • Oscillating

‘round lips’
Experimental Study

Examples of measurements:

Measurement configuration

Pressure, in Pa

-200

0

600

P_{sub}

P_{g1}

P_{g2}

time, in s

Pressure, in Pa

0

500

1000

P_{sub}

P_{g1} P_{g2}

time, in s
1- Steady measurements

COANDA EFFECT!
Asymmetric flow in symmetric channel.
Dominant in steady flows!

The fluid follows the lower wall
Characteristics of Coanda Effect

Not instantaneous!

Definitions:

- \( t_{\text{coanda}} \): time needed for Coanda effect to appear

- \( t_{\text{coanda}}^* = \frac{t_{\text{coanda}}}{(L/U)_{\text{model}}} \): dimensionless time

Result:

\[ t_{\text{coanda}}^* \approx \frac{20 \text{ ms}}{20 \text{mm}/30 \text{ m.s}^{-1}} \approx 30 \]
Characteristics of Coanda Effect

Definitions:

- $t_{\text{div}} = \text{duration of the diverging phase}$
- $t_{\text{div}}^* = \frac{t_{\text{div}}}{(L/U)_{\text{vocal folds}}} = \text{dimensionless time.}$

After measurements:

$t_{\text{div}}^* \approx 3 \text{ ms} \approx \frac{20}{4 \text{ mm}/30 \text{ m.s}^{-1}} \approx 20$

Hard to conclude, open question
Results-2

2- For symmetric oscillating flow:

- Low Strouhal Number: \( Sr \approx 10^{-2} \) (Speech domain)
- \( Re \approx 3000 \)

Fair agreement compared to uncertainties in the mechanical model.
Results-2

- Higher Strouhal Number: $Sr \approx 2.10^{-1}$ *(Out of Speech domain)*
- $Re \approx 3000$

Significant deviation from quasi-steady approximation
Conclusions

1- Existence of Coanda effect (Flow asymmetry)

Still open question, influence of wall movement?

2- In the case of symmetric flow:

Quasi-stationary boundary-layer model valid for $\text{Sr} \leq 10^{-2}$

(speech domain)
Boundary layer parameters

Displacement thickness:
\[
\delta_1(x) = \int_0^\infty (1 - \frac{u(x, y)}{u_e(x)}) dy
\]

Momentum thickness:
\[
\theta(x) = \int_0^\infty \frac{u(x, y)}{u_e(x)} \ast (1 - \frac{u(x, y)}{u_e(x)}) dy
\]