Viscous Flow Features in Normal and Pathological Voiced Speech

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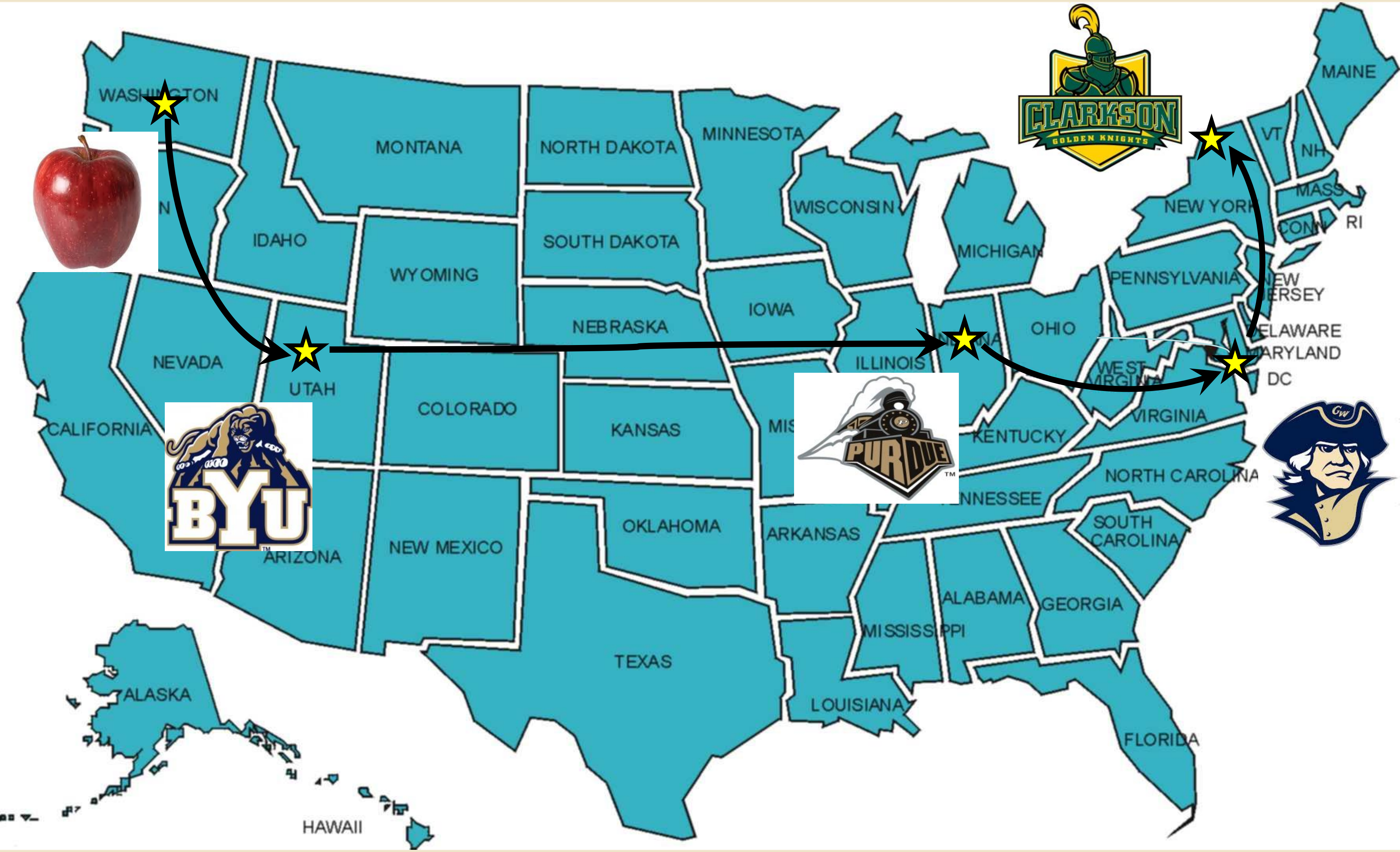
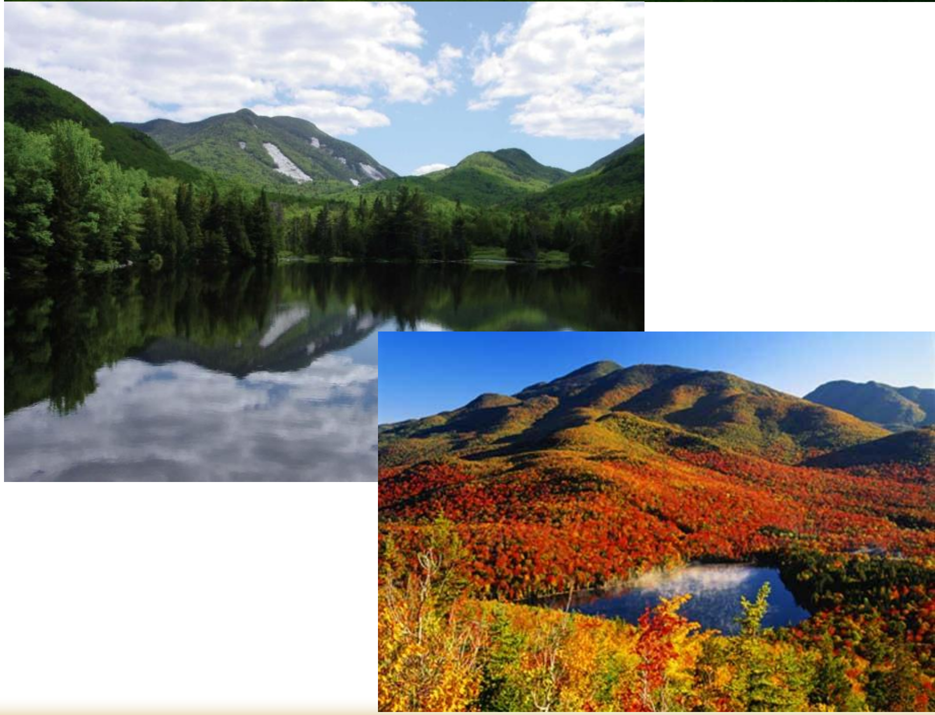
Clarkson, and How I Got There



Clarkson University

- ~3,300 students
- ~25% Mechanical Engineering majors (> 60% engineering majors – Civil, Chemical, Electrical)
- Ranked #1 in USA for students with most internship experience
  - 86% of graduates have internship experience
- Clarkson is 1 of 12 Universities in the USA whose graduates earn more than Harvard graduates



Importance of Speech

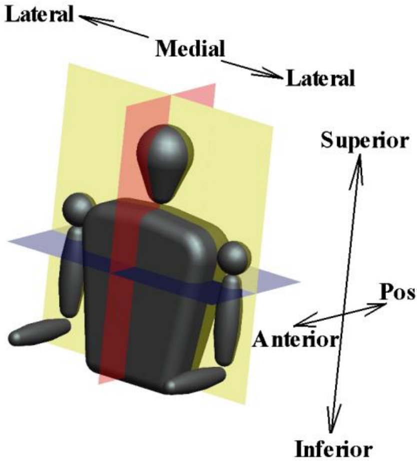
- A few statistics:
  - Voice disorders affect ~ 15 – 20 million US residents
  - 7% of employed individuals miss at least one day of work annually
  - Prevalence of voice disorders as high as 60% among professional voice users (e.g. educators)
  - Estimated cost of voice disorders in teachers ~ $2 billion annually

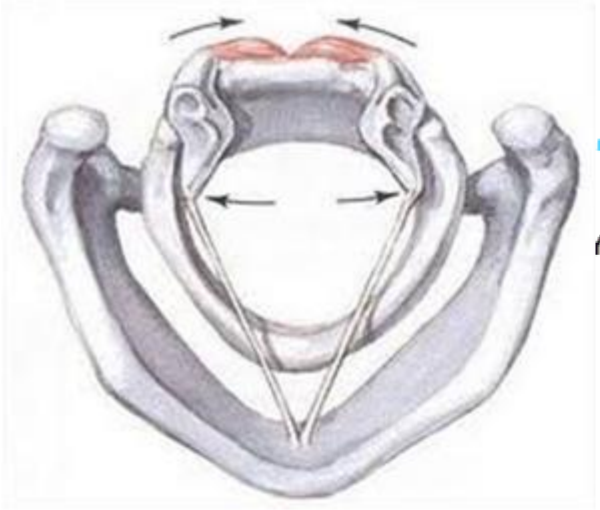
Unilateral vocal fold paralysis

Spasmodic dysphonia

(www.entusa.com)

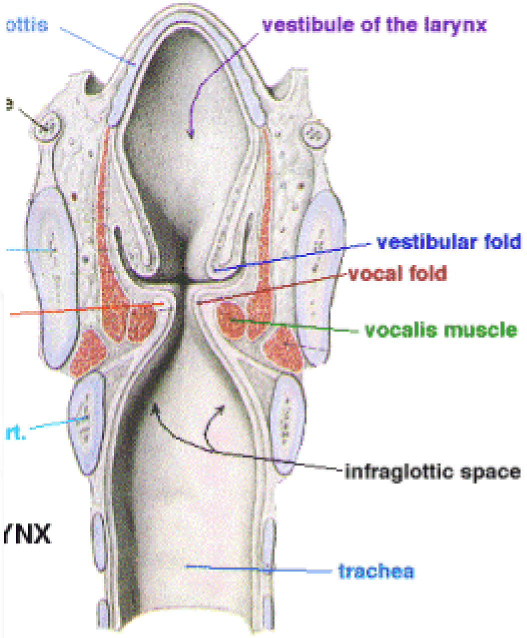
Physiology of Speech





(www.yorku.ca)

Top View



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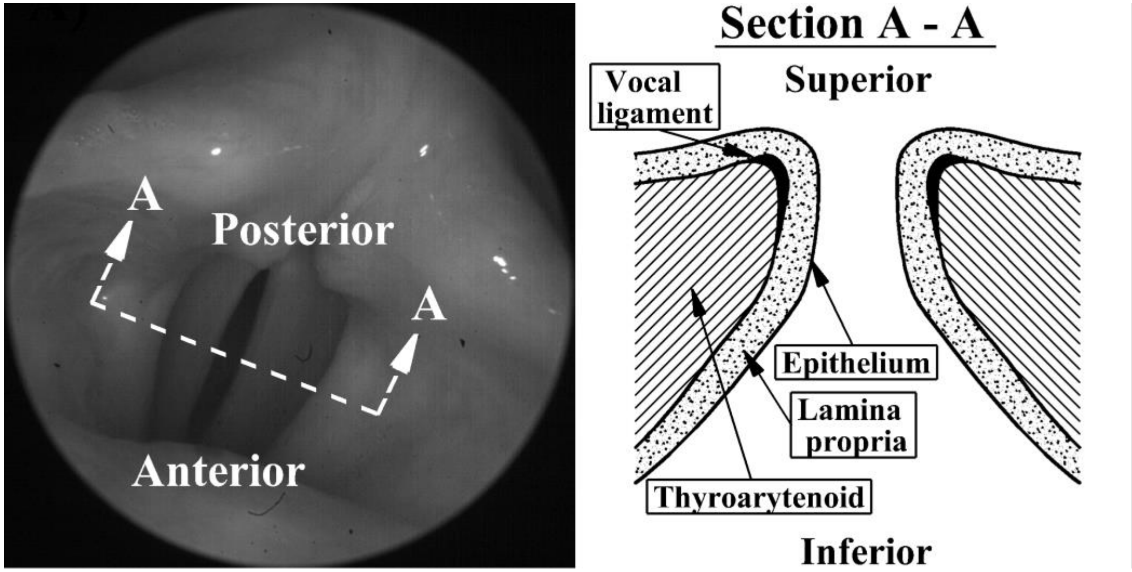
Front Section

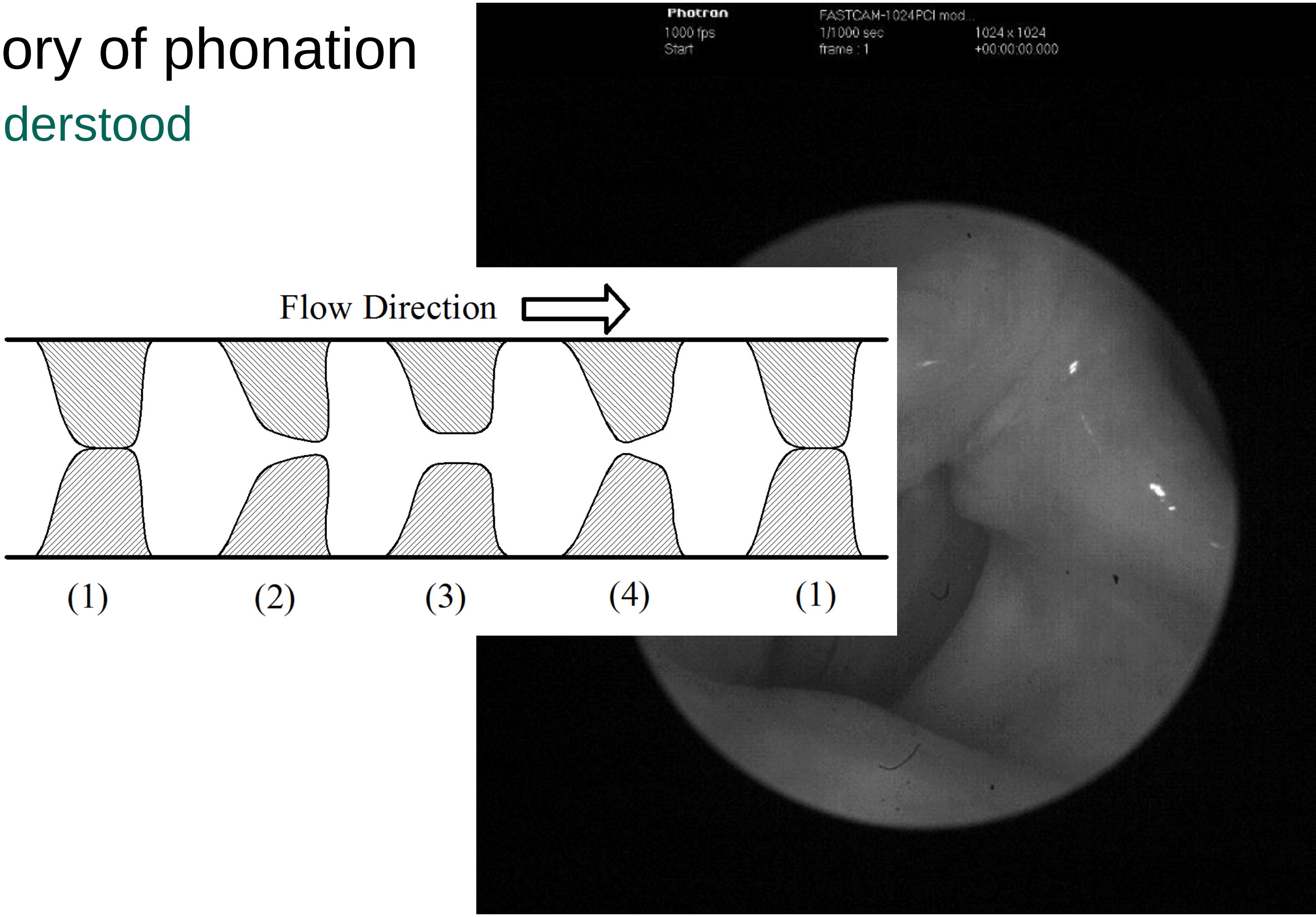
VF Structure



- 5 Layered structure
  - Thyroarytenoid muscle. Deep, Intermediate, and Superficial layers of lamina propria. Epithelium
  - Body-Cover
    - Oscillations occur in the cover

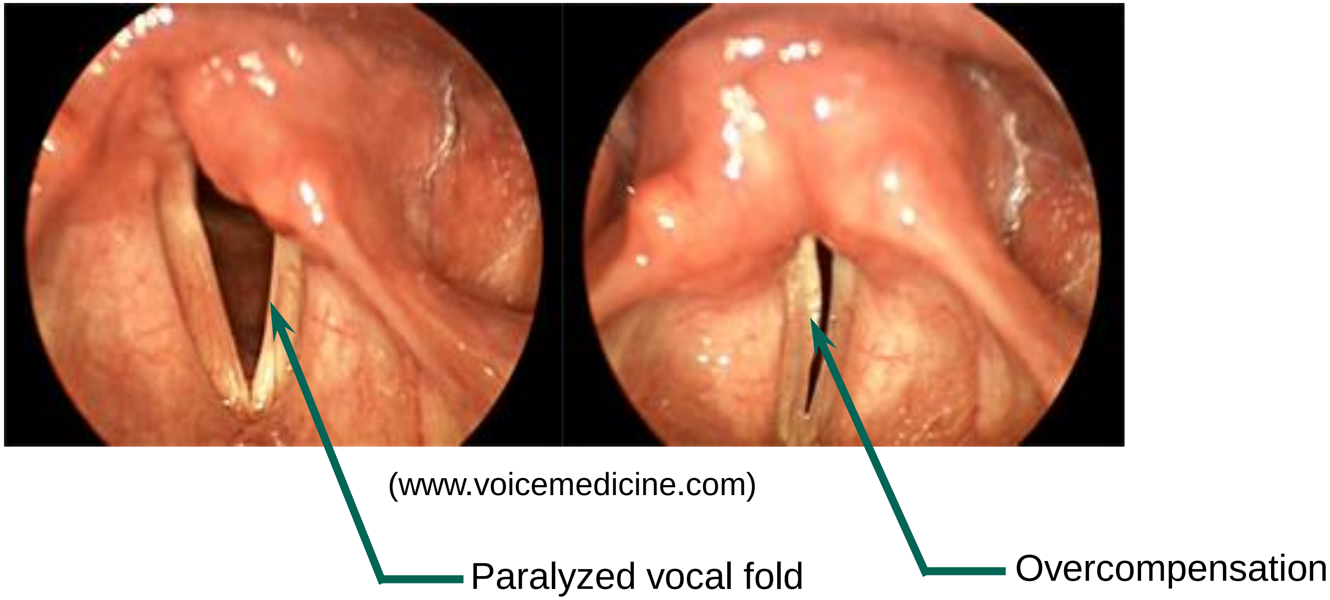
Basics of VF Dynamics

- Myoelastic theory of phonation
  - Basics well understood



Disruption of the Speech Process

Paralysis



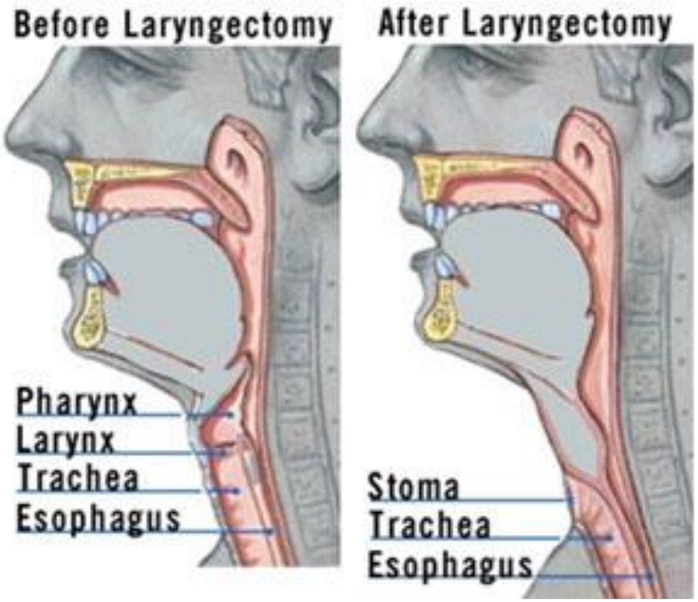
(www.voicemedicine.com)

Paralyzed vocal fold

Overcompensation

- Damaged vocal fold on right unable to adduct towards midline
- Vocal fold on left must overcompensate when adducted
  - Insufficient glottal closure

Laryngectomy

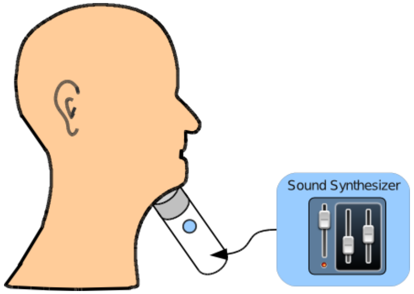


(www.med.nyu.edu)

- Laryngectomy completely removes larynx
- Creates a stoma with the trachea, and seals off the esophagus
- Conventional speech completely lost

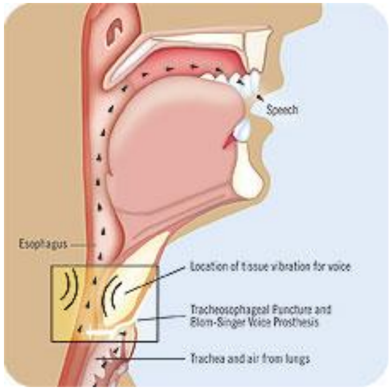
Remediations

- Electrolarynx



(www.griffinlab.com)

- Tracheoesophageal puncture



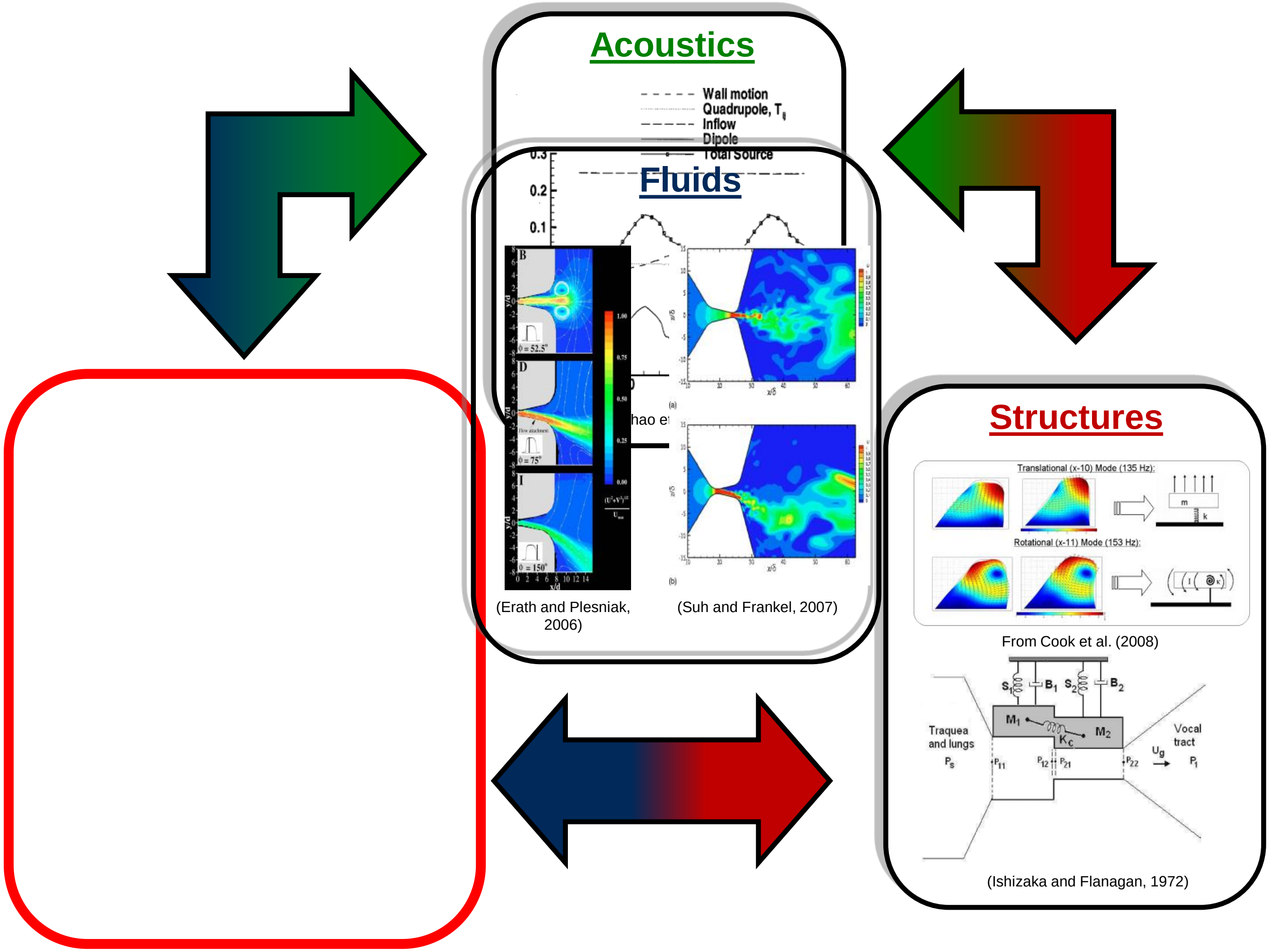
(www.inhealth.com)

(www.webwhispers.org)

Objectives

- Identify predominant intraglottal flow features of voiced speech
- Quantify impact of fluid loading on structural vocal fold response and acoustic output
- Evaluate interactions for both normal and pathological speech

Speech: A Multi-Disciplinary Problem



(Erath and Plesniak, 2006)

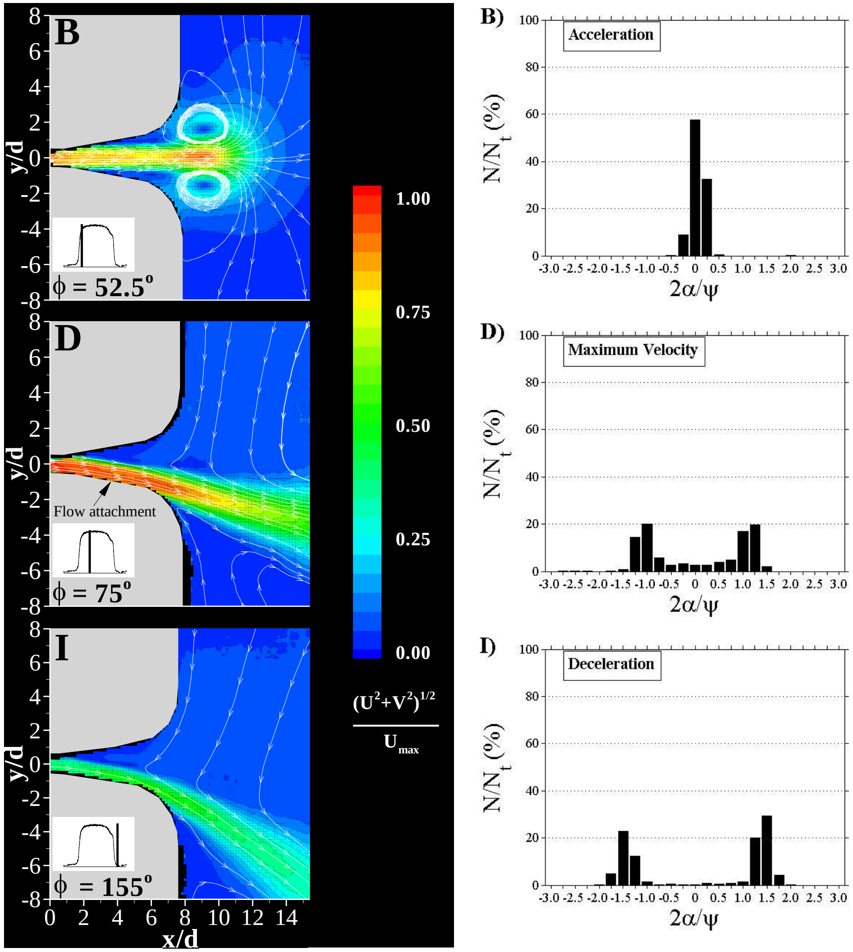
(Suh and Frankel, 2007)

From Cook et al. (2008)

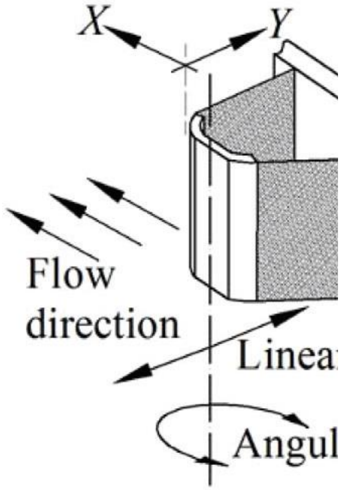
(Ishizaka and Flanagan, 1972)

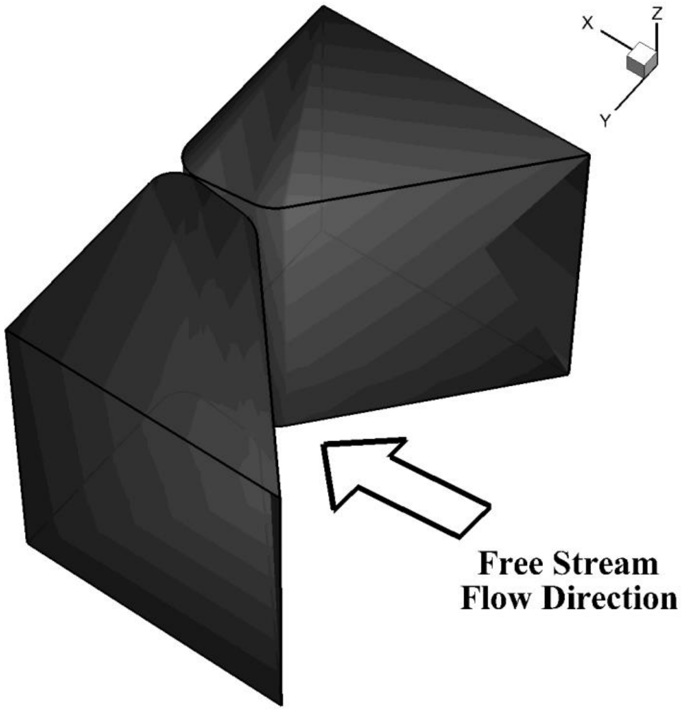
Laryngeal Aerodynamics

- Historically based on assumption of 1-D, inviscid flow
  - Solved by Bernoulli's equation
- Particle Image Velocimetry (PIV) for static divergent models
- Pulsatile flow field
- Asymmetric flow attachment
- Bimodal distribution of jet trajectory



Intraglottal Flow Features



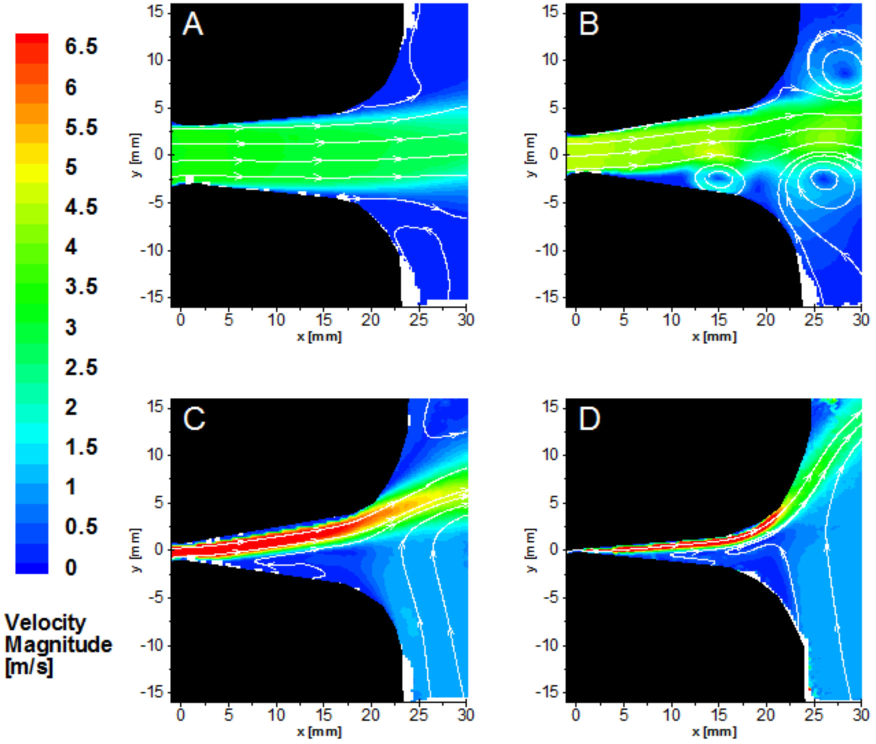


Variable	Life-size	
Scale	1	
VF gap [cm]	0.044	0.30
f_o [Hz]	80 – 250	1.78
U_c [m/s]	0 – 45	7.40
Re	0 – 4,000	0 – 1,470
St	0.0001 – 0.01	0.0007

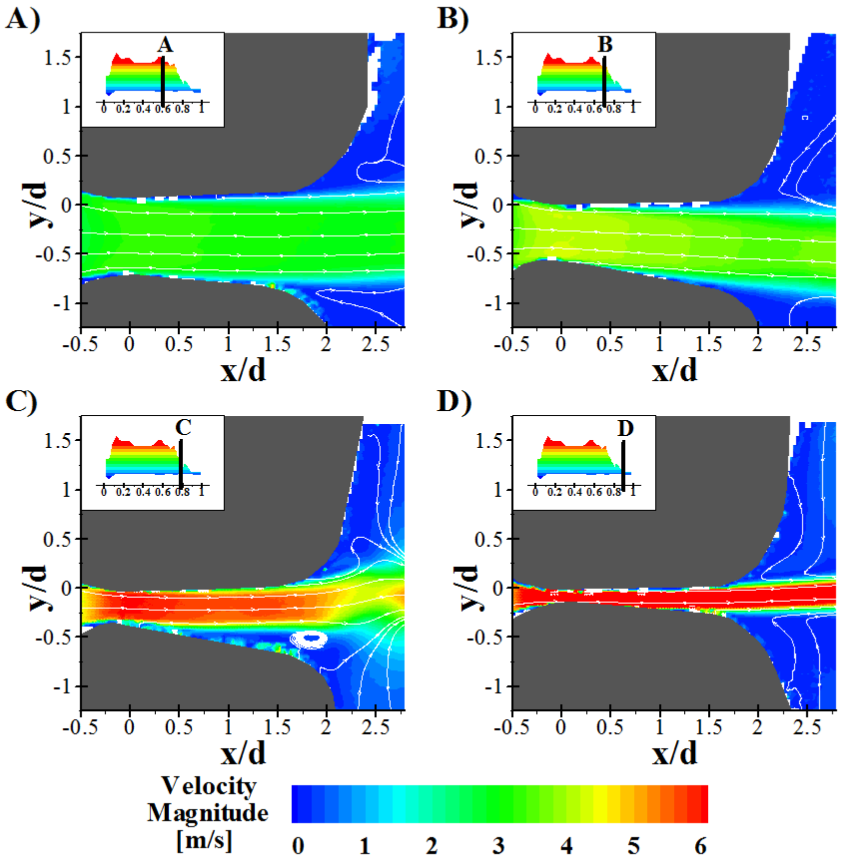
Intraglottal Flow Features

Normal Vocal Fold Motion

Q = 253.0 [mL/s]



Paralyzed Vocal Fold Motion

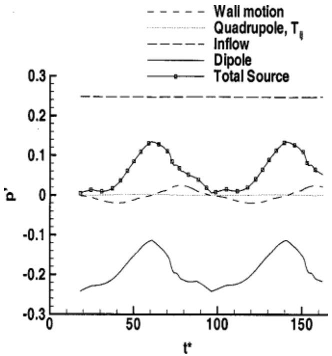


Summation: Laryngeal Aerodynamics

- Viscous flow phenomena during divergent portion of cycle
- Varying flow separation points at glottal exit
- Vortex formation within the glottis
- Intraglottal flow stability determined by divergence angle
- What is the impact on fluid-structure interactions?
  - Basic theory needs updated!

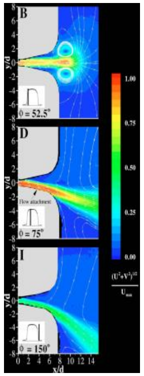
Speech: A Multi-Disciplinary Problem

Acoustics

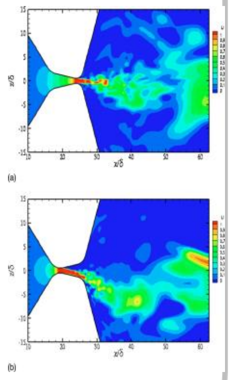


(Zhao et al., 2002)

Fluids

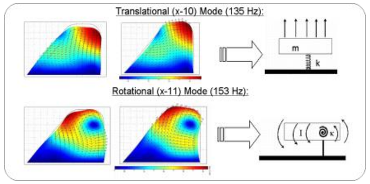


(Erath and Plesniak, 2006)

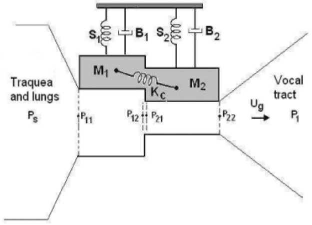


(Suh and Frankel, 2007)

Structures

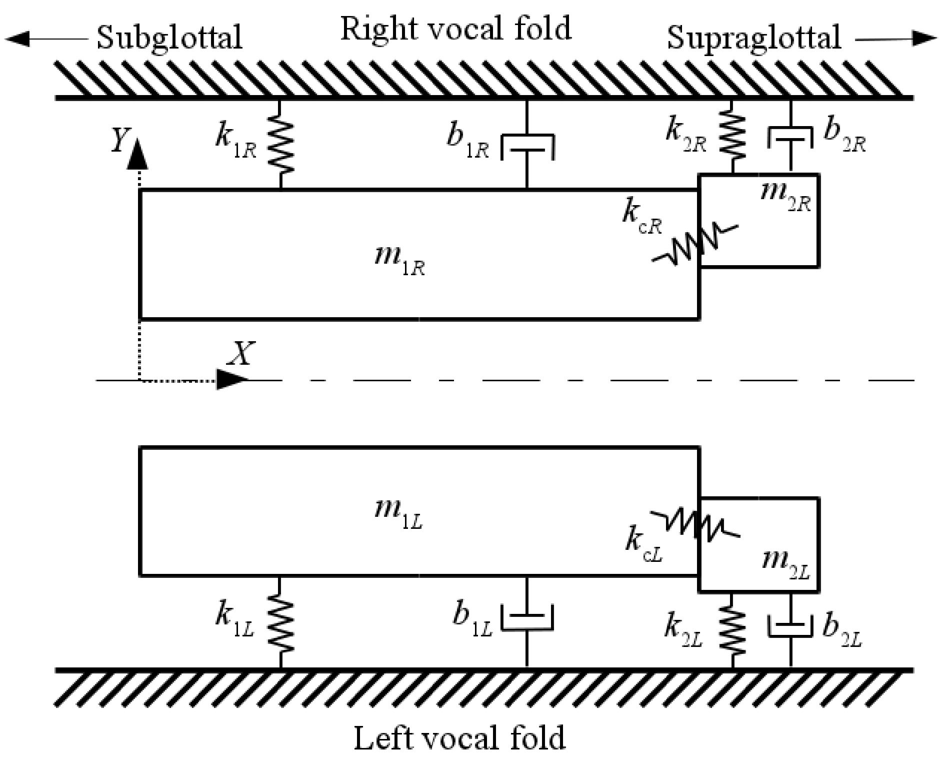


From Cook et al. (2008)



(Ishizaka and Flanagan, 1972)

Quantifying Fluid-Structure Interactions

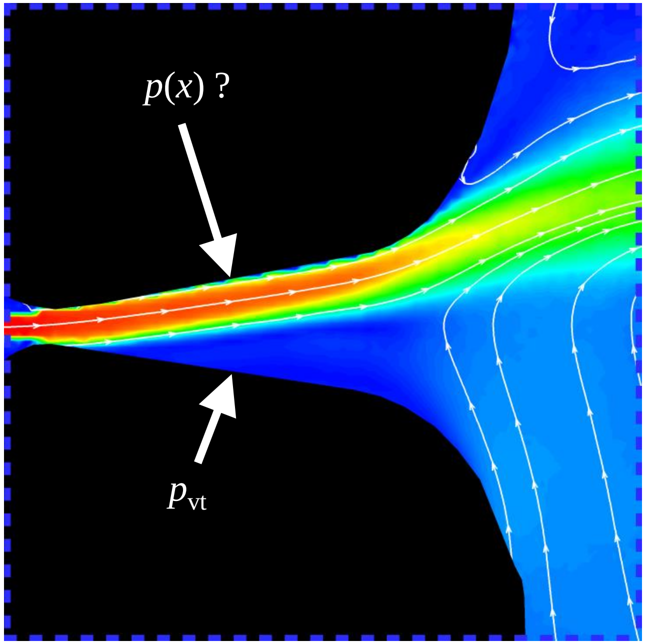


$$\left.\begin{aligned} & m_{1\alpha}\ddot{Y}_{1\alpha} + b_{1\alpha}\dot{Y}_{1\alpha} + k_{1\alpha}Y_{1\alpha} + \Theta(-a_1)\frac{c_{1\alpha}a_1}{2l} \\ & \quad + k_{c\alpha}(Y_{1\alpha} - Y_{2\alpha}) = G(t) \\ & m_{2\alpha}\ddot{Y}_{2\alpha} + b_{2\alpha}\dot{Y}_{2\alpha} + k_{2\alpha}Y_{2\alpha} + \Theta(-a_2)\frac{c_{2\alpha}a_2}{2l} \\ & \quad + k_{c\alpha}(Y_{2\alpha} - Y_{1\alpha}) = 0 \end{aligned}\right.$$

- Reduced order model of speech (Ishizaka and Flanagan, 1972)
- Couple spring-mass-damper model of VF’s with fluid solver
  - Fluid loading, G, drives VF motion

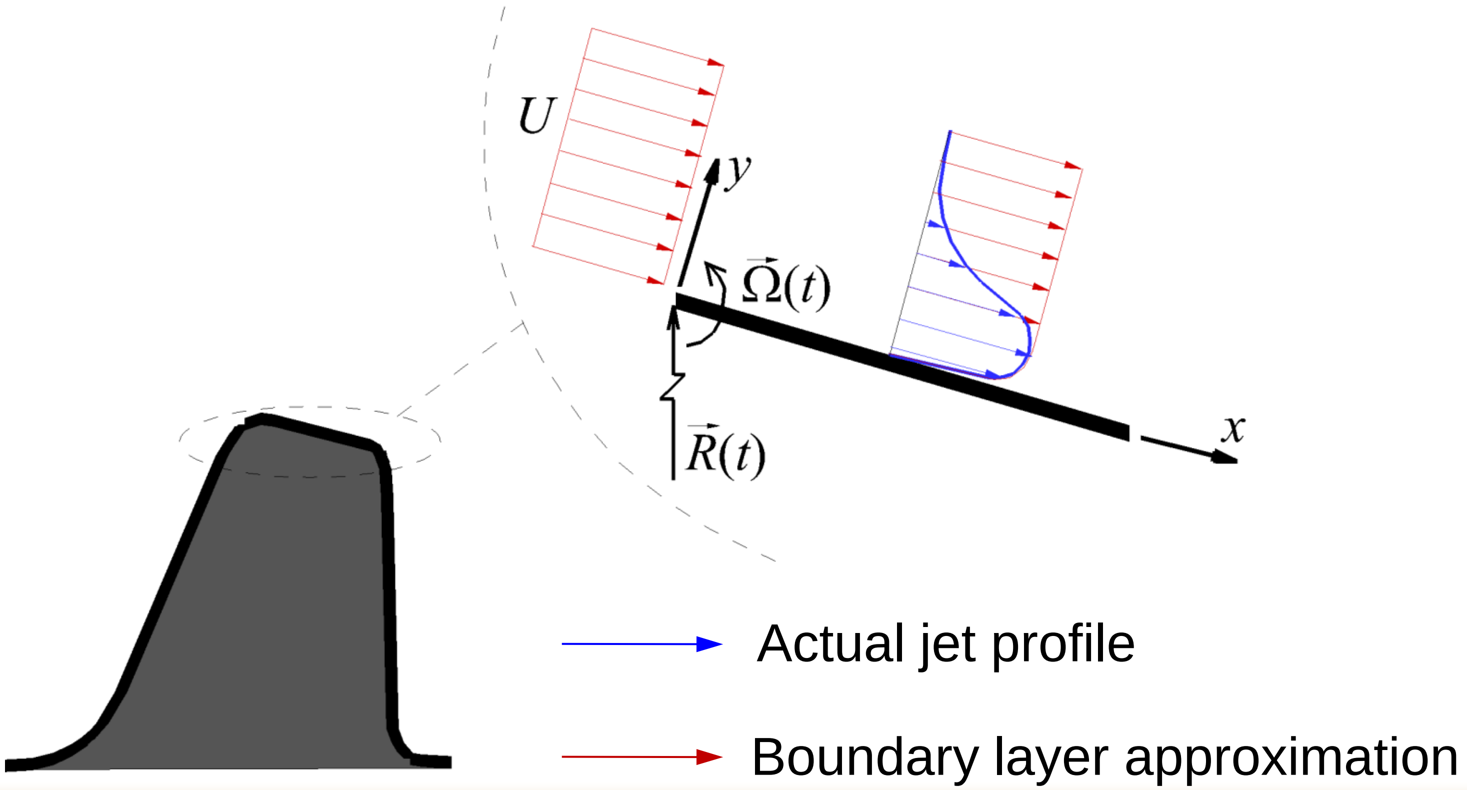
A Similarity Solution for Speech

- Can a similarity solution for glottal flows be found?
  - Find a transformation that reduces a set of partial differential equations (Navier-Stokes) to a system of ordinary differential equations.



Problem Formulation

- For a similarity solution, BC’s must also transform accordingly
  - Not possible with finite, non-zero BC’s (e.g. from wall motion)
  - To circumvent this complexity, solve in a non-inertial reference frame



Boundary Layer Analysis

Navier-Stokes

$$\rho[(\vec{V}_{xyz}\cdot\nabla)\vec{V}_{xyz} + \underbrace{\vec{\Omega}\times\vec{\Omega}\times\vec{r}_{xyz}}_{\text{Centripetal}} + \underbrace{2\vec{\Omega}\times\vec{V}_{xyz}}_{\text{Coriolis}}] = -\nabla p + \mu\nabla^2\vec{V}_{xyz}$$

Apply boundary layer scaling arguments

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} - \boxed{x\Omega_z^2 = -\frac{1}{\rho}\frac{\partial p}{\partial x}} + \nu\frac{\partial^2 u}{\partial y^2}$$

Define a modified pressure

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{\partial \tilde{p}}{\partial x} + \nu\frac{\partial^2 u}{\partial y^2}$$

Standard boundary layer equation recovered

$$\frac{\partial \tilde{p}}{\partial x} = \frac{\partial p}{\partial x} - \rho x\Omega_z^2$$

If $\frac{\partial p}{\partial x} = 0$

$$\frac{\partial \tilde{p}}{\partial x} = -\rho x\Omega_z^2$$

Wall rotation acts as a favorable pressure gradient

- Delays flow separation!
- Independent of direction

Power-Law Relationship

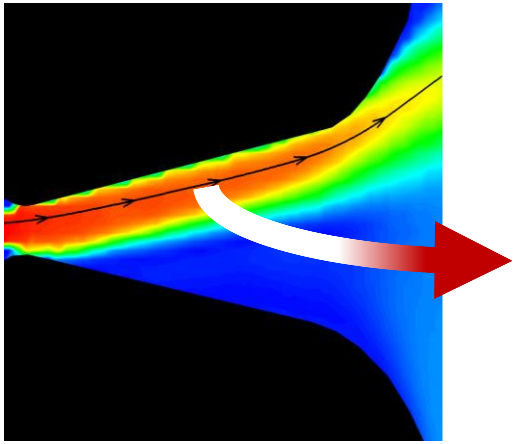
- Relate jet core velocity with wall pressure via Euler’s equation

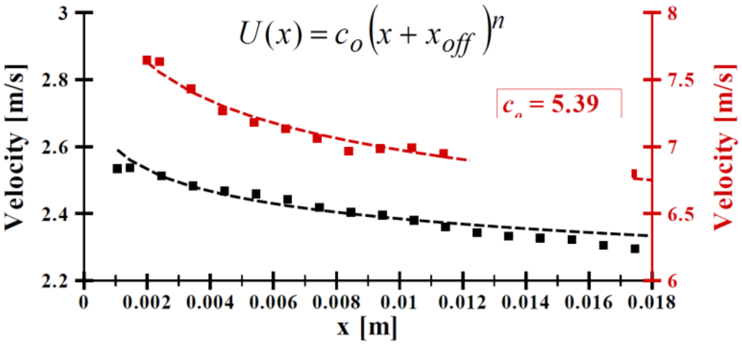
$$U\frac{\partial U}{\partial x} = \boxed{-\frac{1}{\rho}\frac{\partial p}{\partial x} + x\Omega_z^2}$$

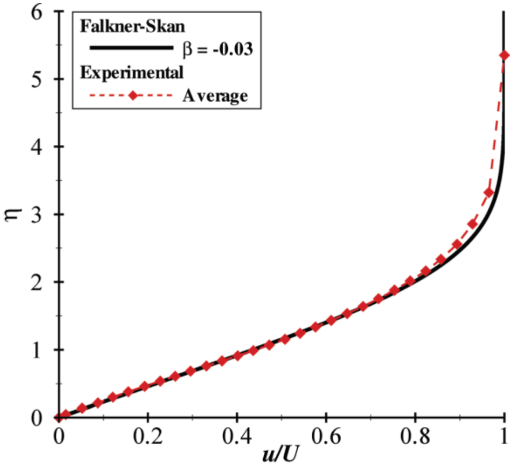
$$\Downarrow$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = U\frac{\partial U}{\partial x} + \nu\frac{\partial^2 u}{\partial y^2}$$

- Falkner-Skan like similarity solution exists if jet core velocity (*U*) varies with power-law relation in *x*

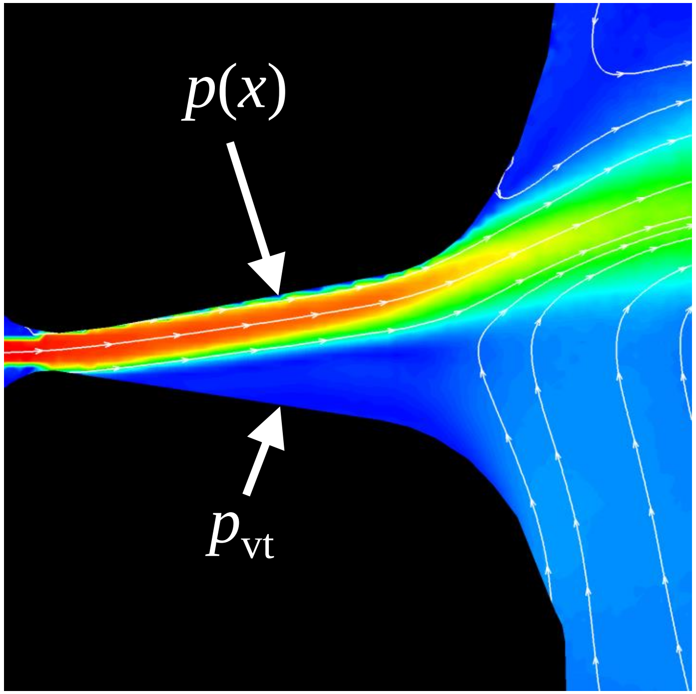






BLEAP

- Boundary layer estimation of asymmetric pressure (BLEAP)



$$p(x) = p_i + \frac{1}{2}\rho\left[U_i^2 - U(x)^2\right]$$

  - Simple algebraic relation for aerodynamic pressure loading
  - Easily assimilated into existing reduced-order models of speech
  - Generates physically-realistic flow solution

Impact of Asymmetric Flows

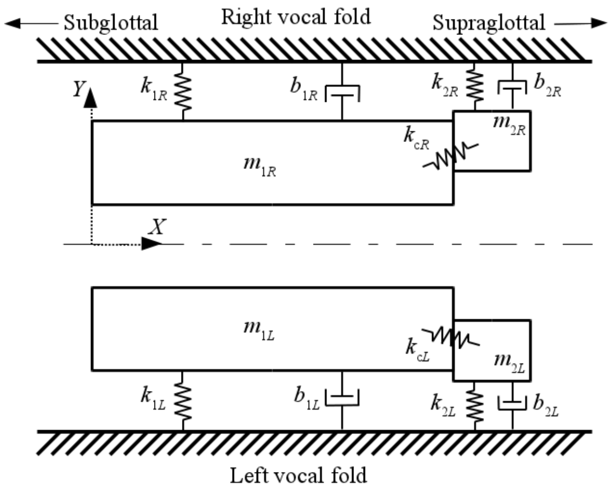
- Define symmetry parameter, Z:

$$m_{j,R} = m_{j,L} / Z$$

$$k_{j,R} = Z k_{j,L}$$

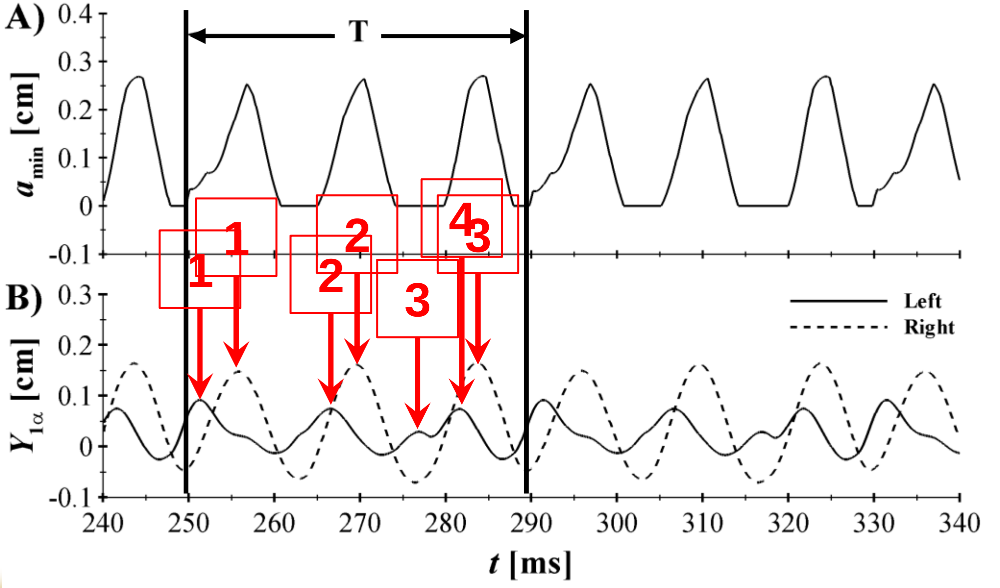
$$k_{c,R} = Z k_{c,L}$$

$$c_{j,R} = Z c_{j,L}$$

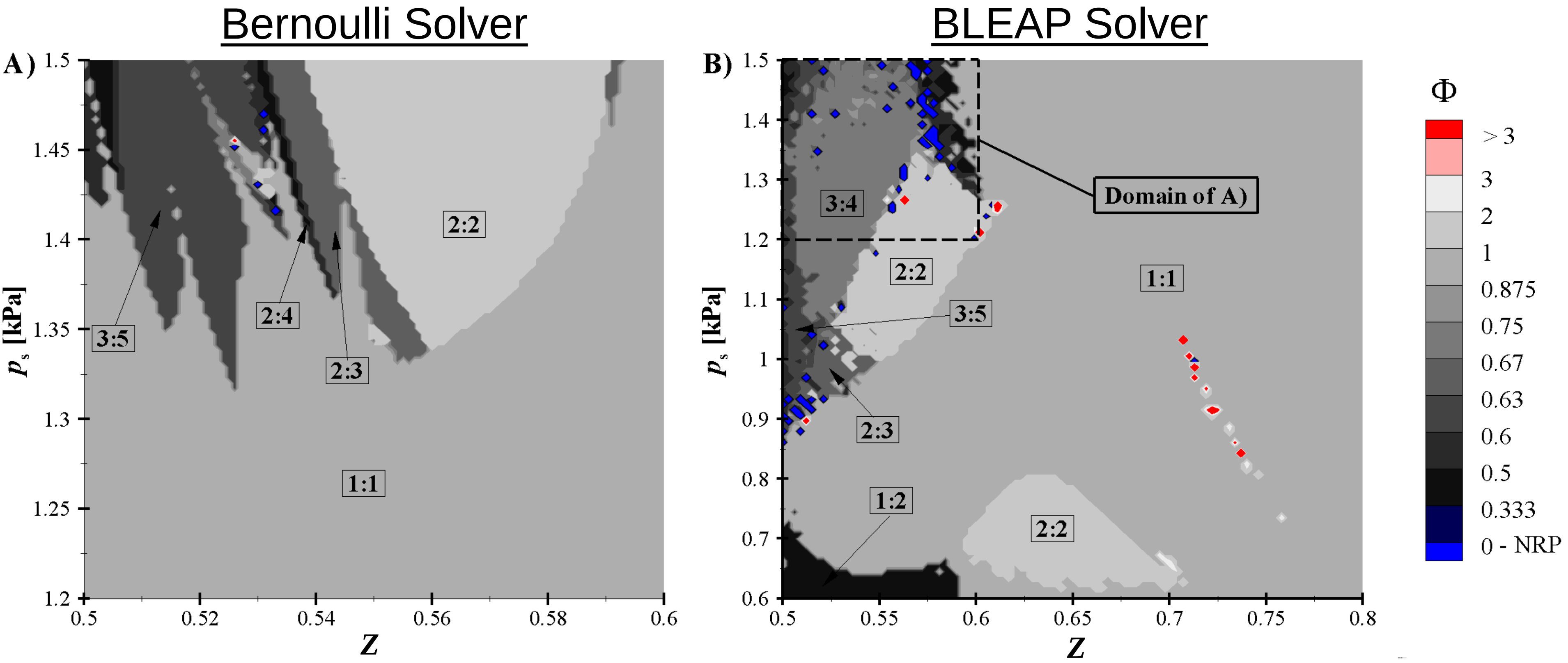


$$\phi_R = 3$$

$$\phi_L = 4$$



Regime Plot



$$\Phi = \begin{cases} \dfrac{\phi_{1R}}{\phi_{1L}} & \text{for} \quad \dfrac{\phi_{1R}}{\phi_{1L}} < 1.0 \\ \phi_{1R} & \text{for} \quad \dfrac{\phi_{1R}}{\phi_{1L}} = 1.0 \\ 0 & \text{for} \quad \text{no repeating pattern (NRP)} \end{cases}$$

Analysis of VF Dynamics

- Linear methods (open quotient, jitter, shimmer, etc.)
  - Work well for “normal” voice
  - Insufficient for investigating dynamics of pathological voice

- Nonlinear methods
  - Reveal more complicated dynamics
  - Show promise as a diagnostic tool for various pathologies

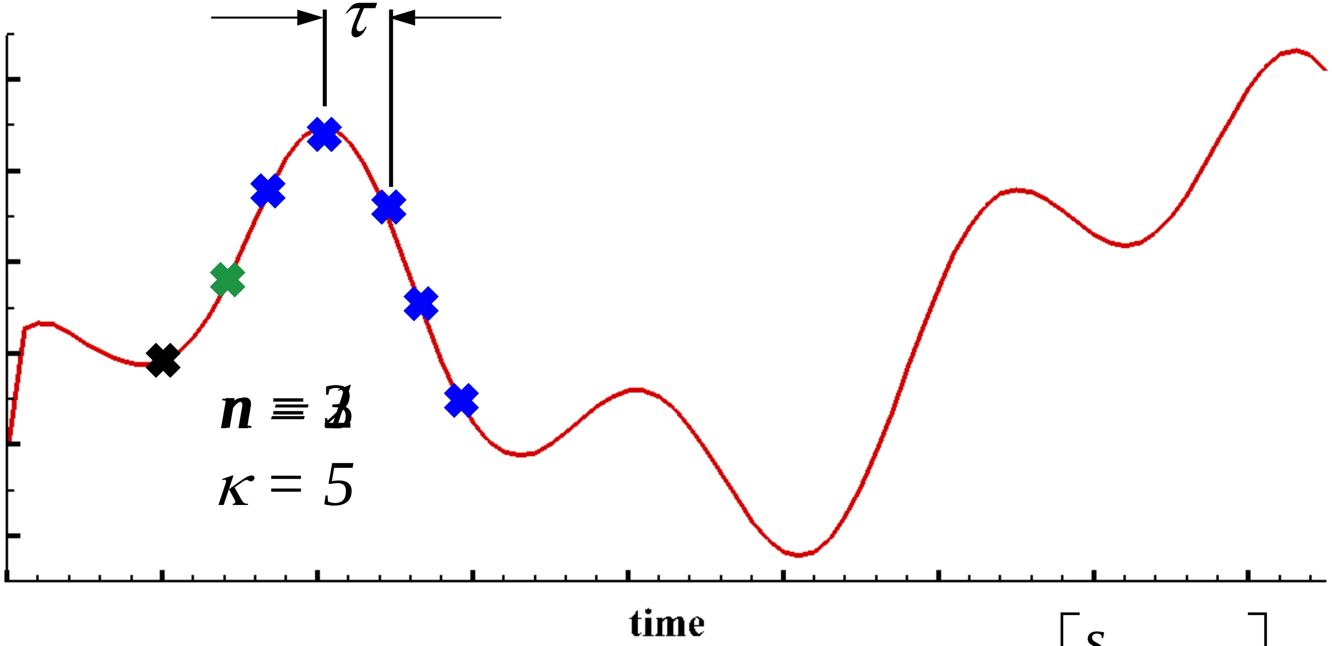
- Techniques employed with reduced-order models
  - Phase-space reconstruction of temporal vocal fold displacement using time-delay and embedding dimensions
  - Compute Information Criteria from Volterra-Weiner-Korenberg series
    - Predicts nonlinear dynamics

Determining State Spaces

- Assume a purely deterministic system
  - If the present state is fixed, all future states are known
- Establish a vector space (state/phase space) for the system
  - Specifying a point in the vector/state space specifies the state of the system, and vice versa
- Can now study the dynamics of the system by studying the dynamics of the state/phase space points

Phase Space Reconstruction

Assume some time series, s_n, with $n = 1, 2, 3, \ldots N$

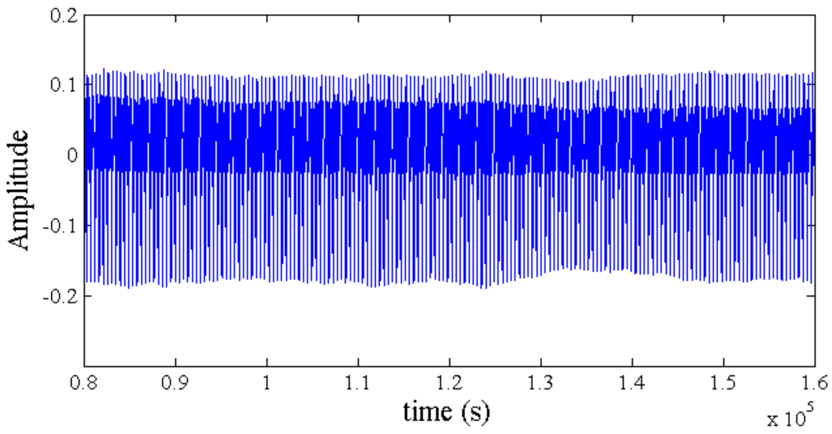


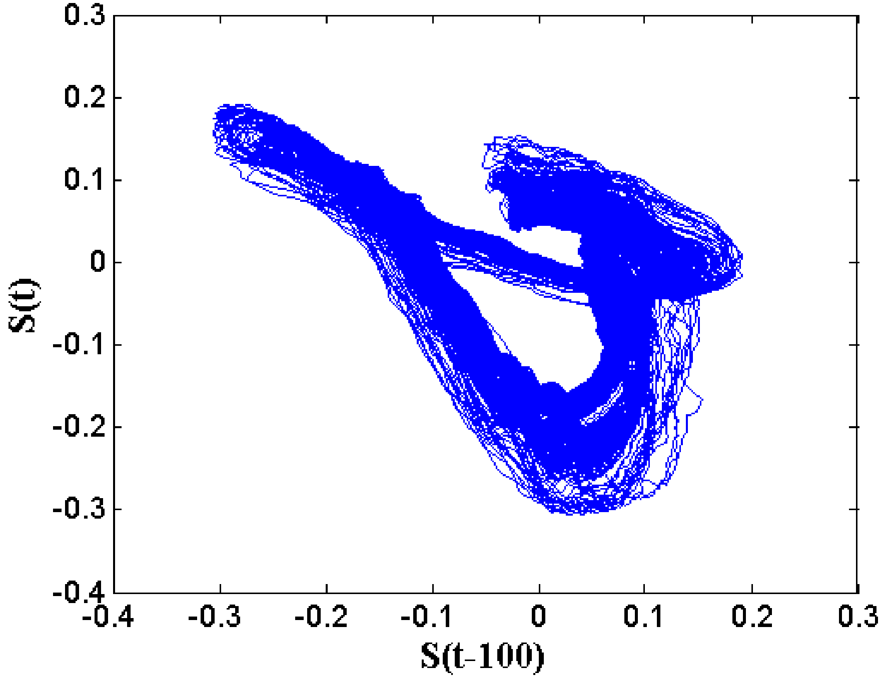
- Time series reconstructed in κ-dimension phase space by the vector $\mathbf{s}_n$
- τ = "time lag"
- κ = embedding dimension

$$\mathbf{s}_n = \begin{bmatrix} s_{1-(\kappa-1)\tau} \\ s_{1-(\kappa-2)\tau} \\ \vdots \\ s_{1-\tau} \\ s_1 \end{bmatrix} \quad \begin{bmatrix} s_{2-(\kappa-1)\tau} \\ s_{2-(\kappa-2)\tau} \\ \vdots \\ s_{2-\tau} \\ s_2 \end{bmatrix} \quad \begin{bmatrix} s_{3-(\kappa-1)\tau} \\ s_{3-(\kappa-2)\tau} \\ \vdots \\ s_{3-\tau} \\ s_3 \end{bmatrix}$$

Phase Portraits

- How is the appropriate state/phase space chosen?
- Reveal nature of a signal by plotting each data point versus its predecessor
  - Creates a "phase portrait" using "time delay embedding"
  - A plot of the trajectories in state/phase space
    - Identifies attractors, etc.





Choosing Embedding Dimension, κ

- Various methods:
  - Inspection
  - First minimum of mutual information plot
  - Stabilization of the slope of the correlation integral with increasing dimension, κ
  - The fundamental period, $T = \tau\kappa$

Identification of Nonlinear Behavior

- Express the time series as a Volterra-Weiner-Korenberg series in terms of the phase space, with degree δ and dimension, κ
  - $\delta = 1$: Linear terms
  - $\delta \geq 2$: Nonlinear terms

$$\tilde{s}_n = e_o + e_1 s_{n-1} + e_2 s_{n-2} + \ldots + e_\kappa s_{n-\kappa} + e_{\kappa+1} s_{n-1}^2 + e_{\kappa+2} s_{n-1} s_{n-2} + \ldots + e_{\Lambda-1} s_{n-\kappa}^\delta = \sum_{\lambda=0}^{\Lambda-1} e_\lambda q_\lambda(n)$$

where, $\Lambda = \dfrac{(\kappa+\delta)!}{(\kappa!\delta!)}$

- Coefficients e_λ are found using Gram-Schmidt reorthonormalization

Information Criterion

- The one-step-ahead prediction error is computed by:

$$\varepsilon(\kappa,\delta)^2 \equiv \frac{\sum_{n=1}^{N}\left(\tilde{s}(\kappa,\delta)-s_n\right)^2}{\sum_{n=1}^{N}\left(s_n-\bar{s}\right)^2}$$

with $$\bar{s} = \frac{1}{N}\sum_{n=1}^{N} s_n$$

Nonlinear Prediction

- The information criterion can then be computed according to:

$C(r)=\log \varepsilon(r)+r/N$, where $r \in [1,\Lambda]$ for any combination of (κ,δ)

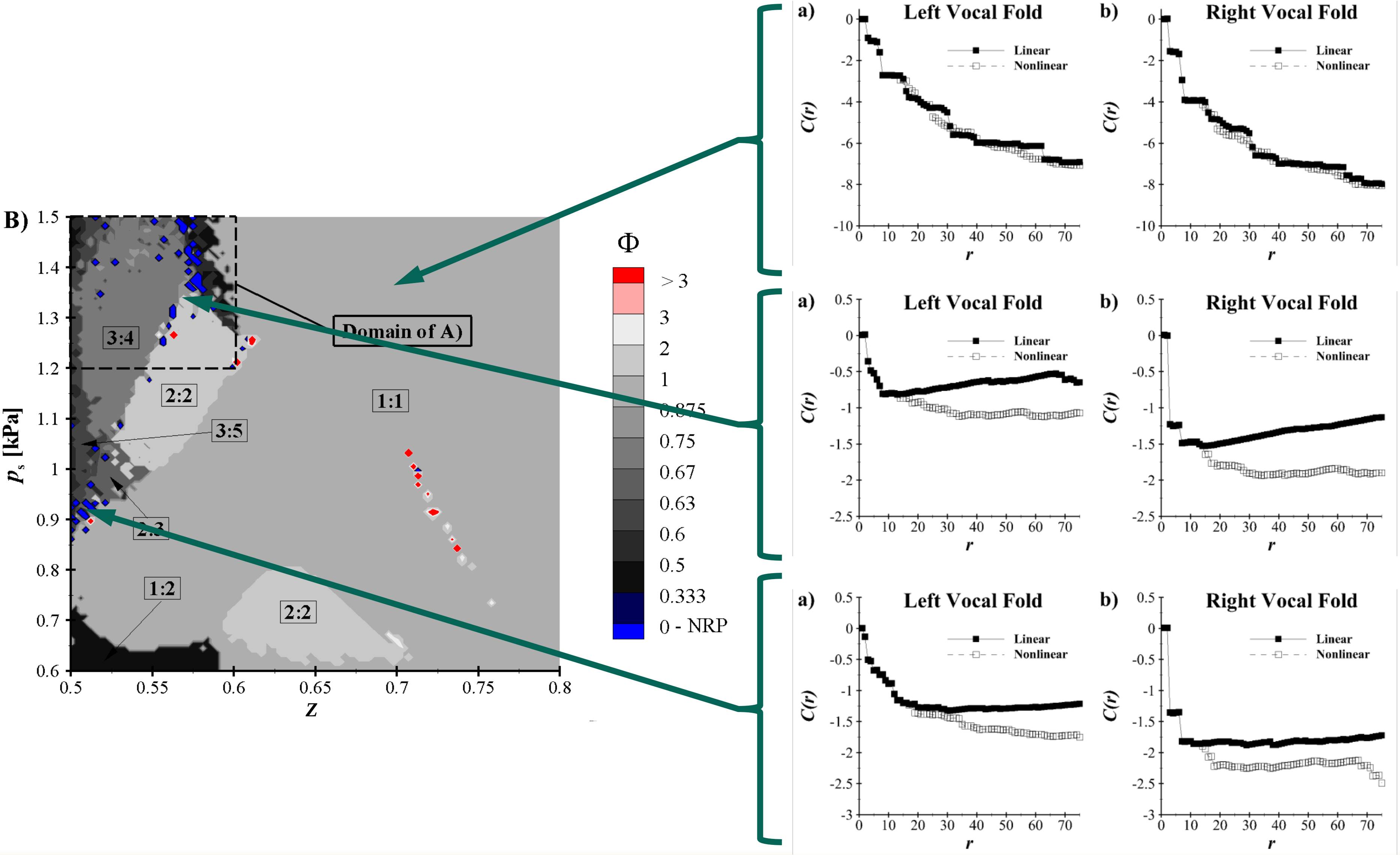
  - And ε is the one-step-ahead error

- C_{lin} is computed for $\delta = 1$

- C_{nl} computed for $\delta > 1$

- If C_{nl} is more predictive than C_{lin} (i.e. $C_{\mathrm{lin}} > C_{\mathrm{nl}}$ for $r > \kappa$)
  - Chaotic dynamics are revealed!

Nonlinear Predictor

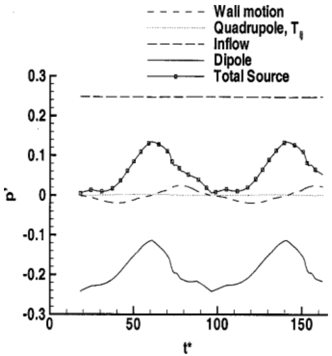


Summation: Fluid-Structure

- Normal speech conditions
  - Asymmetric flow loading has minimal effect
- Tension imbalanced speech (unilateral paralysis)
  - BLEAP flow solver provides more physiologically-realistic dynamics
  - Asymmetric flow is devastating in irregularly-tensioned speech
  - Nonlinear behavior manifest
  - From a clinical perspective, both geometry **and** tension are important
- Influence of vortex shedding, turbulence, higher order viscous flow effects undetermined

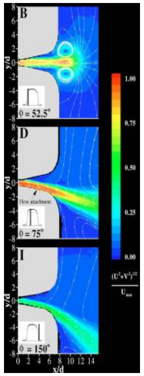
Speech: A Multi-Disciplinary Problem

Acoustics



(Zhao et al., 2002)

Fluids



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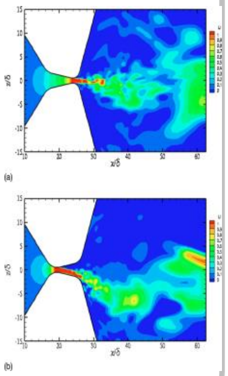
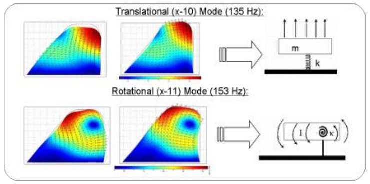
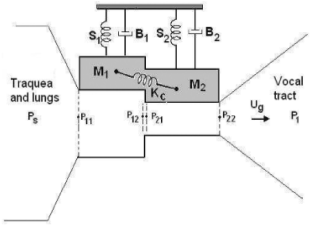


(Suh and Frankel, 2007)

Structures



From Cook et al. (2008)



(Ishizaka and Flanagan, 1972)

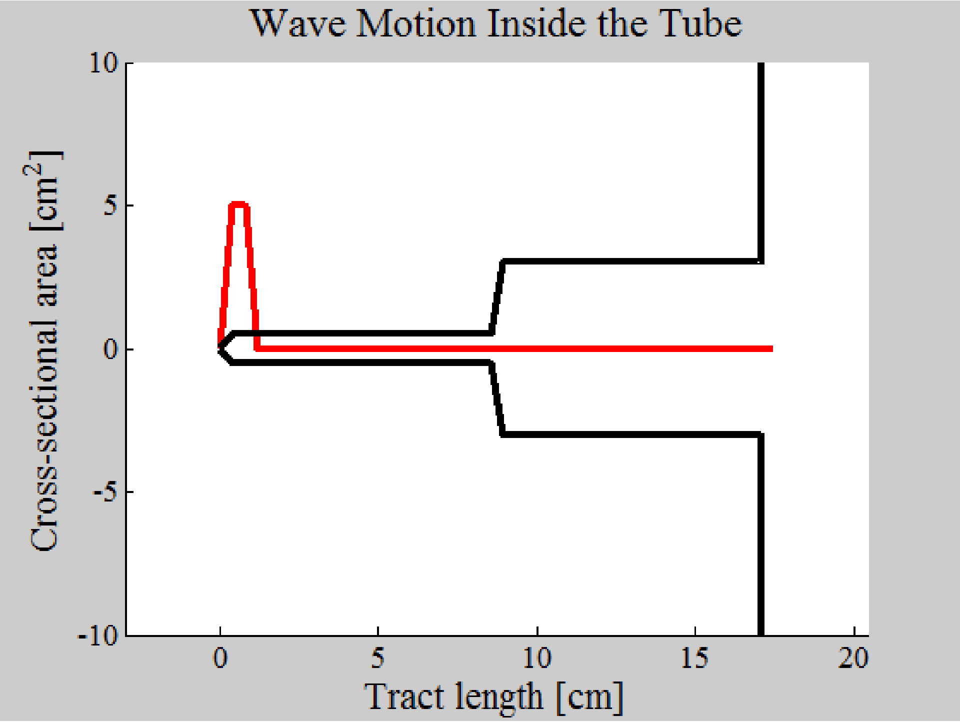
Acoustic Interactions

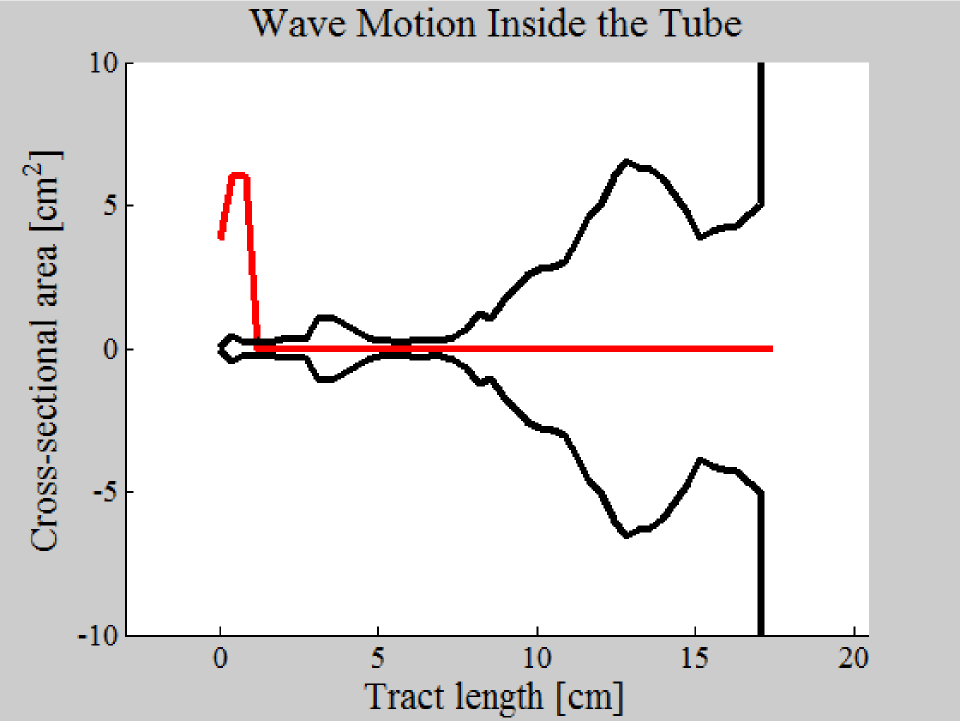
- “Normal Speech”
  - Subglottal pressure ~ 0.3 – 0.8 kPa

- At glottis, sound pressure levels can reach ~ 120 - 130 dB
  - Acoustic pressures on order of subglottal pressures ~*O*(0.3 kPa)
  - Great enough to modulate driving pressure gradient

- Solve using Wave Reflection Analog (WRA)
  - Unsteady volume velocity acts as acoustic source
  - Vocal tract area acts as acoustic filter

Wave Reflection Analog (WRA) Method





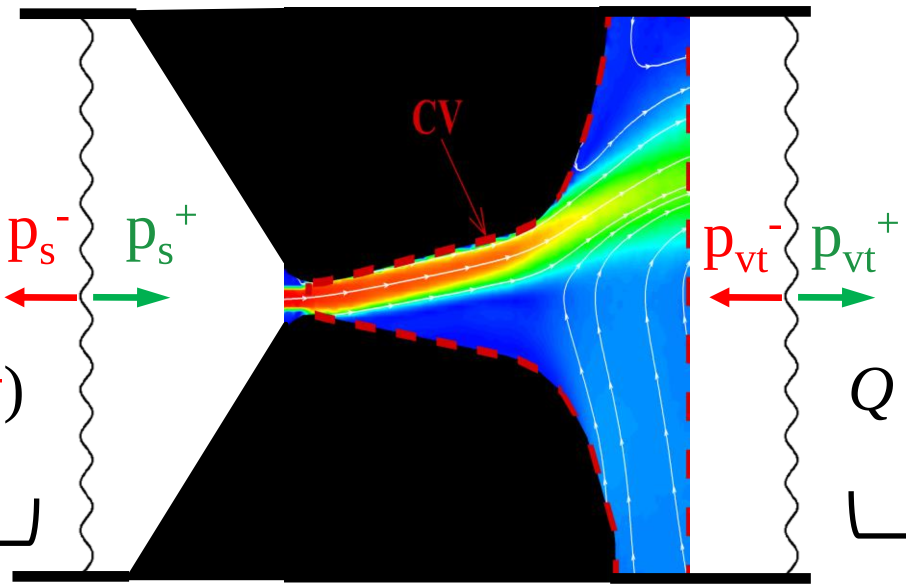
WRA + BLEAP

→ Forward traveling wave ← Backward traveling wave

$$p_s = p_s^+ + p_s^-$$

$$\underbrace{Q = A_s/\rho c\,(p_s^+ - p_s^-)}$$

$$p_s = 2p_s^+ - \frac{\rho c Q}{A_s}$$



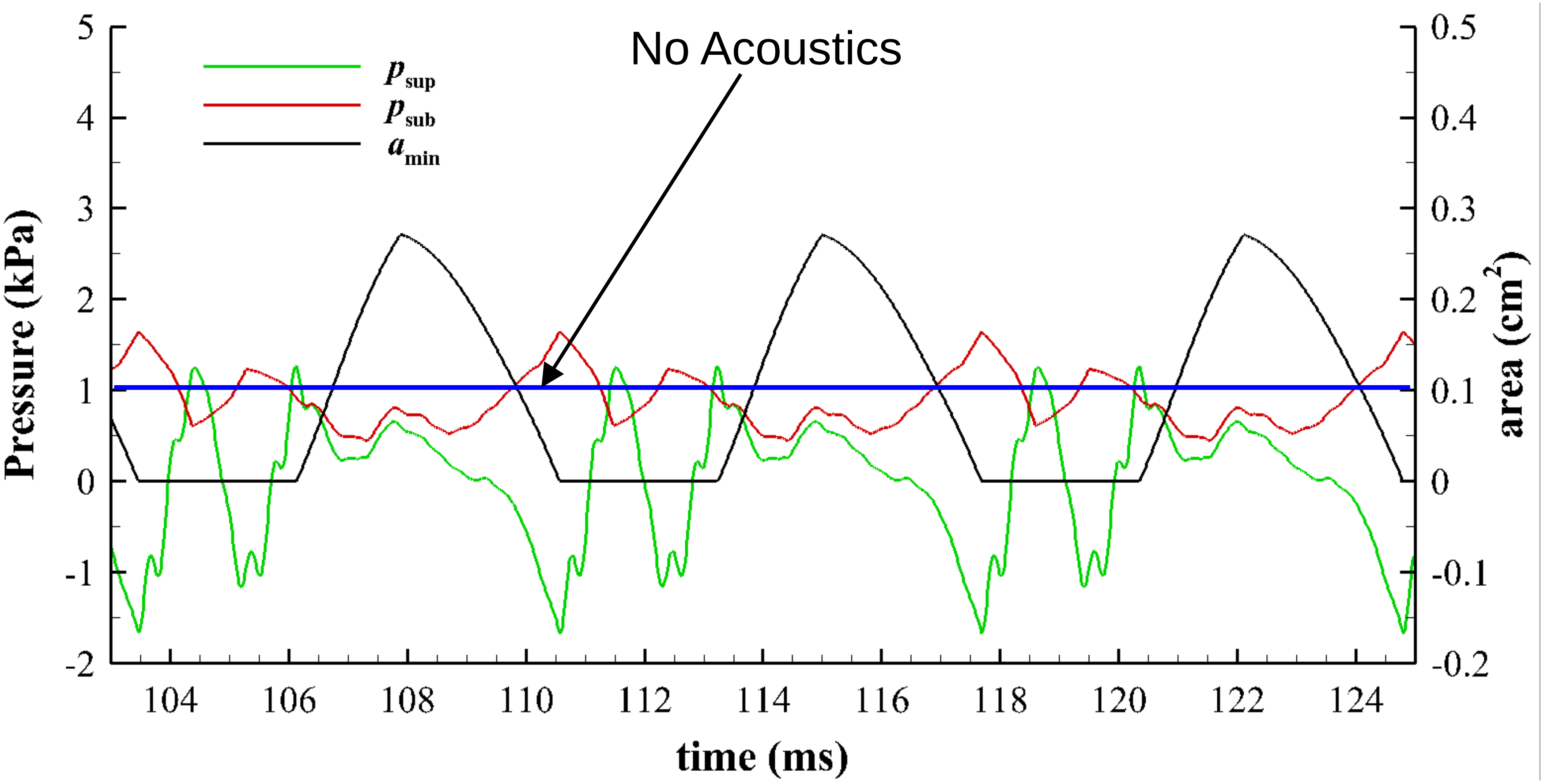
$$p_{vt} = p_{vt}^+ + p_{vt}^-$$

$$\underbrace{Q = A_{vt}/\rho c\,(p_{vt}^+ - p_{vt}^-)}$$

$$p_{vt} = 2p_{vt}^- - \frac{\rho c Q}{A_{vt}}$$

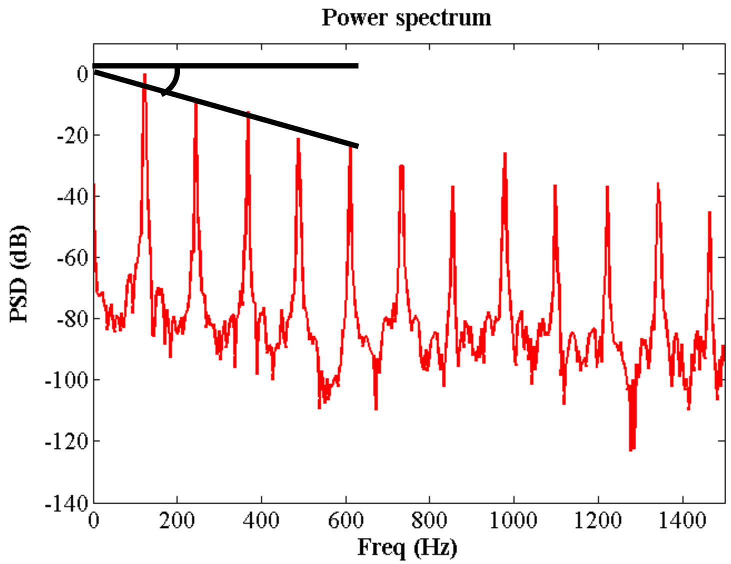
$$\frac{1}{2}\rho C_1\left(\frac{Q}{A_i}\right)^2 + \rho c\left(\frac{Q}{A_i}\right)\left(\frac{A_{vt}}{As}+1\right) - 2\left(p_s^+ - p_{vt}^-\right)\frac{A_{vt}}{A_i} = 0$$

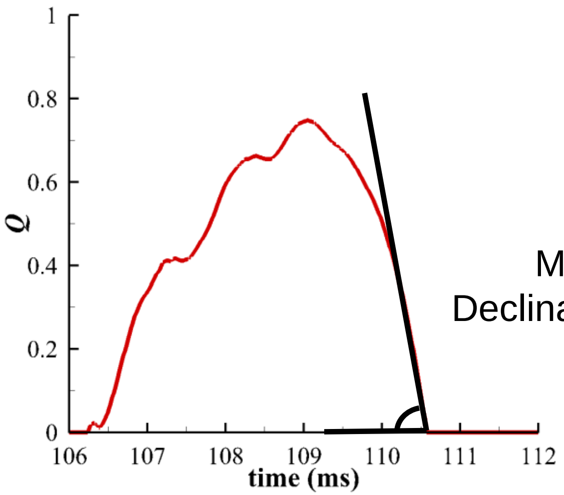
Acoustic Pressures



Acoustic Parameters

Change due to WRA + BLEAP	
Spectral tilt	- 2.9 %
MFDR	+ 30.2 %
L_p at mouth	+ 2.1 dB
Q_{max}	+ 2.5 %





Maximum Flow Declination Rate (MFDR)

Summation: Acoustics

- Acoustic loading has significant impact!
  - Radiated sound
  - Pressures
    - Aerodynamic loading
    - Transglottal pressure that drives flow
  - Vocal fold dynamics

- Speech is truly a fluid-structure-acoustic interaction!

- Validation of acoustic theory?

Modeling Voiced Speech: Summary

- Asymmetric fluid loading
  - Small influence on tissue forces for symmetrically tensioned speech
  - Has significant impact on tension imbalanced speech
  - Effects are magnified when acoustics are considered

- Outstanding questions
  - Fidelity of reduced-order models
  - How to model higher order flow effects
    - Vortex shedding
    - Turbulence
    - Changing flow separation points
  - More realistic acoustic modeling
    - Additional sound sources
    - Running speech

Questions/Comments