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

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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.

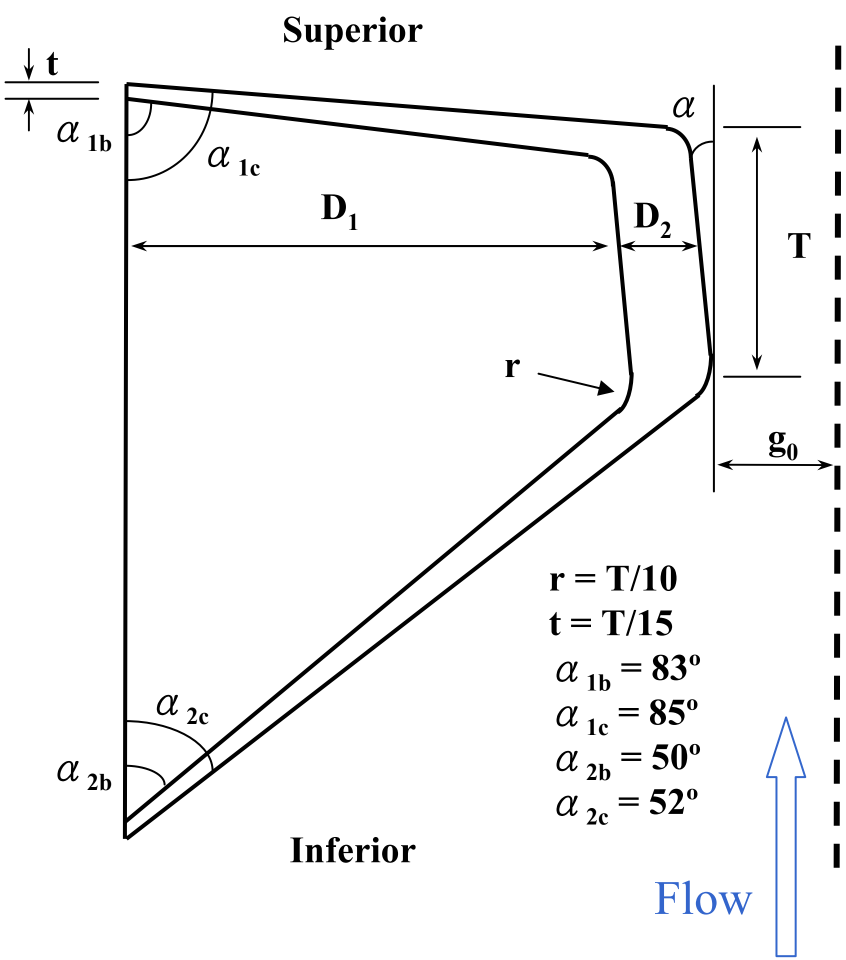
Limitations of Lumped-mass models

- 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: α
- 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

Glottal Flow

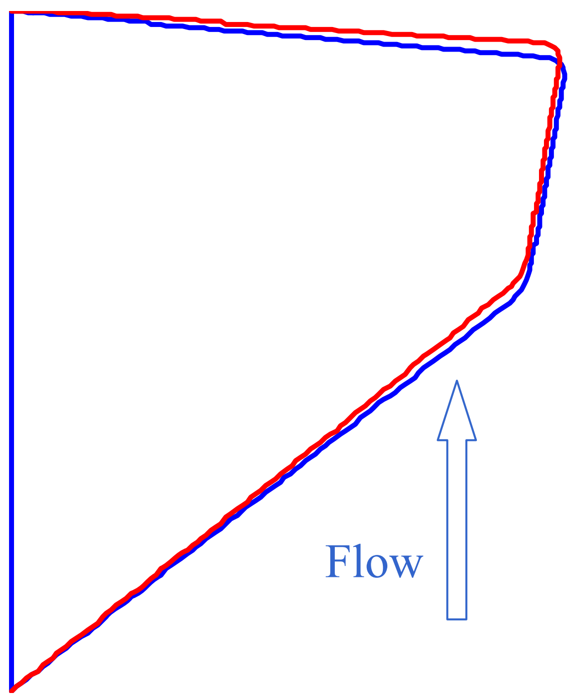
- One-dimensional potential flow up to the point of flow separation;
- Flow separation was assumed to occur at a point as determined by a separation constant $H_s/H_{min}=1.2$
  - At a point downstream of the minimum glottal constriction with a glottal width equal to 1.2 times the minimum glottal width.
- 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 ρ
- Pressure: Young's modulus of the vocal fold cover layer: E_c
- Velocity: wave velocity of the vocal fold structure $\sqrt{\frac{E}{\rho_{vf}}}$
- Time: $\frac{1}{T}\sqrt{\frac{E}{\rho_{vf}}}$
- Frequency: $T\sqrt{\frac{\rho_{vf}}{E}}$

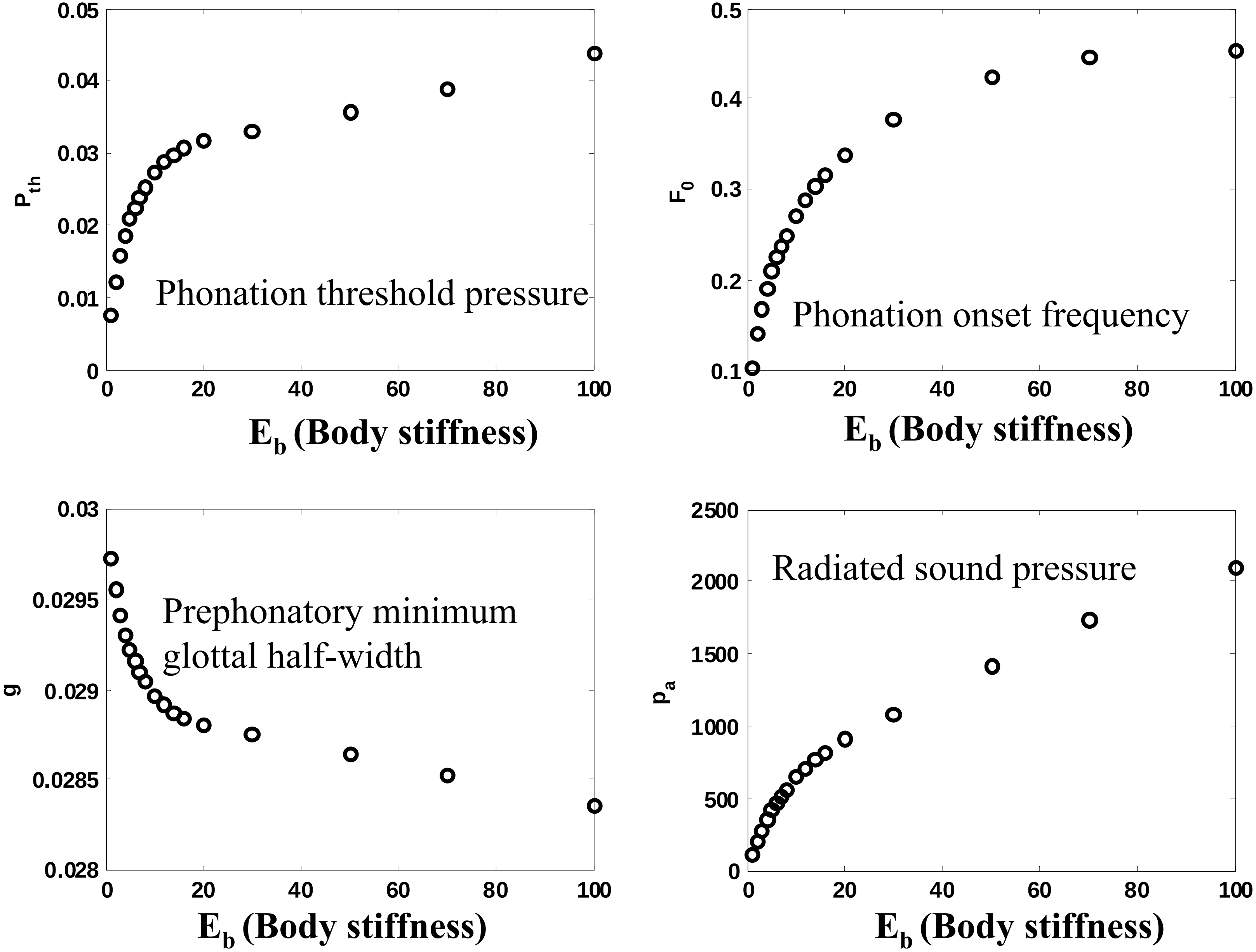
Model Parameters Used

	Non-dimensional values	Physical value
Structural Damping Loss factor	0.4	0.4
VF Thickness T	1	3 mm
VF Cover Depth	0.333	1 mm
VF Body Depth	2	6 mm
Glottal Channel Gap	0.03	0.09 mm
VF Density	1	1030 kg/m^3
Flow Density	0.0012	1.2 kg/m^3

Results

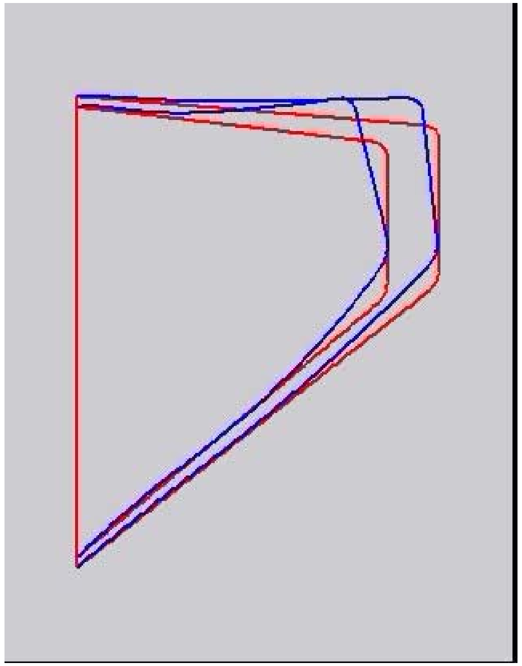
- Phonation threshold pressure
- Phonation onset frequency
- Vocal fold vibration pattern
- Sound production efficiency

Straight Glottis

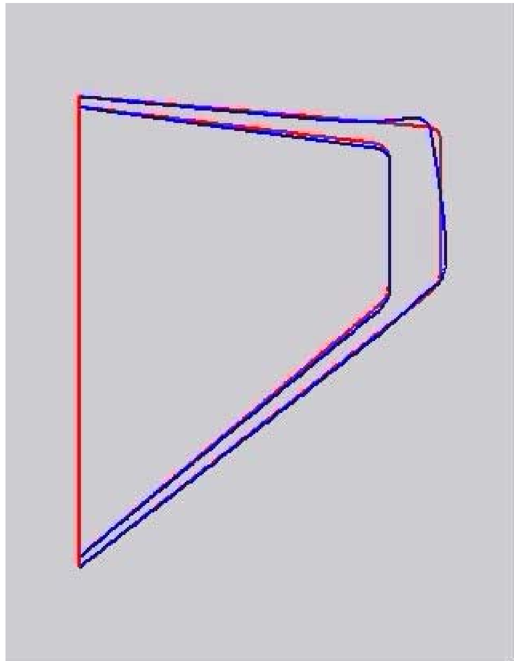


Vocal Fold Vibration

$E_b/E_c=1$

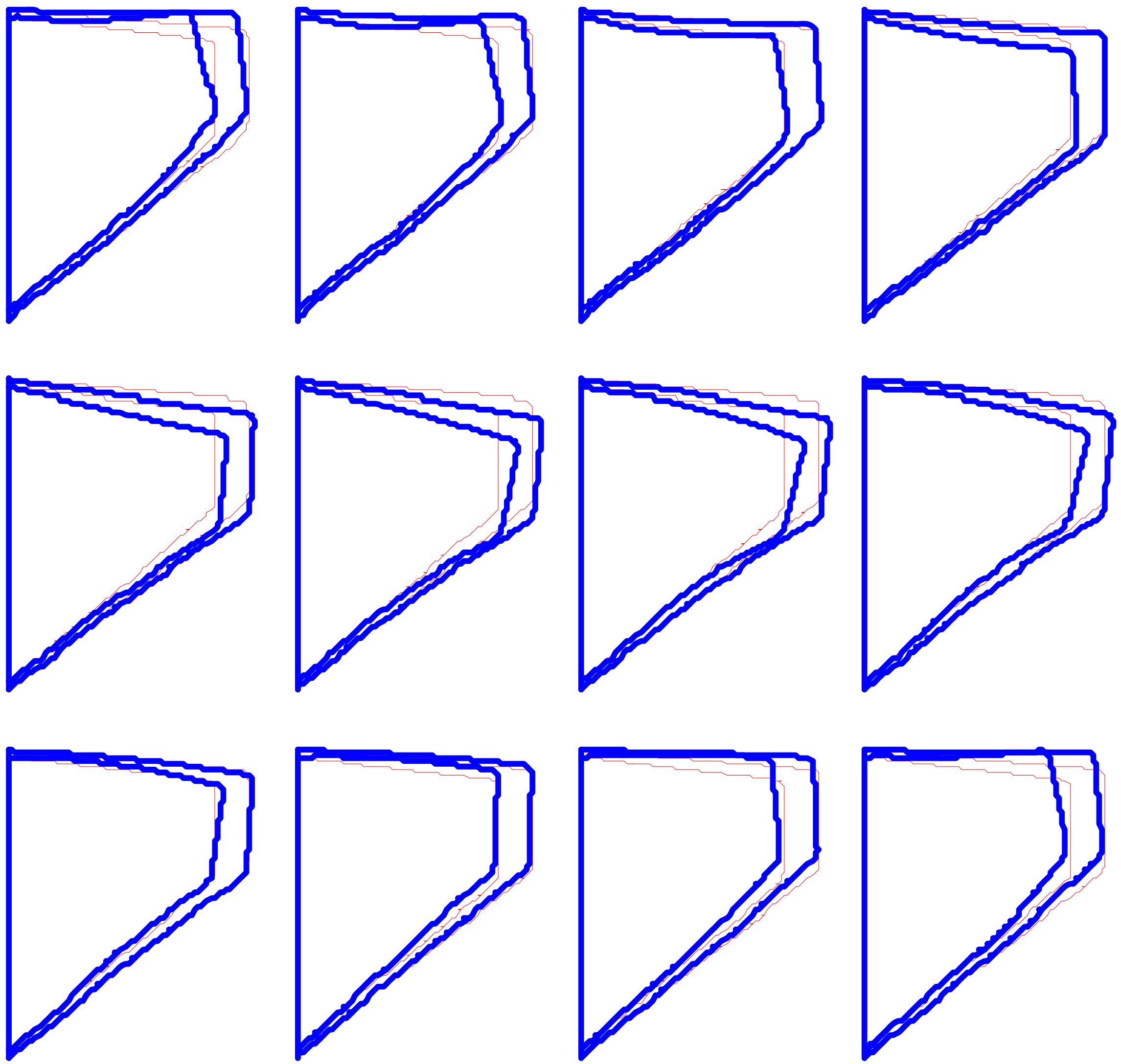


$E_b/E_c=100$



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

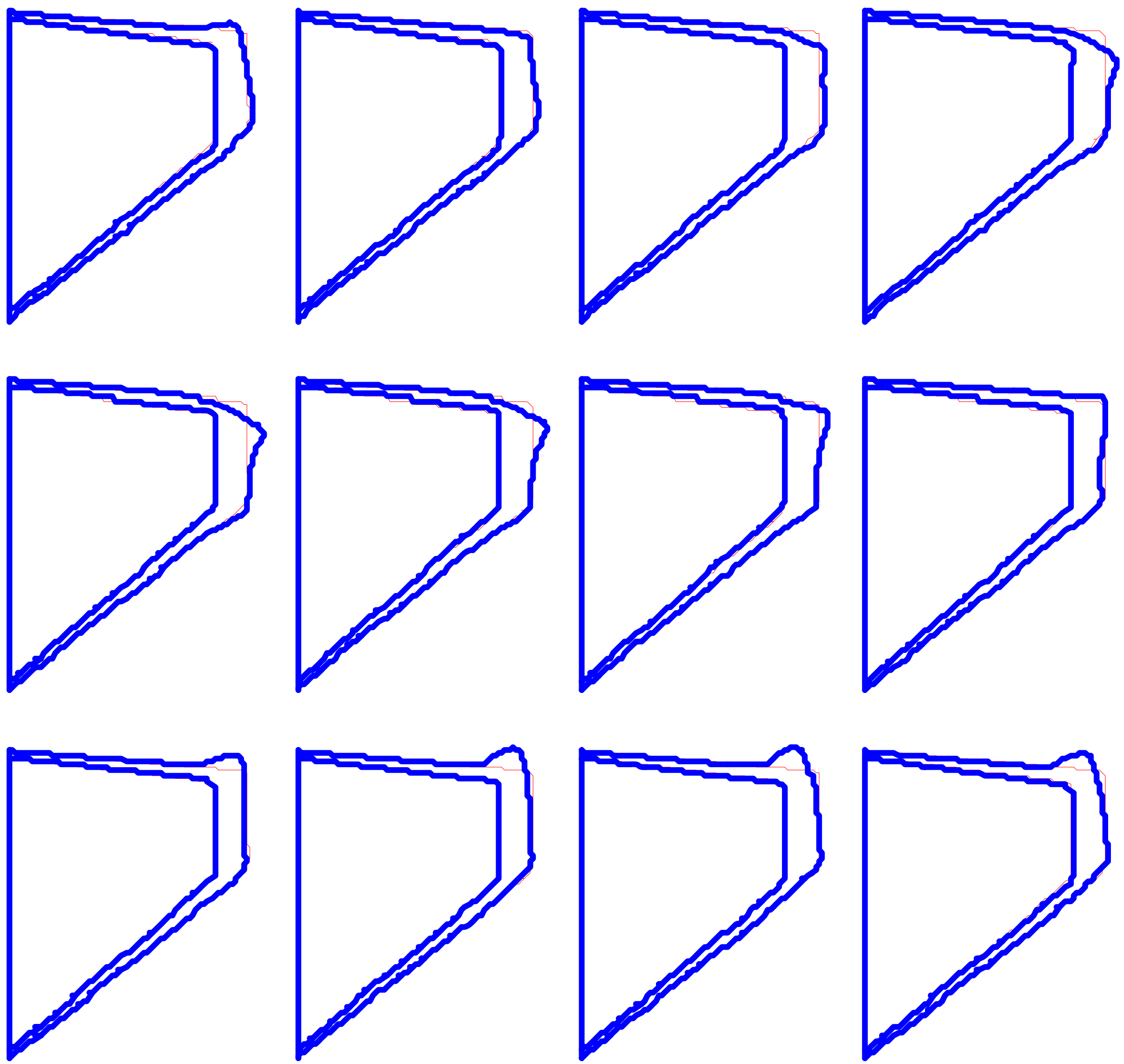
Vocal Fold Vibration



$E_b/E_c=1$

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

Vocal Fold Vibration



E_b/E_c=100

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

Restriction of motion to the medial surface

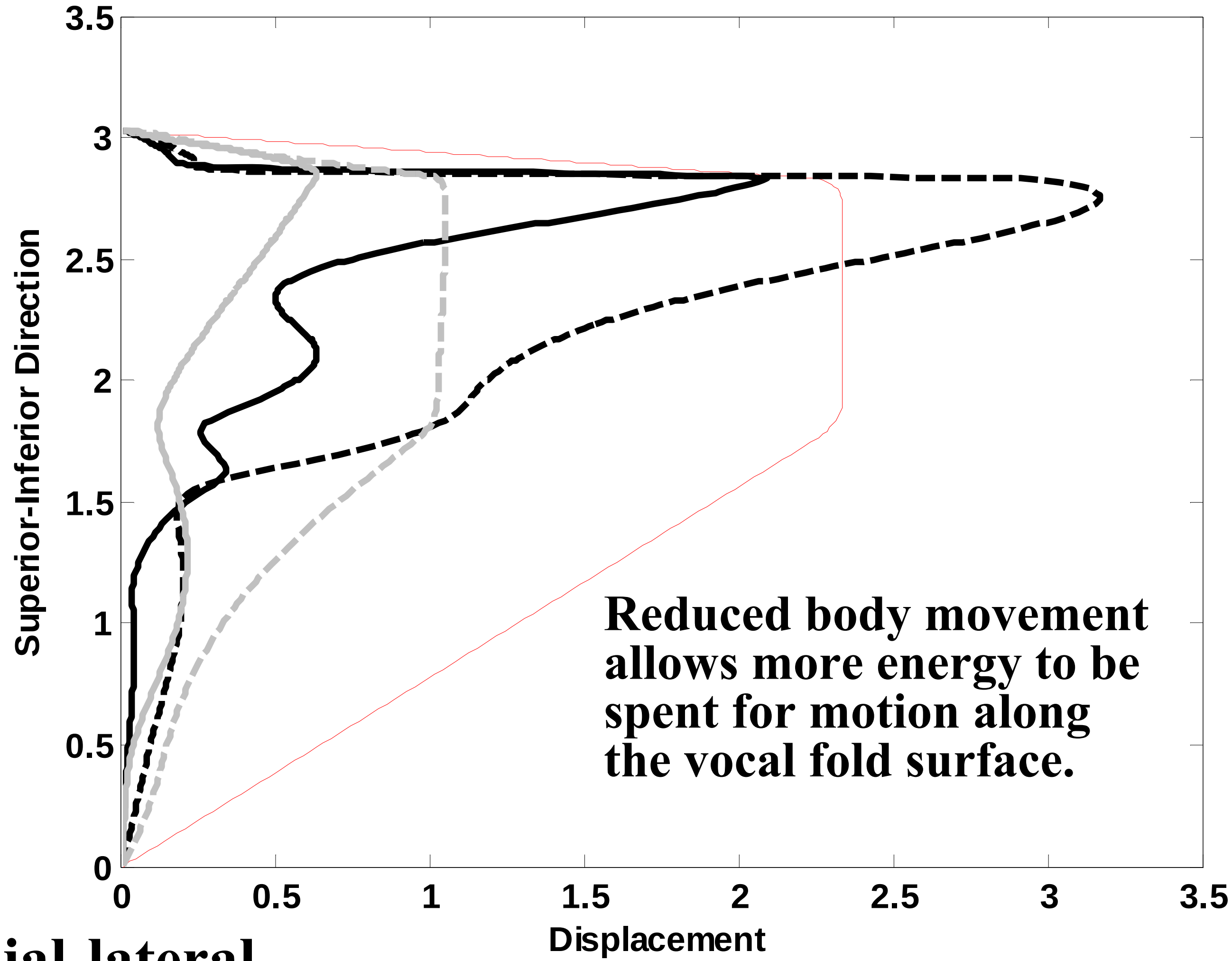
- Each FSI eigenmode at onset was normalized so that, for each eigenmode, the kinetic (vibrational) energy of the vocal fold structure equals one.
  - Vocal fold structure has the same vibrational energy no matter at which eigenmode it vibrates

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

Acoustic Consequence: Radiated Acoustic Pressure to an infinitely long vocal tract

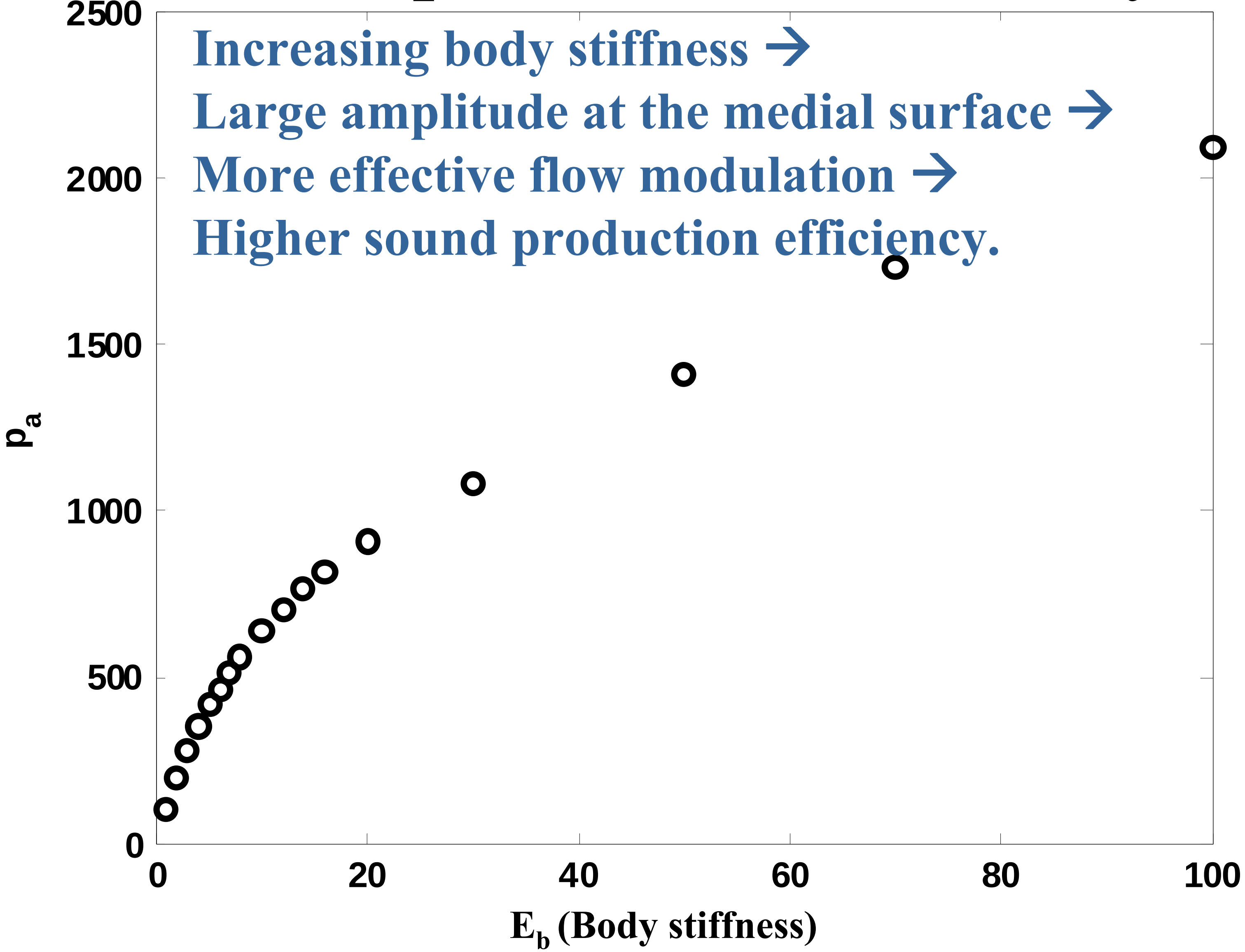
- Zhang et al. (2002)

$$P_a = -\frac{1}{2H_{in}}\int_S p n_z \cdot dS - \frac{1}{2H_{in}}\int_S \rho_f c\dot{w} \cdot n dS$$

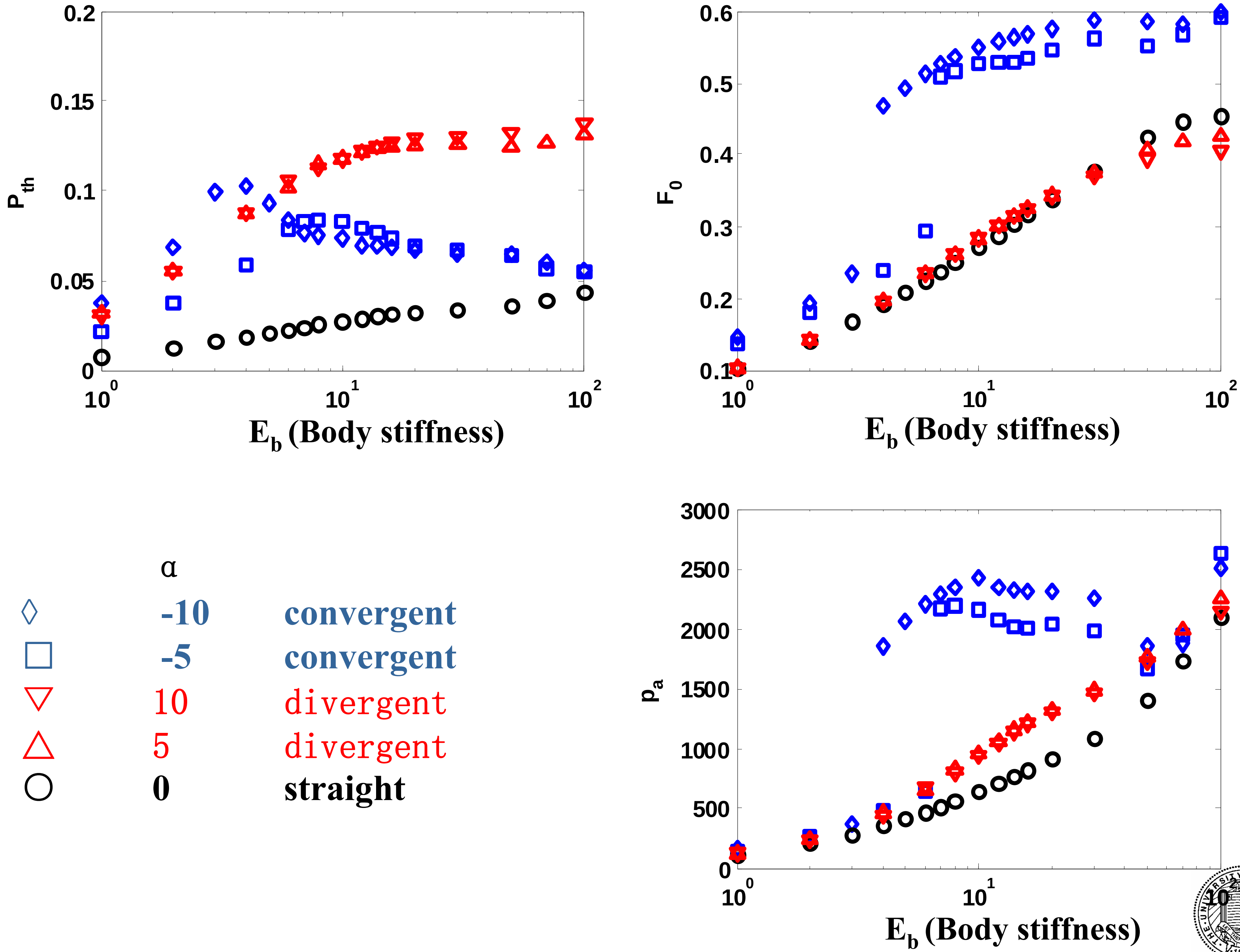
P: flow pressure along the vocal fold surface
W: vocal fold displacement
S: vocal fold surface
H_{in}: glottal width at glottal entrance

- 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



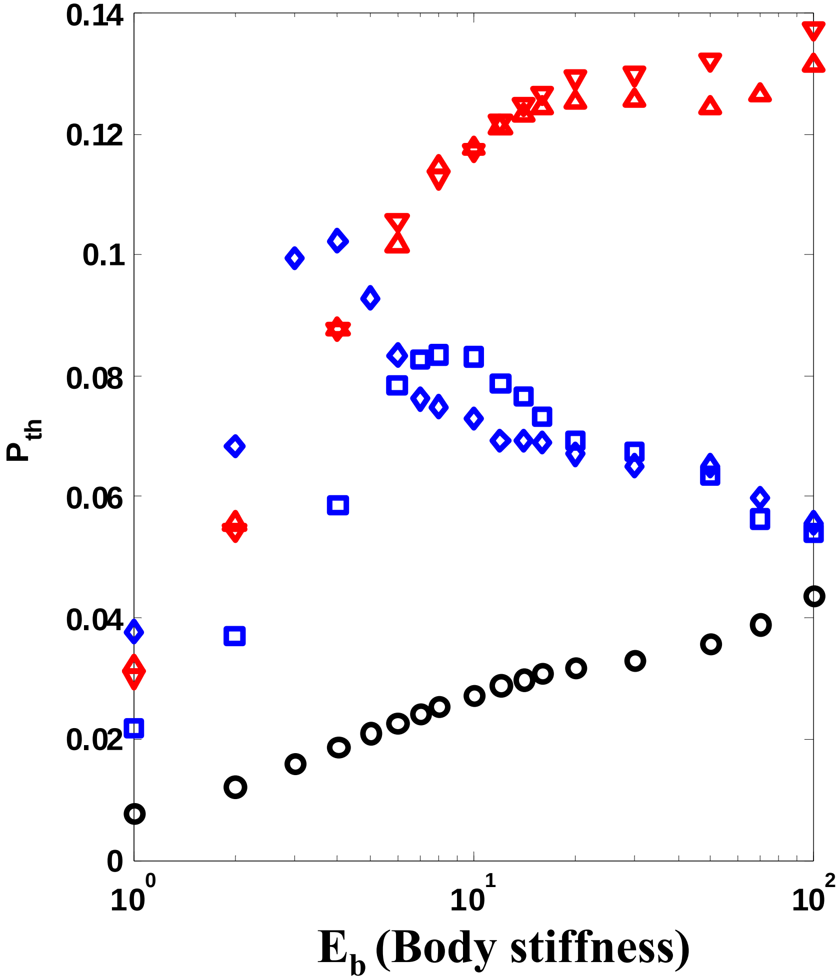
Convergent and Divergent Glottis



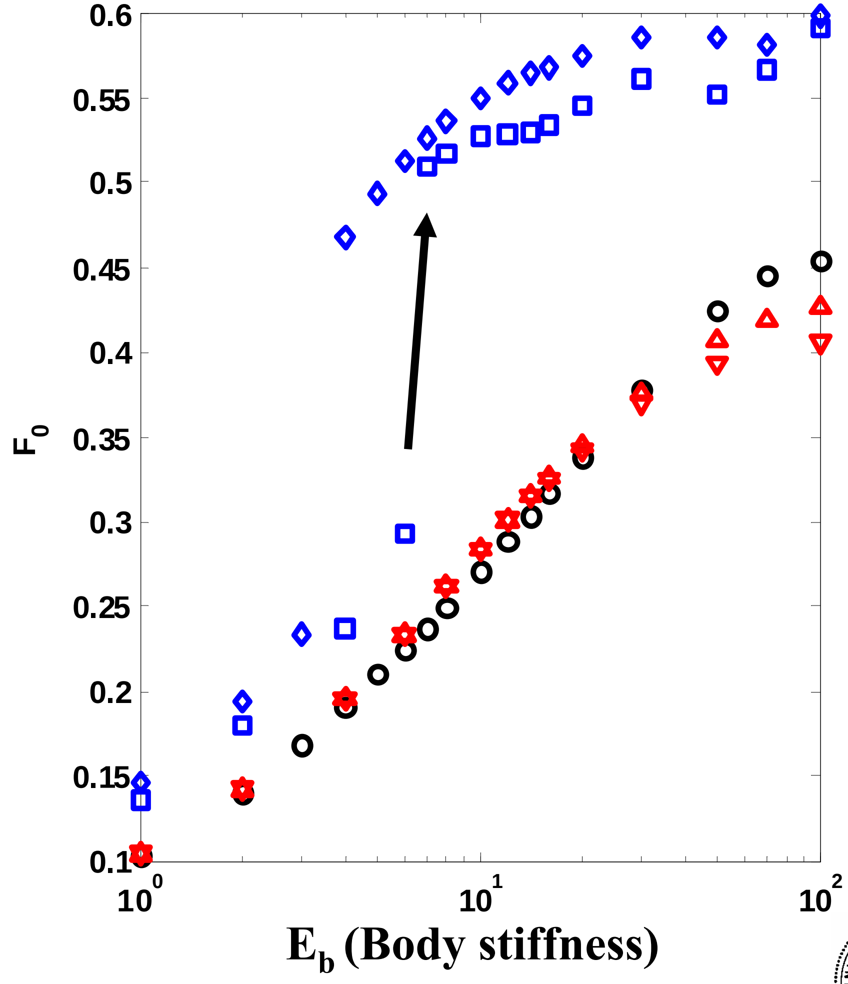
P_th
F_0
p_a
E_b (Body stiffness)
E_b (Body stiffness)
E_b (Body stiffness)
α
-10 convergent
-5 convergent
10 divergent
5 divergent
0 straight

Red: divergent
Blue: convergent
Black: straight

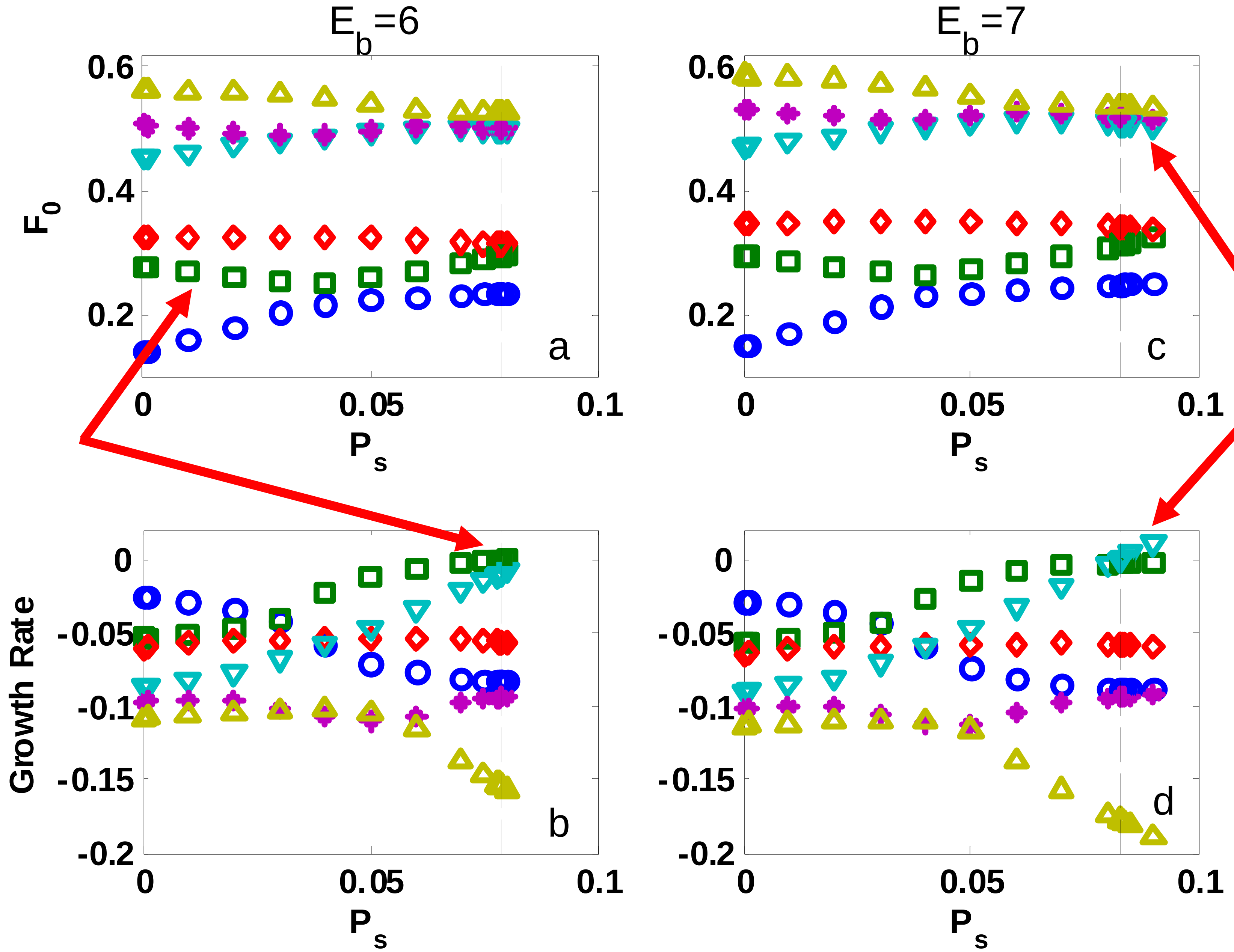
Phonation threshold pressure



Phonation onset frequency

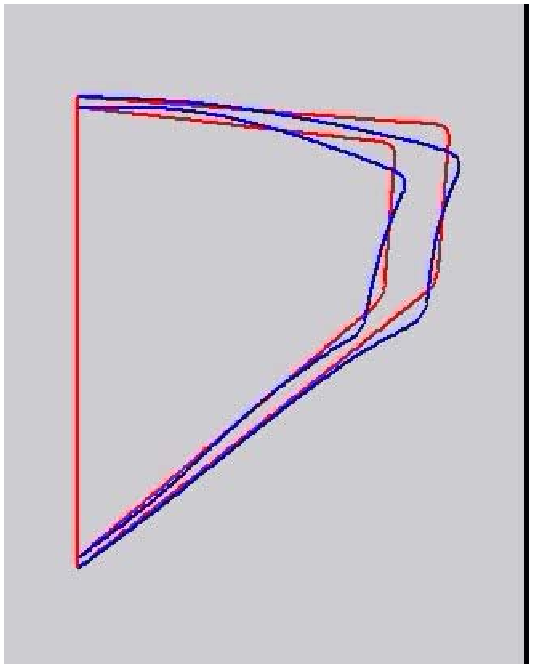


Change in eigenmode-synchronization pattern

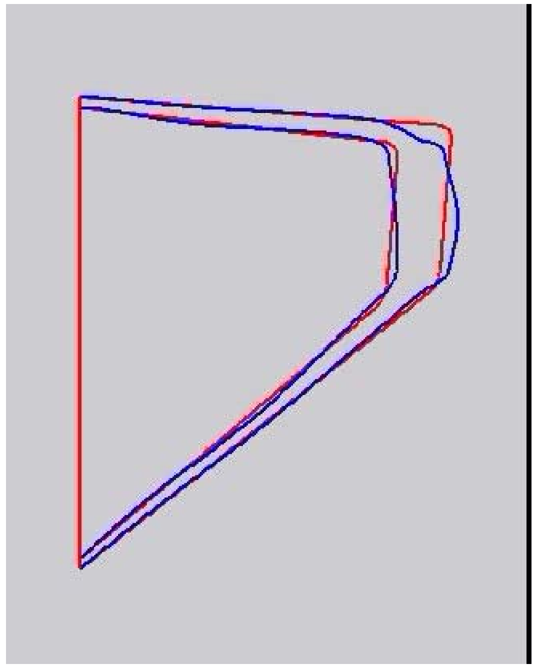


Vocal Fold Vibration

$E_b/E_c=6$
$\alpha = -5$

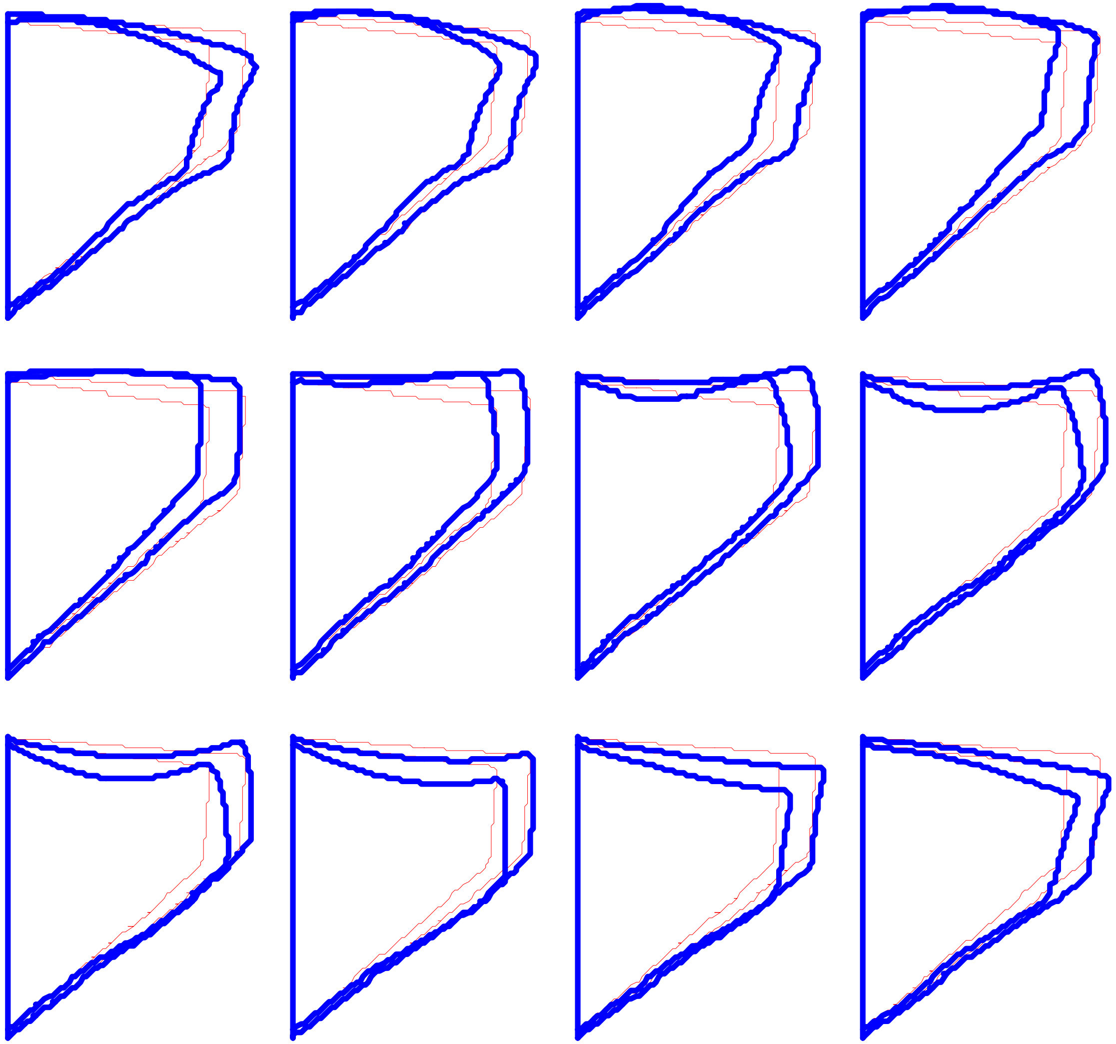


$E_b/E_c=7$
$\alpha = -5$



Oscillation at a higher-order mode exhibits a more wave-like motion (smaller wavelengths).

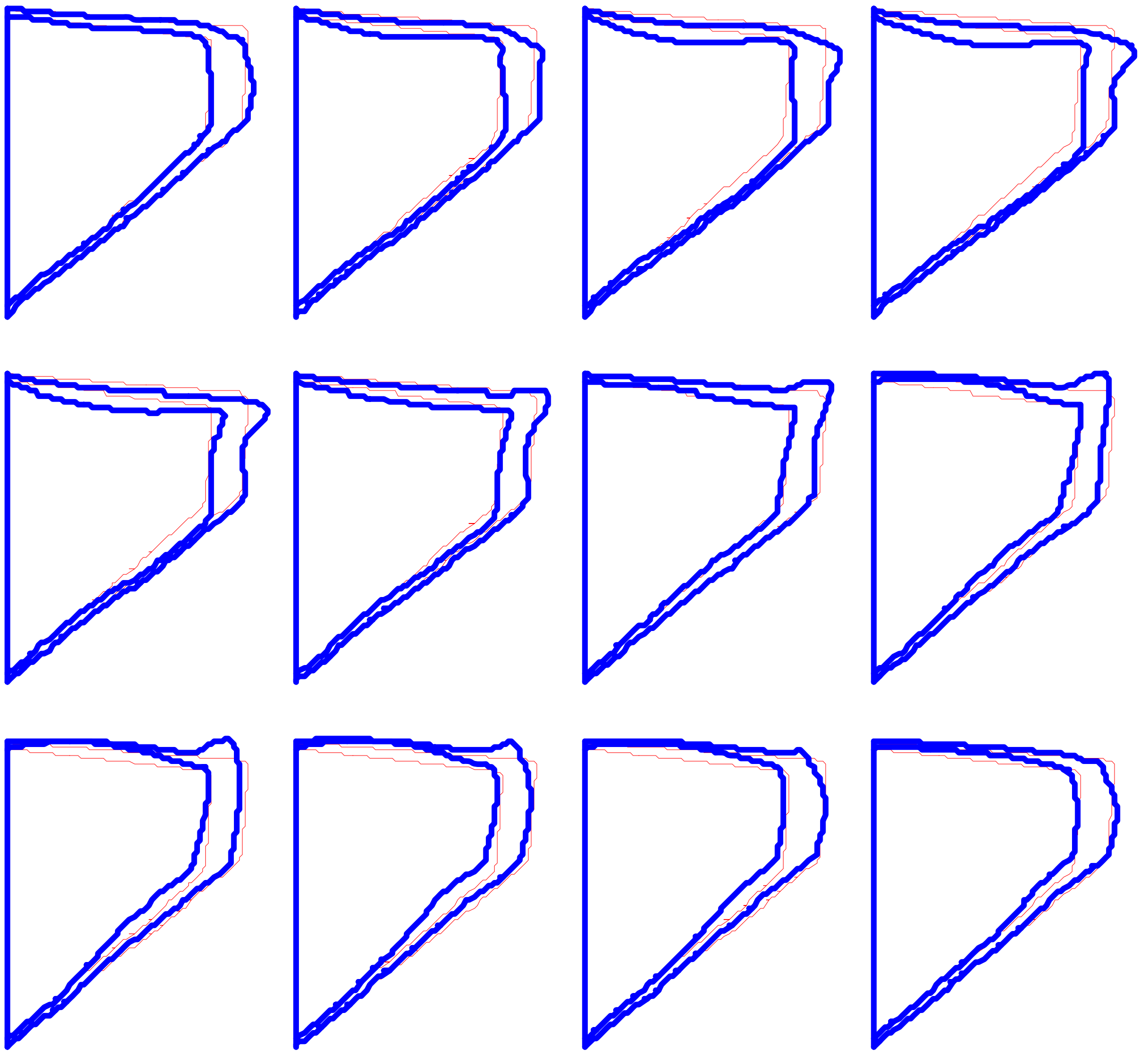
Vocal Fold Vibration



$E_b/E_c=6$

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

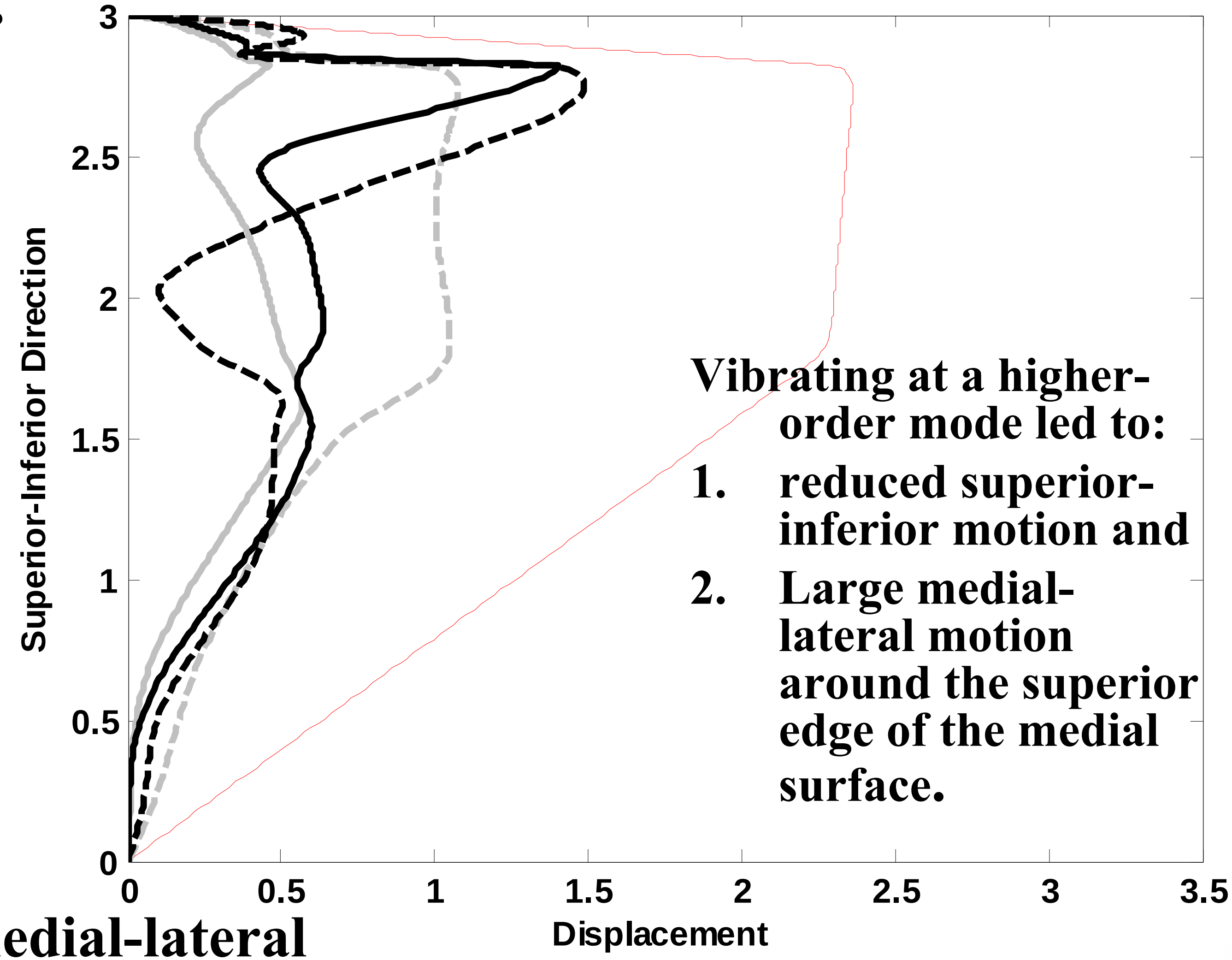
Vibrating at a higher-order mode led to reduced superior-inferior motion and a smaller wavelength and therefore a wave-like motion

Vocal fold Surface Displacement

dark lines:
$E_b/E_c=7$

gray lines:
$E_b/E_c=6$

Red lines:
vocal fold surface



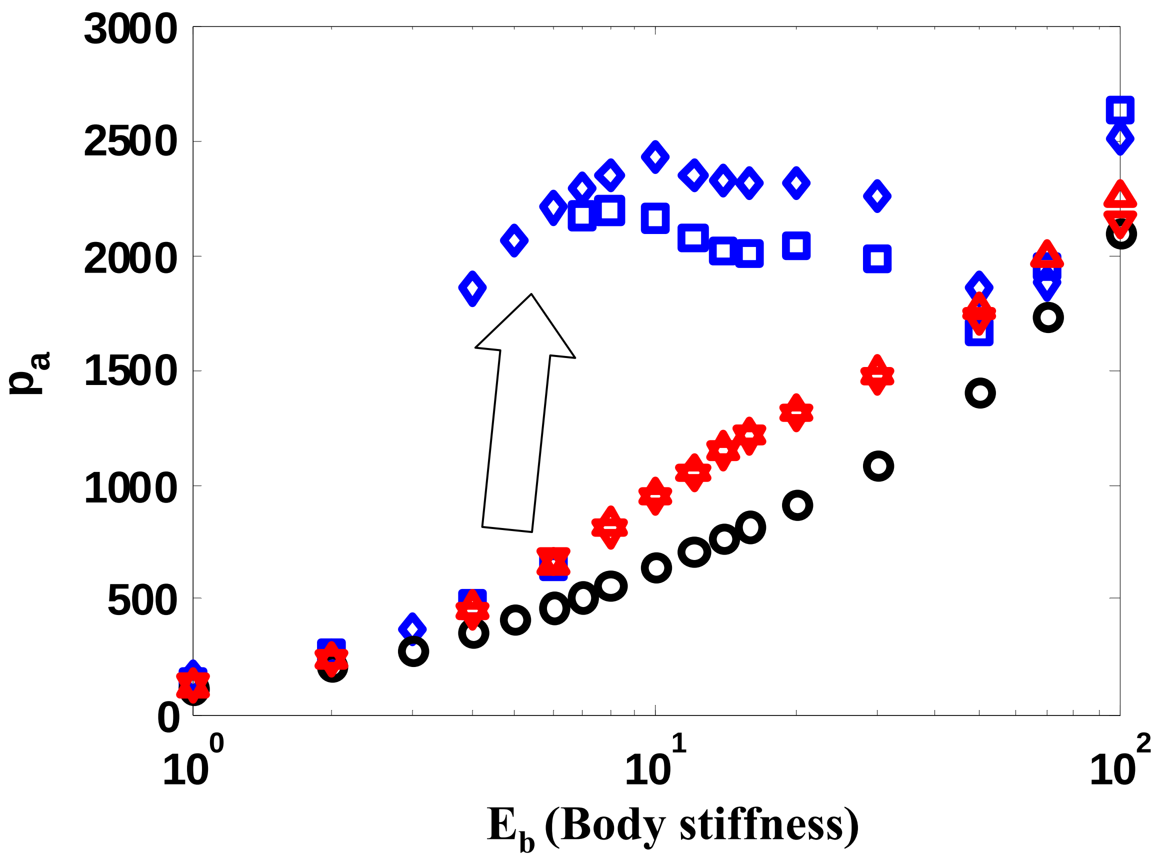
Vibrating at a higher-order mode led to:

1. **reduced superior-inferior motion and**
2. **Large medial-lateral motion around the superior edge of the medial surface.**

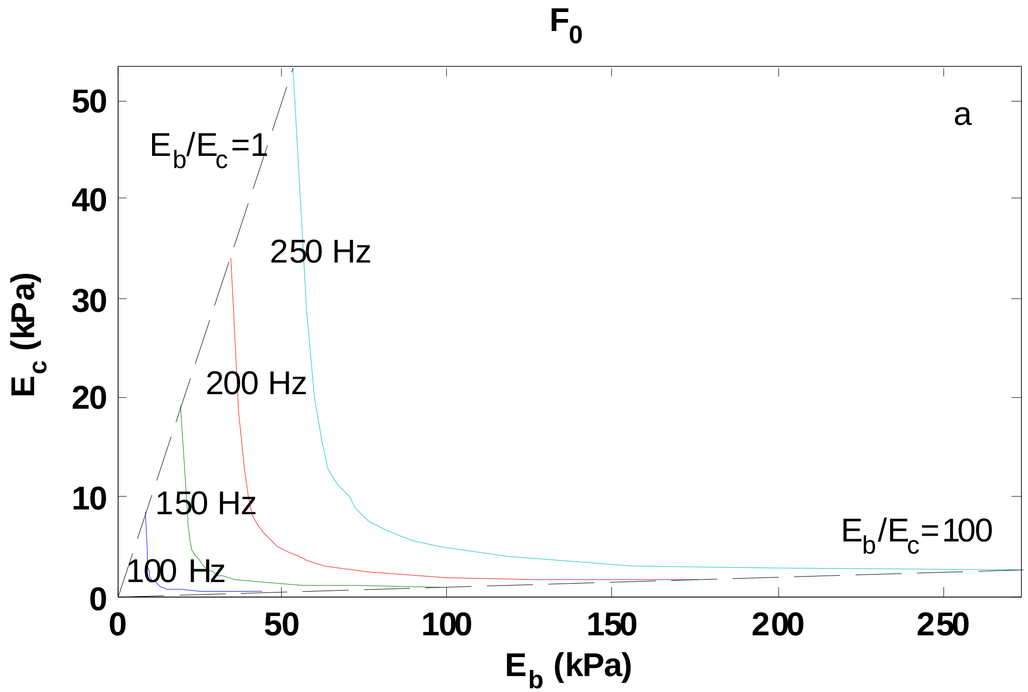
Solid lines: medial-lateral

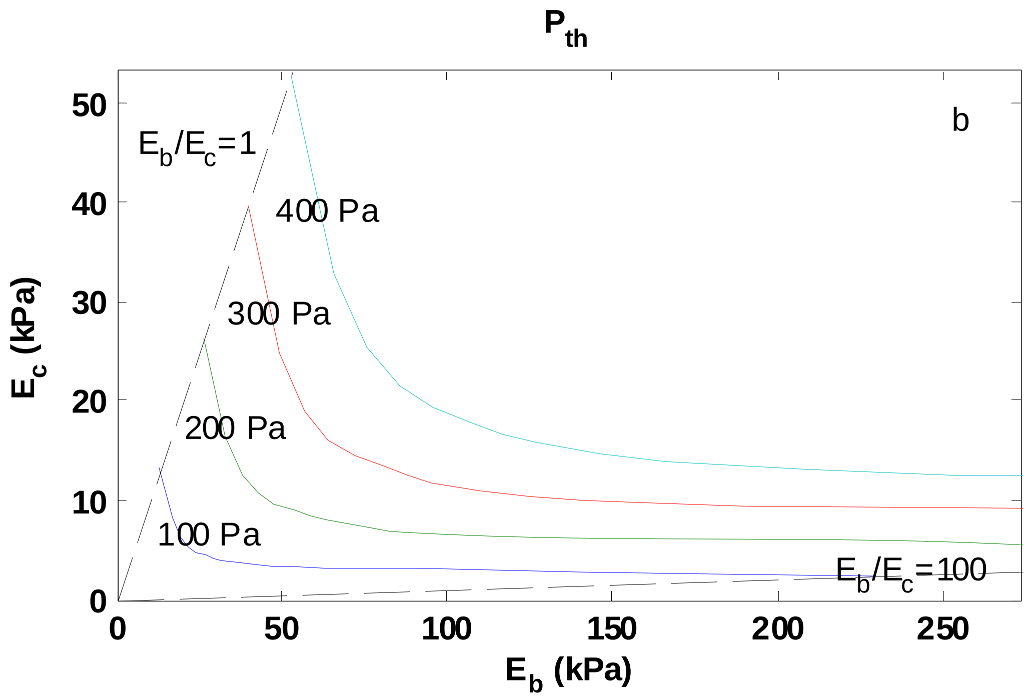
Dashed lines: inferior-superior

Red: divergent
Blue: convergent
Black: straight



Vibrating 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 achieved 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:

Zhang, Z., Neubauer, J., Berry, D., (2007), “Physical mechanisms of phonation onset: A linear stability analysis of an aeroelastic continuum model of phonation,” JASA, 122, 2279-2295.

Zhang, Z., Mongeau, L., Frankel, S., (2002), “Experimental verification of the quasi-steady approximation for aerodynamic sound generation by pulsating jets in tubes,” JASA, 112, 1652-1663.