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Factors affecting the phonation threshold pressure and frequency

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Motivation/Objective

- How vocal fold geometry and material properties affect voice production
  - Phonation threshold pressure
  - Phonation onset frequency
- A better understanding of physical mechanisms of phonation
  - Provide a theoretical knowledge base towards better planning of thyroplastic surgery.

Previous work

- Mucosal wave model: Titze (1988)

$$P_{th} = (2k_t / T) Bc \xi_{01}^{\ 2} / (\xi_{01} + \xi_{02})$$

  - k_t: transglottal pressure coefficient
  - B: mean damping coefficient
  - c: mucosal wave velocity
  - $\xi_{01,02}$: prephonatory glottal half-width
  - T: vocal fold thickness.

- The mucosal wave velocity is a dynamic variable of the coupled fluid-structure system, and its dependence on biomechanical properties is unclear

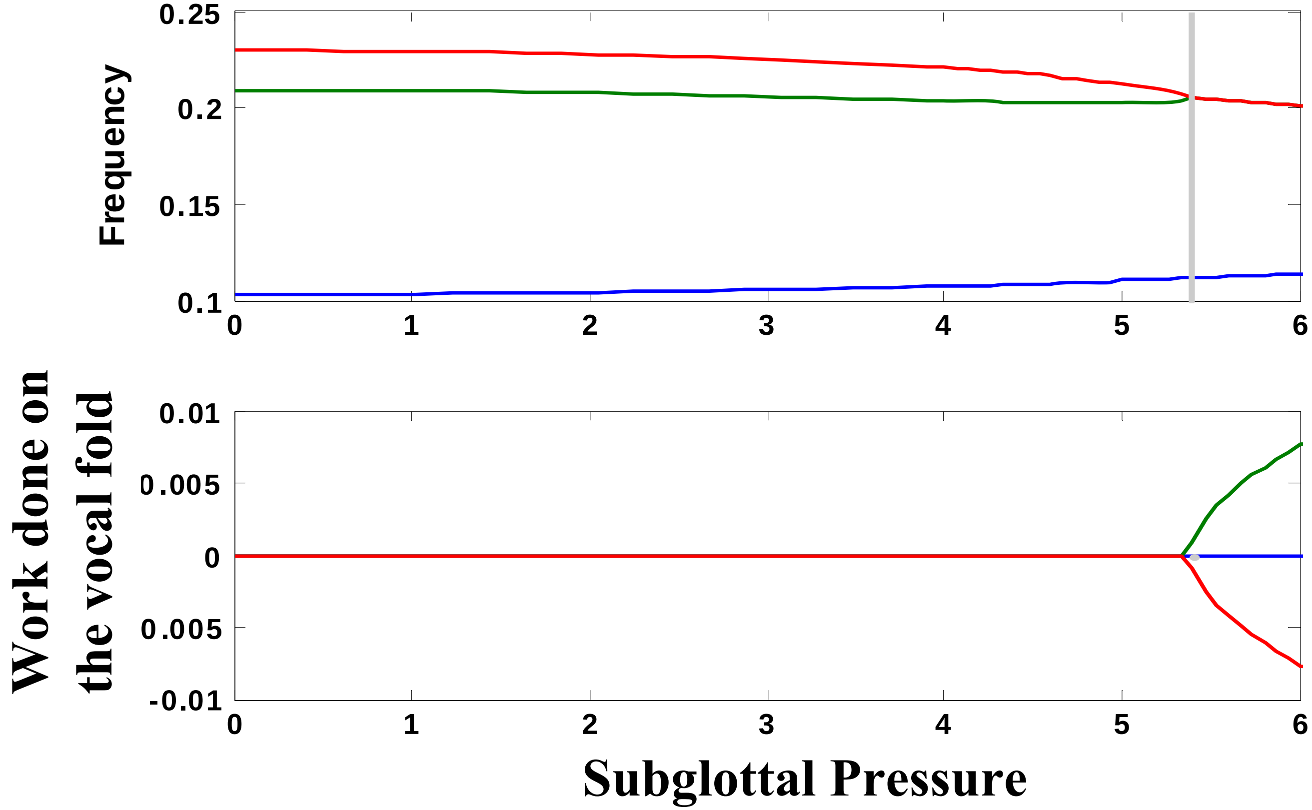
Previous work – cont'd

- Two-mass model, Ishizaka (1981)
- Linear stability analysis of the two-mass model
  - Phonation onset occurs as two modes of the two-mass model are synchronized by the glottal flow
  - Synchronization of two modes leads to a phase difference between the motions of the two masses.
- Lumped model: model parameters not directly related to physical variables of the vocal system.

Previous work – cont'd

- Continuum model of the coupled airflow-vocal fold system: Zhang et al. (2007)
- Continuum model of the vocal folds allow the effect of individual geometric parameter on phonation threshold pressure to be studied.
- Linear stability analysis of the continuum model showed:
  - Phonation onset occurs as two structural modes of the vocal fold are synchronized by the flow-induced stiffness of the glottal flow
  - Synchronization of two modes allows the flow pressure of one mode to interact with the velocity field of the other mode, and establishes an energy transfer from the flow into the vocal folds

Phonation onset occurs as two modes are synchronized by the flow-induced stiffness Q_0



Two eigenmodes merge and lead to phonation onset

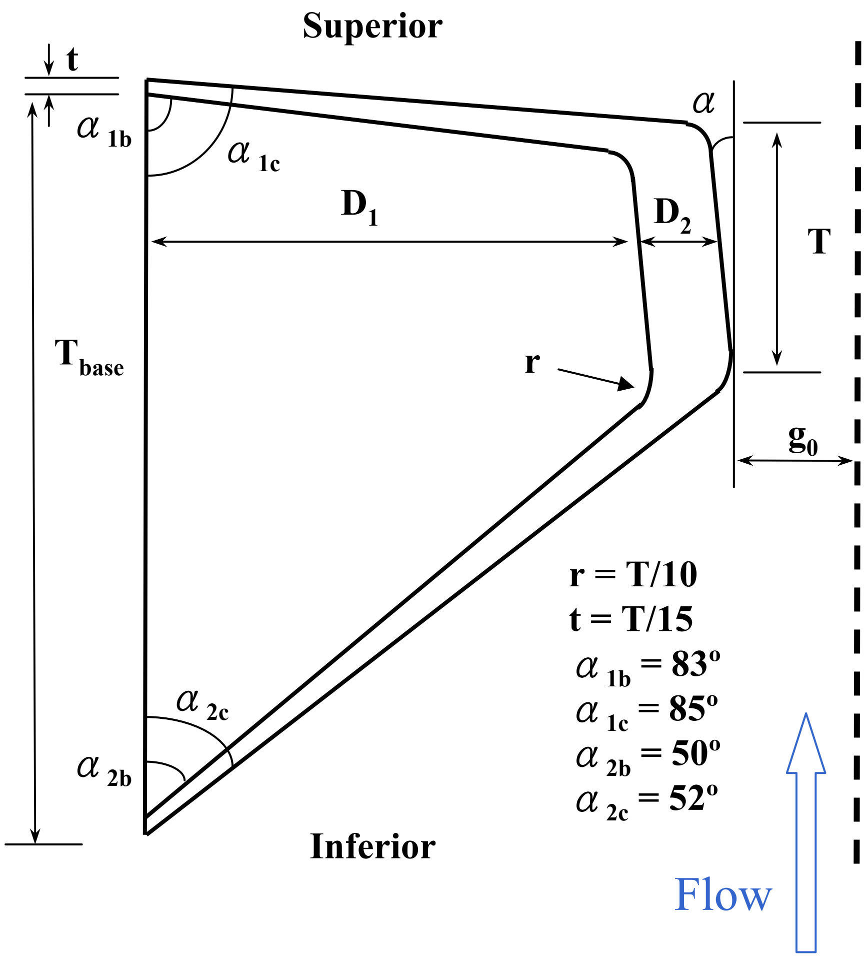
The net work done by the airflow on the vocal folds remains zero until the two modes synchronize

What determines how and which eigenmodes get synchronized?

In This Study

- Examine the factors affecting the synchronization process:
  - Use the continuum model of Zhang et al. (2007)
  - 1. To illustrate the factors affecting Pth and F0,
    - Two-mode approximation of the vocal fold motion
    - No structural or flow-induced damping
  - 2. Include more modes and damping terms
- Example: geometric dependence of PTP will be studied:
  - Medial surface thickness
  - Depth of cover layer
  - Over all depth of the vocal folds

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

Model Parameters Used

	Non-dimensional values	Physical value
Structural Damping Loss factor	0-0.4	0-0.4
VF Lateral Thickness T_{base}	1	9 mm
VF Cover Depth	variable	
VF Body Depth	varible	
Glottal Channel Gap	0.01	0.09 mm
VF Density	1	1030 kg/m^3
Flow Density	0.0012	1.2 kg/m^3

Model assumptions and Derivation of governing Equations of the coupled airflow-vocal fold system

For details see Zhang et al., 2007, JASA, 122, 2279-2295.

- Two-dimensional simplification
- Vocal fold
  - Plane strain isotropic for each layer
- 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.
- 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: **Onset occurs when the growth rate of one of the eigenvalues first becomes positive**
- Simulations Procedure
  - 1. Solve for steady state for a given flow rate at glottal entrance
  - 2. Perform linear stability analysis of the deformed state of the coupled airflow-vocal fold system. Solve the eigenvalue problem, checking for phonation onset. If no onset, increase flow rate, and repeat steps 1 and 2. If onset, stop.

Eigenvalue Problem

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

Structure

- **Mass:** $\boldsymbol{M}$
- **Stiffness:** $\boldsymbol{K}$
- **Damping:** $C = \sigma\omega M$

Flow:

$$Q = Q_2\ddot{q} + Q_1\dot{q} + Q_0 q$$

- Phonation onset occurs when the growth rate of one of the eigenvalues first becomes positive (linearly unstable)

Two-mode approximation

- Vocal fold motion [ξ, η] is approximated as the linear superposition of the first two natural modes of the vocal fold
  - ξ: medial-lateral direction; η: inferior-superior direction;
  - ϕ : natural modes of the vocal fold structure;
  - q: coefficients

$$\xi = q_1\varphi_{1,x} + q_2\varphi_{2,x}; \quad \eta = q_1\varphi_{1,z} + q_2\varphi_{2,z}$$

- The flow-induced stiffness matrix Q_0:

$$Q_0 = \gamma \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}$$

$$\gamma = \frac{1}{2}\rho_f U_0^{\ 2},\ a_{ij} = \frac{4}{g_0}\frac{\int_{l_{fsi}}[(\frac{g_0}{H_0}\varphi_{j,x} - \varphi_{j,x}^{\ *})\varphi_{i,x}n_x + (\frac{g_0}{H_0}\varphi_{j,x} - \varphi_{j,x}^{\ *})\varphi_{i,z}n_z)]dl}{\int_V \rho_{vf}(\varphi_{i,x}^{\ 2} + \varphi_{i,z}^{\ 2})dV}$$

Two-mode approximation and no damping terms

- Neglecting damping and flow inertial terms:

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

$$M\ddot{q} + (K - Q_0)q = 0$$

- Two-mode approximation:

$$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \end{bmatrix} + \begin{bmatrix} {\omega_{0,1}}^2 + \gamma a_{11} & \gamma a_{12} \\ \gamma a_{21} & {\omega_{0,2}}^2 + \gamma a_{22} \end{bmatrix}\begin{bmatrix} q_1 \\ q_2 \end{bmatrix} = 0$$

Solving the eigenvalue problem

- Assuming $q = q_0 e^{st}$, the characteristic equation of the eigenvalue problem is:

$$s^4 + [(\omega_{0,1}{}^2 + \gamma a_{11}) + (\omega_{0,2}{}^2 + \gamma a_{22})]s^2 + [(\omega_{0,1}{}^2 + \gamma a_{11})(\omega_{0,2}{}^2 + \gamma a_{22}) - \gamma^2 a_{12} a_{21}] = 0$$

$$s^2 = \frac{-[(\omega_{0,1}{}^2 + \gamma a_{11}) + (\omega_{0,2}{}^2 + \gamma a_{22})] \pm \sqrt{[(\omega_{0,1}{}^2 + \gamma a_{11}) - (\omega_{0,2}{}^2 + \gamma a_{22})]^2 + 4\gamma^2 a_{12} a_{21}}}{2}$$

- Onset conditions: eigenvalues lie on the imaginary axis in the state space until onset. At onset:

$$[(\omega_{0,1}{}^2 + \gamma a_{11}) - (\omega_{0,2}{}^2 + \gamma a_{22})]^2 + 4\gamma^2 a_{12} a_{21} = 0$$

Solving the eigenvalue problem - II

$$[(\omega_{0,1}{}^{2} + \gamma a_{11}) - (\omega_{0,2}{}^{2} + \gamma a_{22})]^2 + 4\gamma^2 a_{12}a_{21} = 0$$

Phonation threshold pressure *P_{th}*

$$\gamma_{th} = \frac{\omega_{0,2}{}^{2} - \omega_{0,1}{}^{2}}{a_{11} - a_{22} + 2\sqrt{-a_{12}a_{21}}}$$

Phonation onset frequency *F_0*

$$\omega_{th} = \sqrt{\frac{\omega_{0,1}{}^{2} + \omega_{0,2}{}^{2} + \gamma_{th}(a_{11} + a_{22})}{2}}$$

P_{th}* and *F_0

$$\gamma_{th} = \frac{1}{a_{11} + a_{22}}(2\omega_{th}{}^{2} - \omega_{0,1}{}^{2} - \omega_{0,2}{}^{2})$$

Phonation threshold pressure

$$\gamma_{th} = \frac{\omega_{0,2}{}^2 - \omega_{0,1}{}^2}{a_{11} - a_{22} + 2\sqrt{-a_{12}a_{21}}} = \frac{\omega_{0,2}{}^2 - \omega_{0,1}{}^2}{\alpha}$$

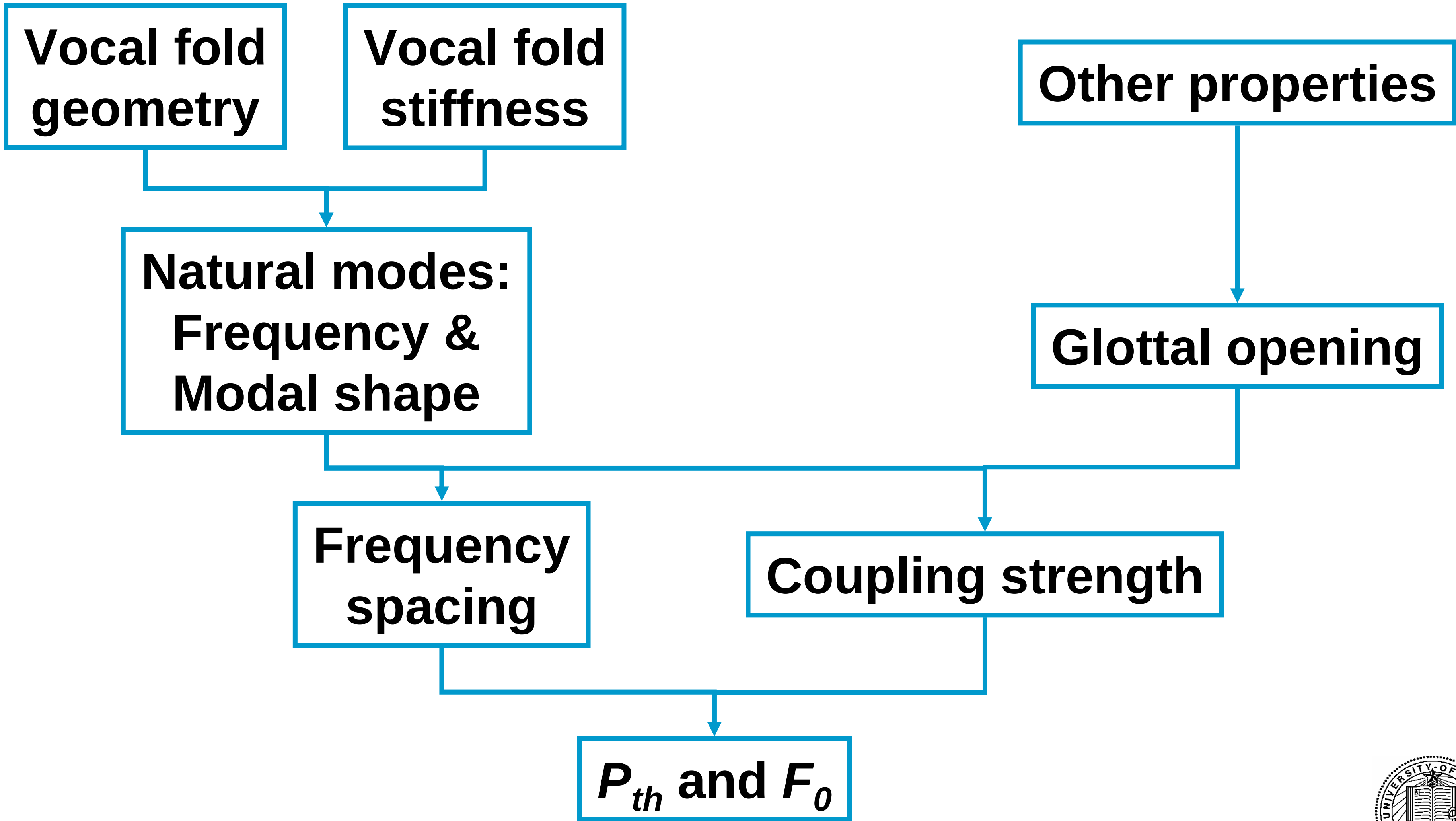
- Phonation threshold pressure depends on:
  - Frequency spacing between the two natural modes being synchronized: $\omega_{0,2}{}^2$ - $\omega_{0,1}{}^2$;
  - Coupling strength between these two modes due to fluid-structure coupling.
- Both two are completely determined by the properties of the vocal folds, including:
  - Material properties: stiffness
  - Geometry

Phonation onset frequency

$$\omega_{th} = \sqrt{\frac{\omega_{0,1}{}^2 + \omega_{0,2}{}^2 + \gamma_{th}(a_{11} + a_{22})}{2}}$$

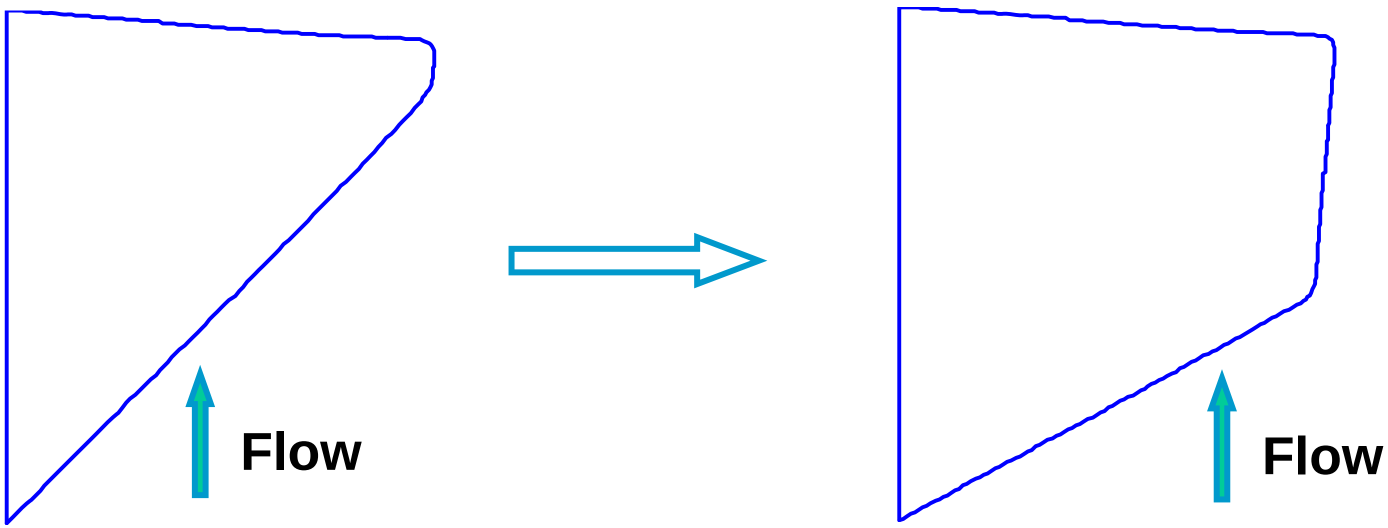
- Phonation onset frequency depends on:
  - Natural frequency of the two natural modes being synchronized: $\omega_{0,2}$ and $\omega_{0,1}$;
  - Ability of the flow to merge the two modes.
- The value of phonation onset frequency can be
  - in between the two natural frequencies,
  - or quite lower than either of the two, depending on the threshold pressure or presence of damping.

Factors affecting P_{th} and F_0



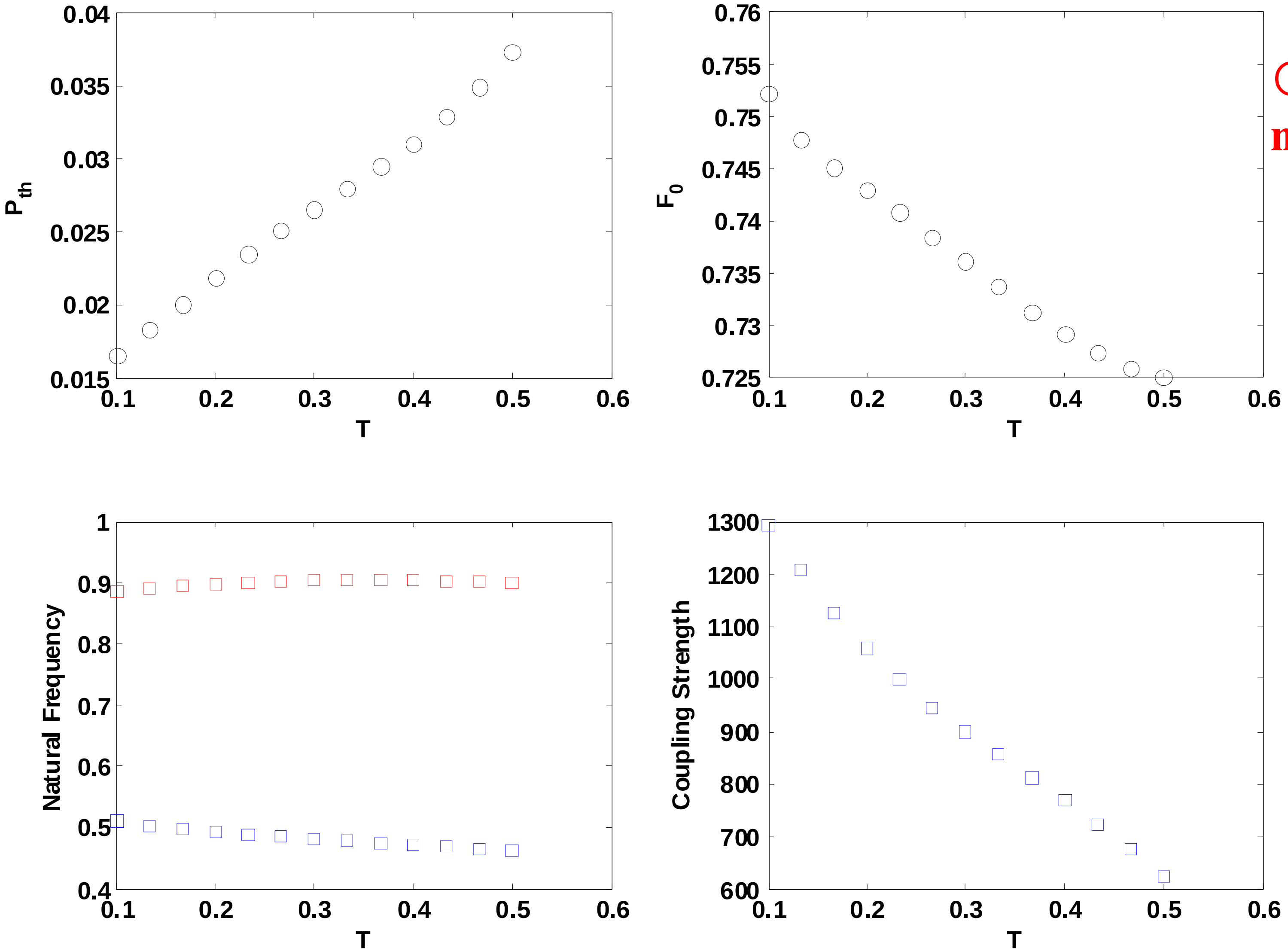
Example

- Effects of Medial Surface Thickness *T*



Medial surface thickness T

***D*$_1$=0.17, *D*$_2$=0.67, convergent**



○: two-mode, no damping.

Coupling strength:

Blue: 1 &2

Effects of high-order modes

When there are more than two modes present:

- Synchronization can occur at a different pair of eigenmodes
- Competition between different pairs of eigenmodes to reach onset first
- Sudden changes in phonation onset frequency F_0

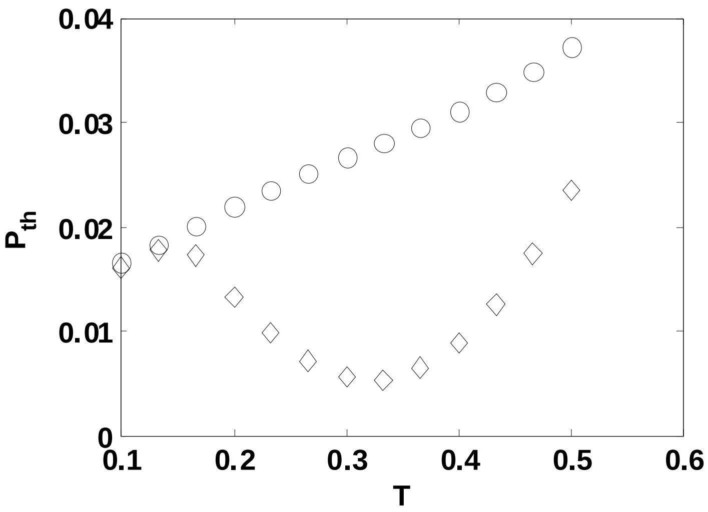
Coupling Strength

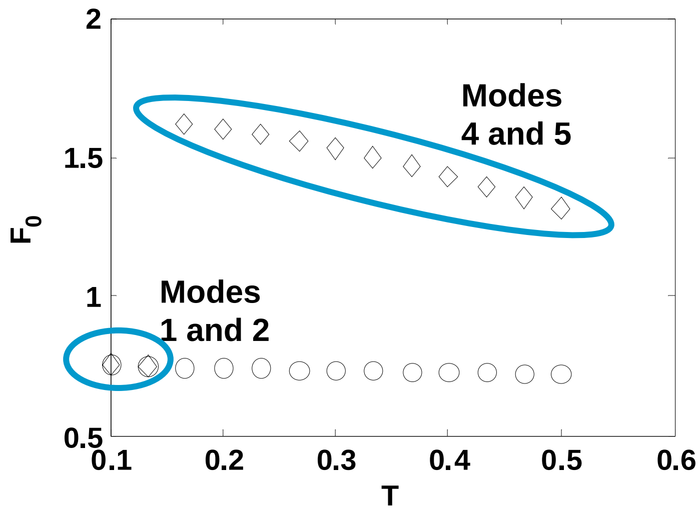
T=0.33
D_1=0.17
D_2=0.67
convergent

Coupling Strength	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
Mode 1		767.22			962.33
Mode 2			82.432	17.939	
Mode 3				S.D.	924.2
Mode 4					904.46
Mode 5					

S.D.: static divergence, or a zero-frequency instability

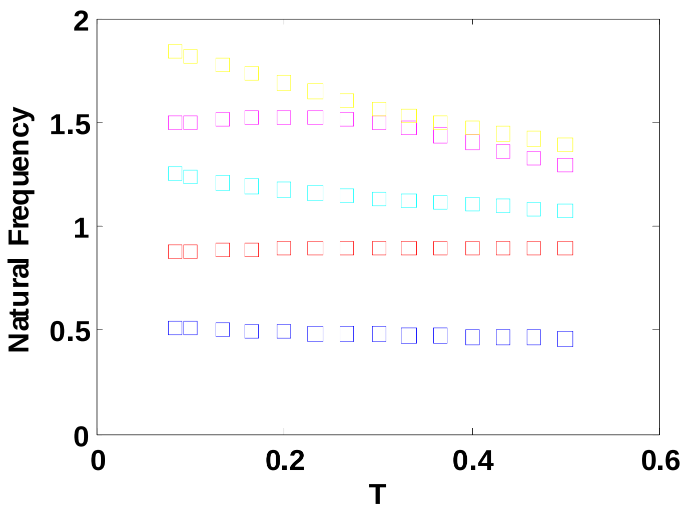
Medial surface thickness T

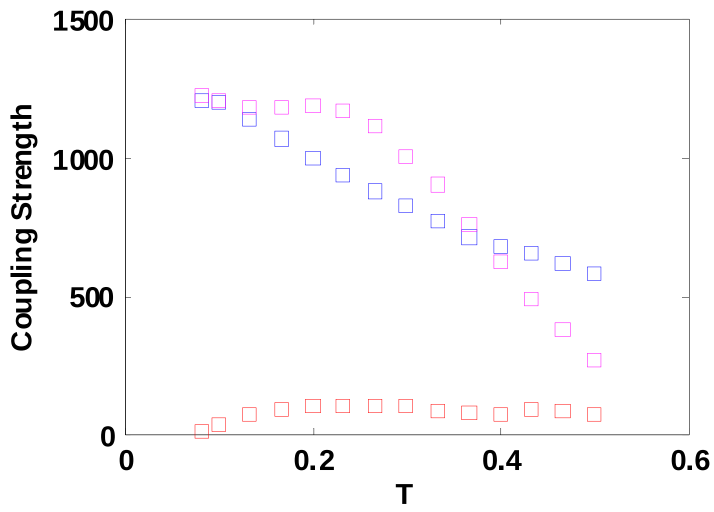




○: two-mode, no damping;

◊ : 10-modes, no damping;





Coupling strength:

Blue: 1 &2

Red: 2 &3;

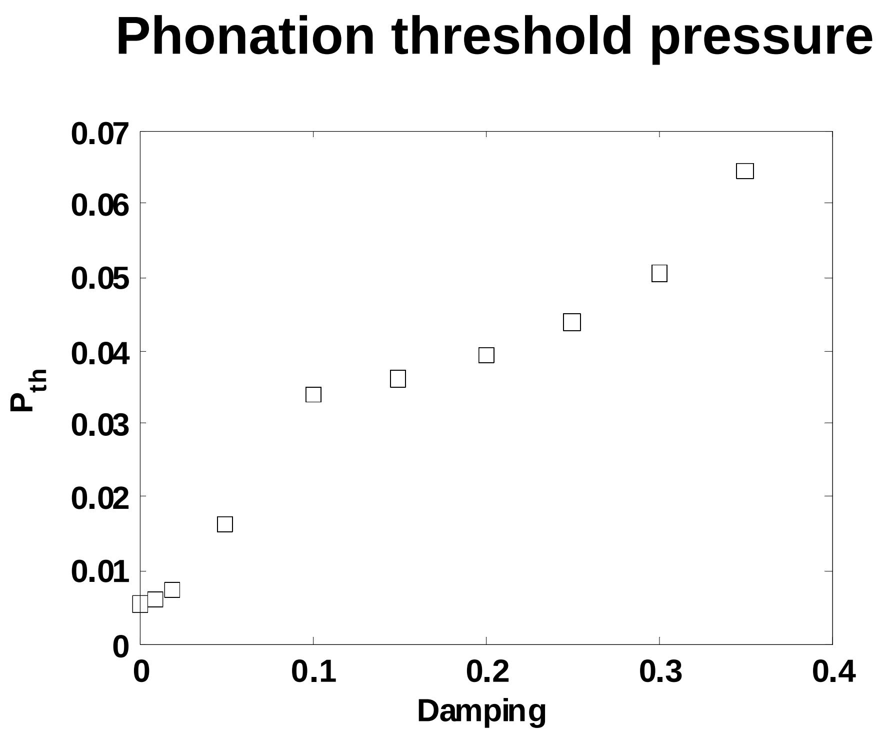
Purple: 4&5.

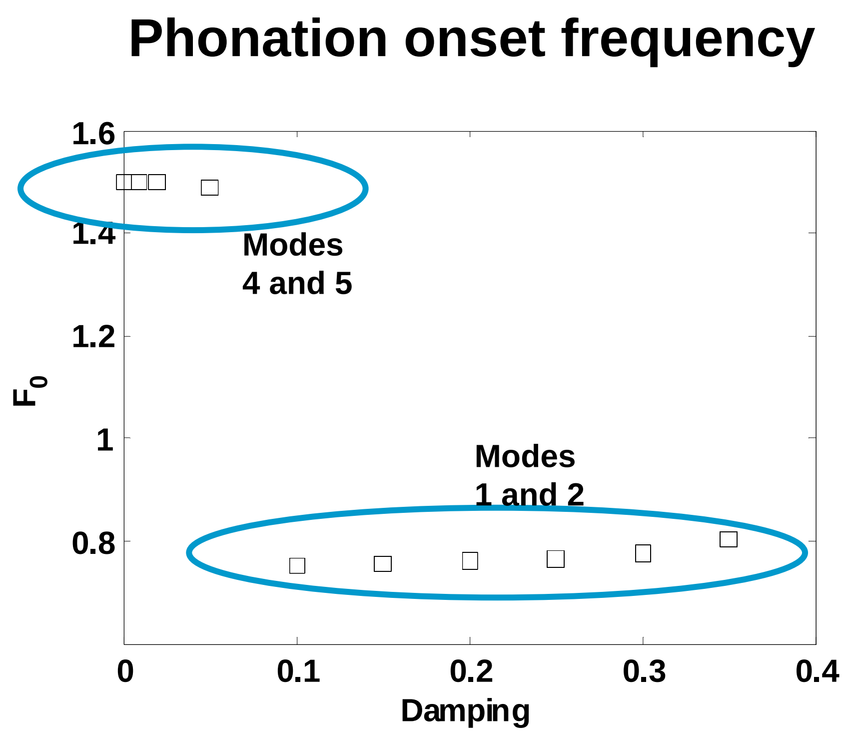
Effects of damping

When damping (structural or flow) is included:

- Delay phonation onset to a higher threshold pressure
- May change the relative dominance of one pair of eigenmode over the other at onset, causing sudden changes in phonation onset frequency F_0
- Stabilize higher-order modes so that phonation onset is more likely to occur as two lower-order modes become synchronized
  - if the damping is larger at higher frequencies so that a strong coupling and high threshold pressure are needed to reach onset

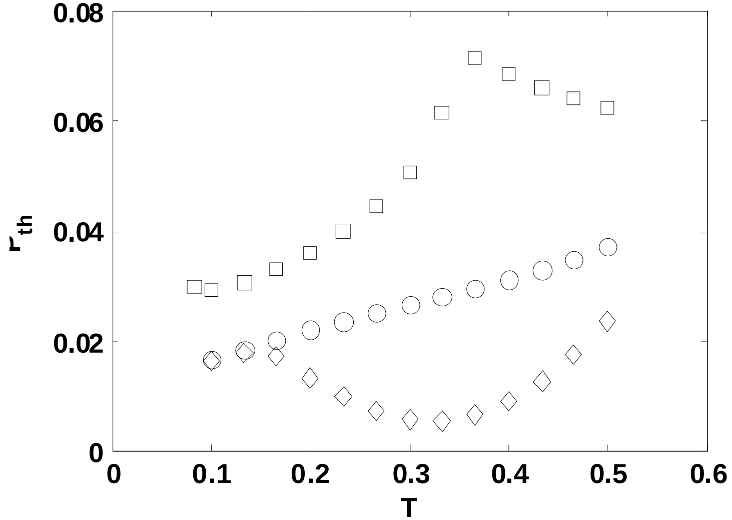
Inclusion of damping may change the relative dominance of eigenmode groups at onset

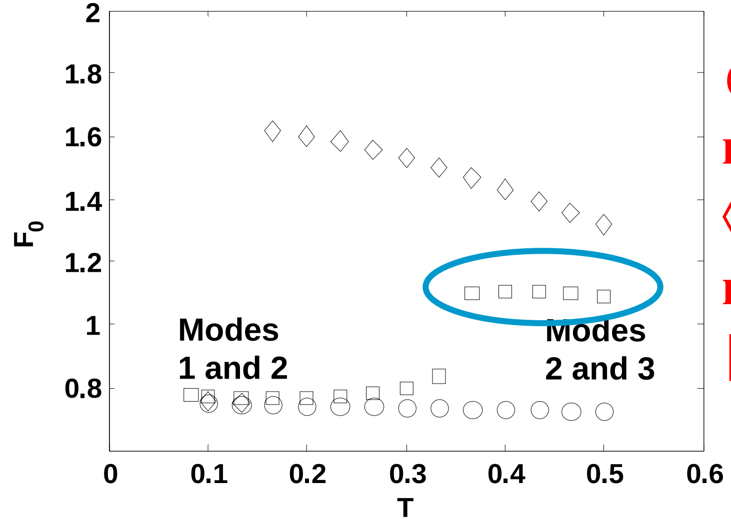




vocal fold geometry remained unchanged when the damping was varied

Large damping at high frequencies lowers the chance for higher-order modes to be destabilized at onset

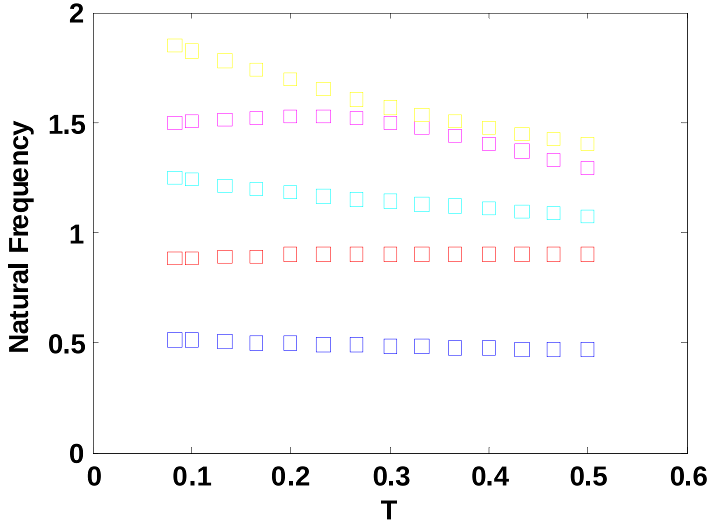


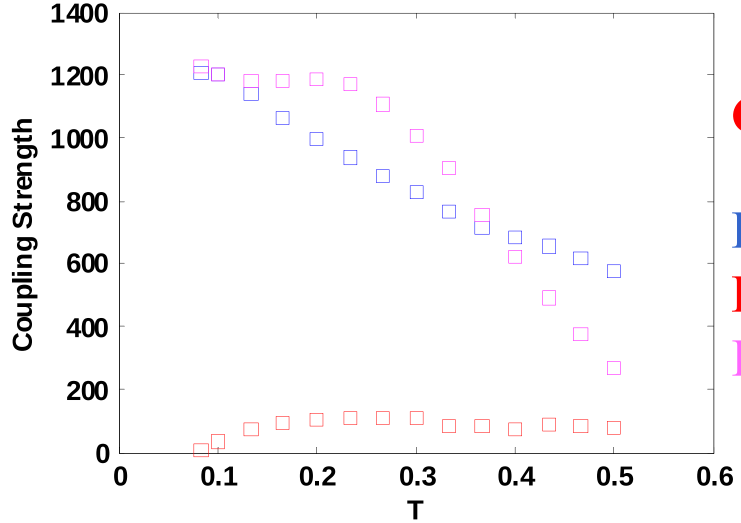


○: two-mode, no damping;

◊ : 10-modes, no damping;

□: 10-modes, with damping, σ =0.4





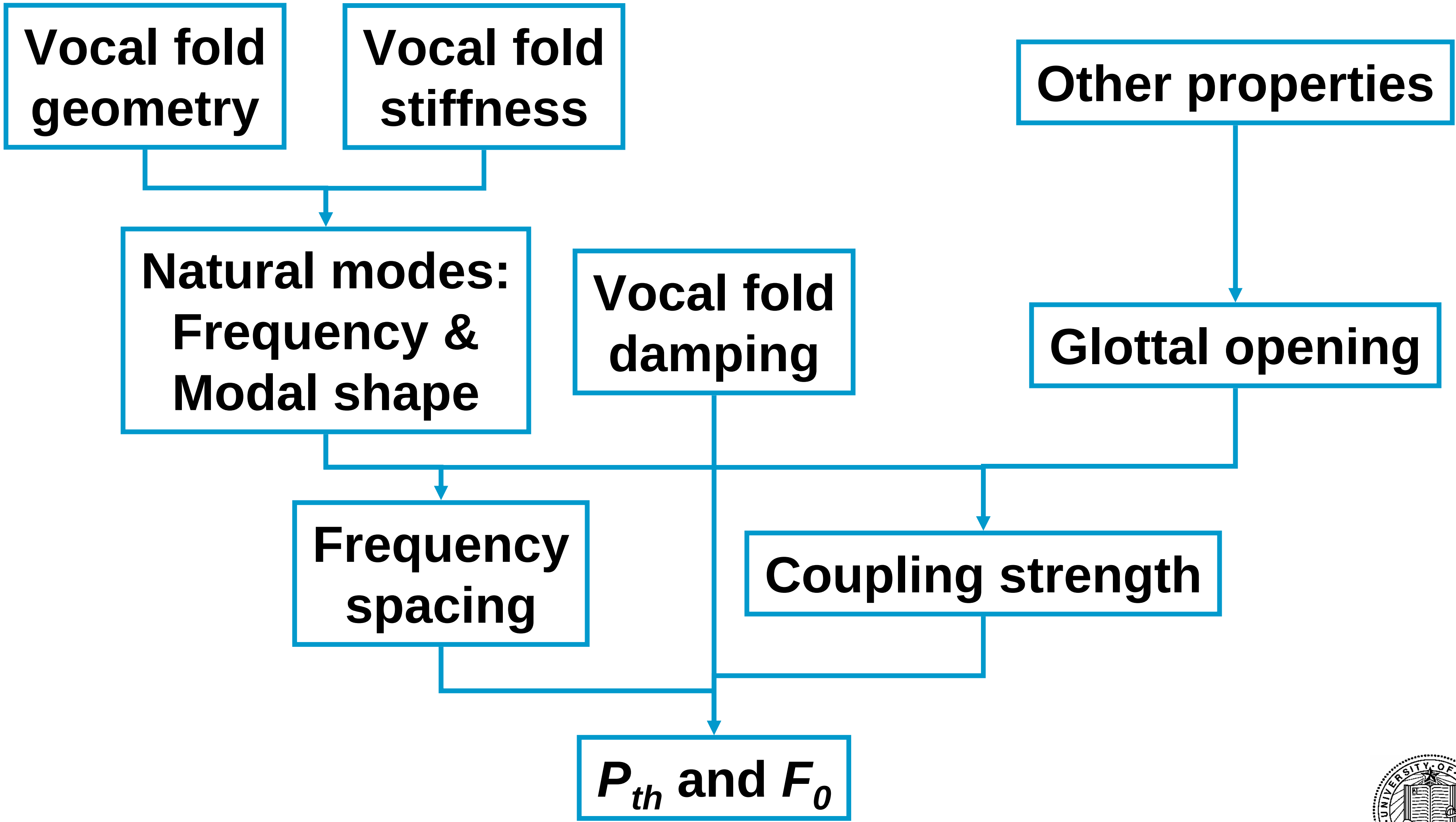
Coupling strength:

Blue: 1 &2

Red: 2 &3;

Purple: 4&5.

Factors affecting P_{th} and F_0 -- updated



Summary

- Phonation threshold pressure depends on the frequency spacing and coupling strength between corresponding natural modes of the vocal fold structure.
- For accurate prediction of P_{th} and F_0:
  - Higher-order modes need to be modeled
    - More than two modes can interact with each other
    - There are more than one group of eigenmodes that are synchronized and compete for dominance.
  - Accurate description of vocal fold biomechanical properties (geometry, material properties, in particular structural stiffness and damping)
    - Damping in the coupled system delays onset to a higher threshold pressure,
    - Damping may also determine which group of interacting eigenmodes becomes unstable and reaches onset first.

Reference

Ishizaka, K. (1981). “Significance of Kaneko’s measurement of natural frequencies of the vocal folds,” in *Vocal Physiology: Voice Production, Mechanisms and Function*, edited by Osamu Fujimara (Raven, New York), pp. 181-190.

Titze, I.R. (1988), “The physics of small-amplitude oscillation of the vocal folds,” JASA, 83, 1536-1552.

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