Interaction of vocal fold and vocal tract oscillations

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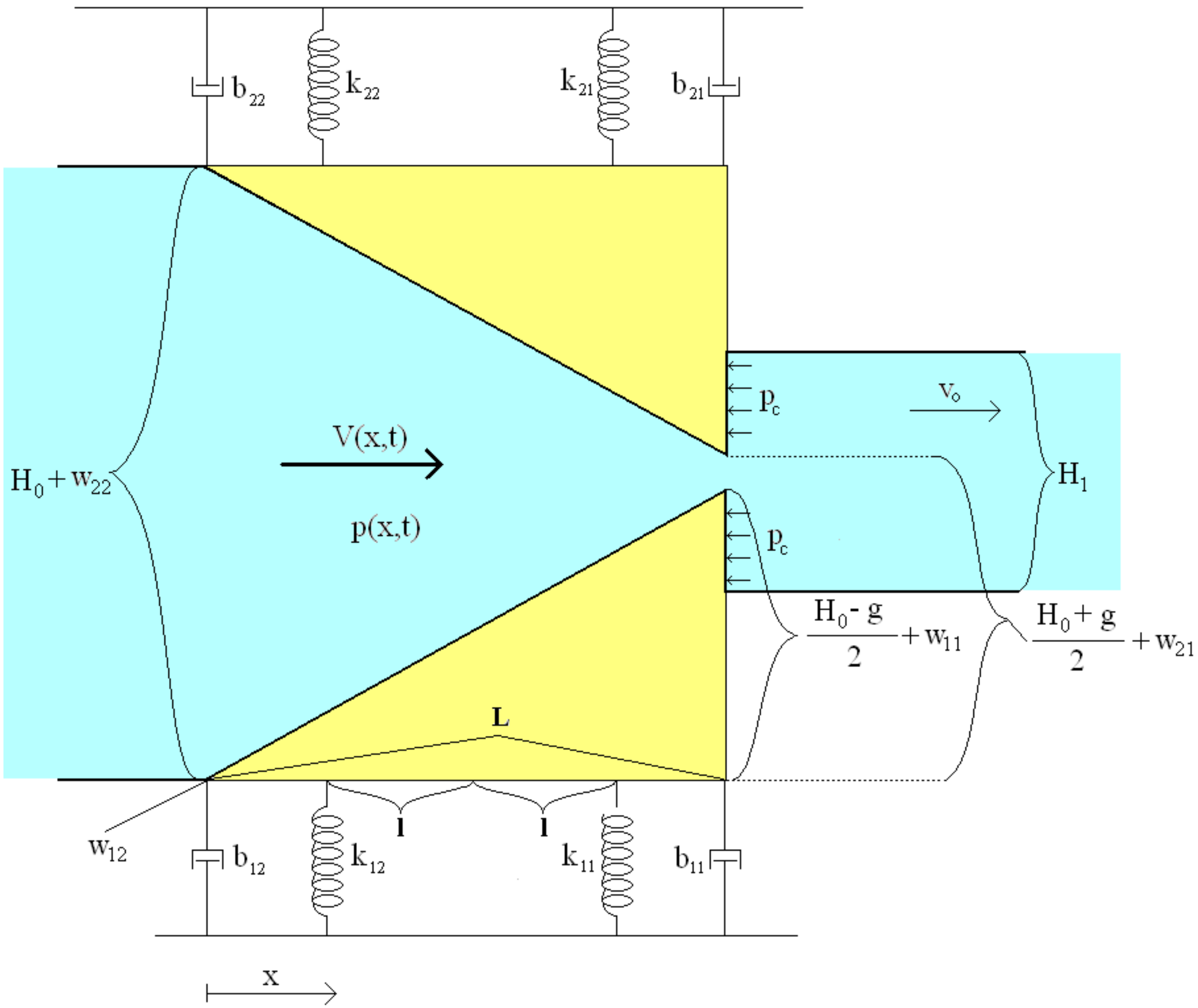
Introduction

- We study the feedback coupling between human vocal folds and vocal tract (VT). The work consists of computational and experimental parts.

- The model consists of three subsystems:
  1. a mass-spring model of the vocal folds,
  2. an incompressible 1D flow model, and
  3. a vocal tract model based on Webster's equation.

- In the experiments, subjects produce fundamental frequency glides over the lowest VT resonance.

The vocal fold model (1)



The vocal fold model (2)

The equations of motion are

$$\begin{cases} \mathbf{M}_1 \ddot{\mathbf{W}}_1(t) + \mathbf{B}_1 \dot{\mathbf{W}}_1(t) + P\mathbf{K}_1 \mathbf{W}_1(t) = -\mathbf{F}(t), \\ \mathbf{M}_2 \ddot{\mathbf{W}}_2(t) + \mathbf{B}_2 \dot{\mathbf{W}}_2(t) + P\mathbf{K}_2 \mathbf{W}_2(t) = \mathbf{F}(t) \end{cases}$$

Here $\mathbf{W}_1 = \begin{pmatrix} w_{11} \\ w_{12} \end{pmatrix}$ and $\mathbf{W}_2 = \begin{pmatrix} w_{21} \\ w_{22} \end{pmatrix}$ are the positions of the upper and lower vocal fold and $\mathbf{M}_j$, $\mathbf{B}_j$, and $\mathbf{K}_j$ are the corresponding mass, damping, and stiffness matrices. Tuning parameter $P \in \mathbb{R}^+$ is used for producing fundamental frequency glides.

Load force

$$\mathbf{F} = \mathbf{F}(\mathbf{W}_1, \mathbf{W}_2, v_o, p_c)$$

- For the open glottis*, $\mathbf{F}$ contains the aerodynamic pressure (from the Bernoulli law) and the counter pressure p_c from the VT.

- When the glottis is closed, $\mathbf{F}$ contains a contact force given by the Hertz impact model and the VT counter pressure.

*Glottis is the aperture between vocal folds.

Glottal flow

We assume an incompressible 1D flow through the glottis whose velocity v_o satisfies

$$p_{sub} = \underbrace{\widehat{C}_{iner}\dot{v}_o(t)}_{\text{inertive pressure}} + \underbrace{\frac{C_g}{\Delta W_1(t)^3}v_o(t)}_{\text{viscous pressure loss}}$$

- p_{sub} is the subglottal pressure (above ambient pr.),
- $\widehat{C}_{iner}$ $(= hH_1C_{iner})$ regulates the flow inertia,
- C_g regulates the viscous pressure loss at the glottis,
- ΔW_1 is the glottal opening at the narrowest point.

Vocal tract

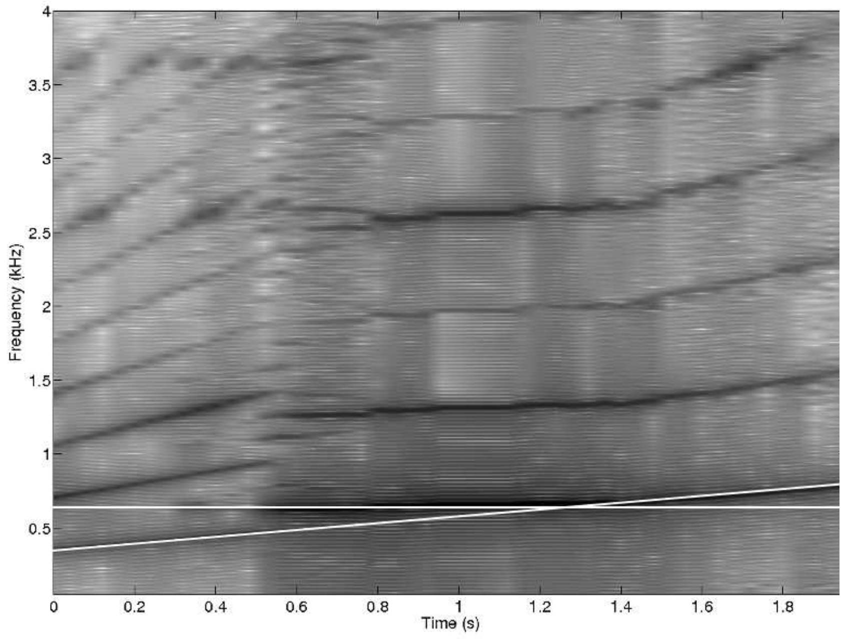
The VT dynamics is governed by Webster's equation:

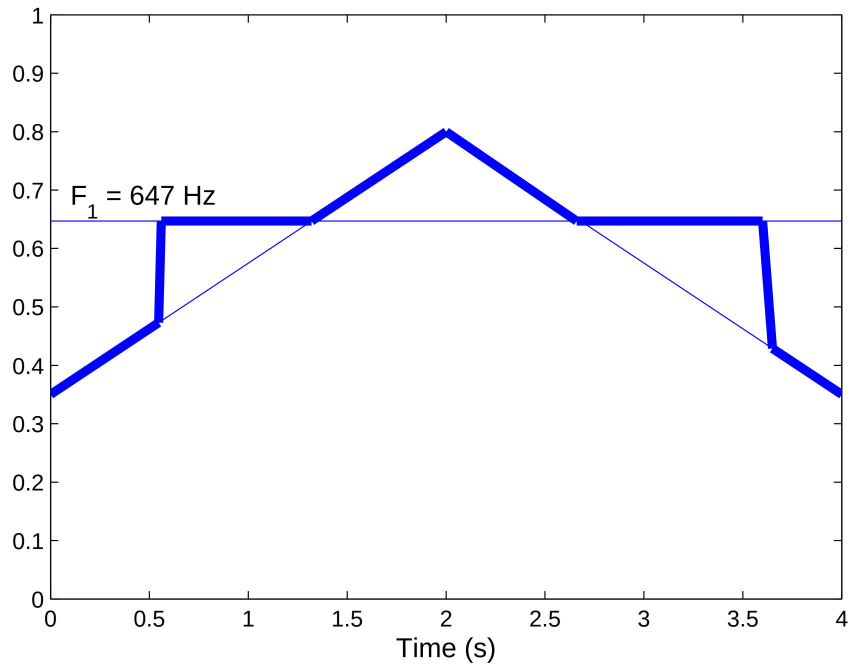
$$\begin{cases} \frac{\partial^2 \Psi}{\partial t^2}(x,t) = \frac{c^2}{A(x)} \frac{\partial}{\partial x} \left(A(x) \frac{\partial \Psi}{\partial x}(x,t) \right), & x \in [0, L_{VT}], \\ \Psi_x(0,t) = -v_o(t), \\ \Psi_t(L_{VT},t) + \theta c \Psi_x(L_{VT},t) = 0, \\ p_c(t) = \rho \Psi_t(0,t). \end{cases}$$

Ψ is a velocity potential and $A(\cdot)$ is the cross-sectional area of the vocal tract (corresponding to vowel [ø]).

Numerically solved by FEM.

Computational results

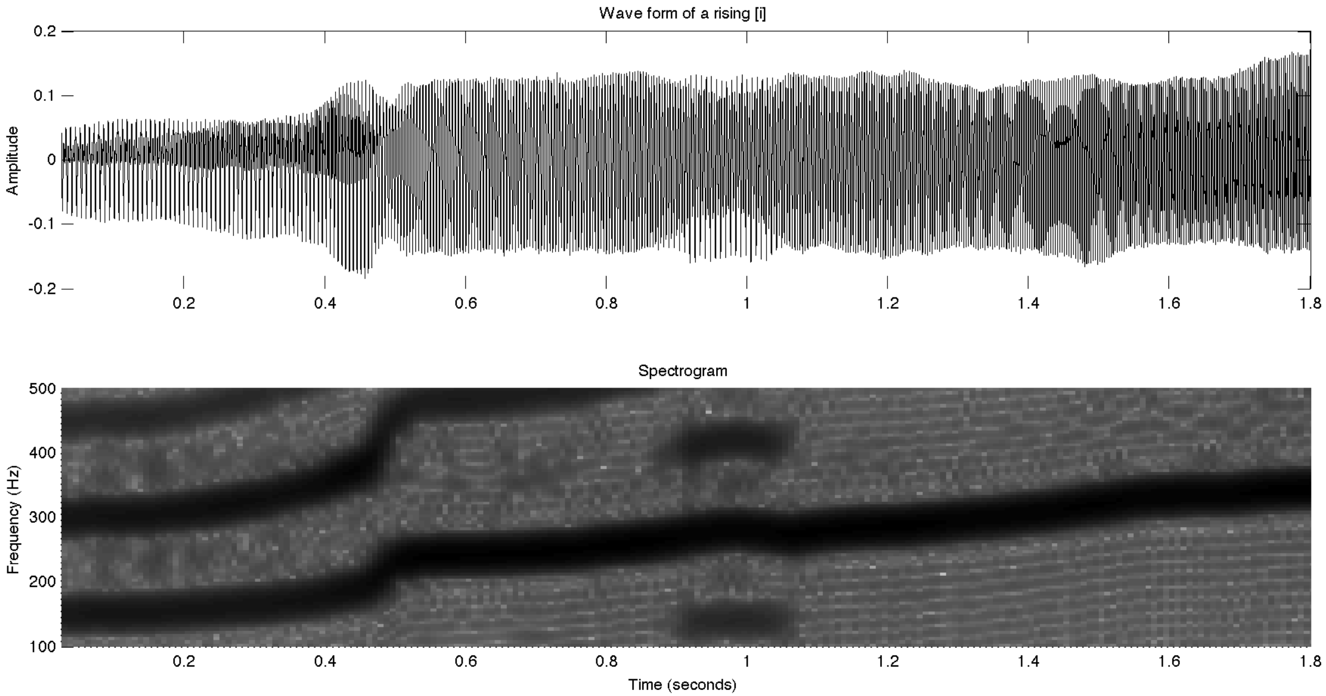




Left: A simulated fundamental frequency glide 350–810 Hz.

Right: A sketch of the vocal fold oscillation frequency in a glide first upwards and then downwards.

Experimental results



Wave form and spectrogram of a fundamental frequency glide over the lowest VT resonance with static vowel [i].

Conclusions

We presented a simple model for simulating human vowel production. The model was used for studying the feedback effect from the vocal tract to the vocal folds:

- The coupling is significant when vocal folds' oscillation frequency is close to the lowest VT resonance.
- We have observed fundamental frequency jumps, and we propose that they are related to modal locking between the vocal vold and VT oscillations.

The simulations are (qualitatively) well in line with experimental results, but...

Conclusions

… the experimental results are complex:

- Similar fundamental frequency jumps may also occur because of register shifts.

- Professional singers can automatically avoid the coupling (by various techniques) and also non-professionals can learn it quickly.

- The VT resonances are difficult to determine.

- Subglottal resonances may also play a role.

Thank you for your attention