3aSC2

Physical mechanisms of phonation onset

- influence of flow separation on phonation onset

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Introduction

- Phonation sustained by a net energy transfer from the glottal flow into the vocal folds.
- **Mucosal wave, or Synchronization of two structural eigenmodes by the glottal flow**
  - **Provide a favorable phase relationship between the intraglottal pressure and the vocal fold tissue velocity**
  - **Primary mechanism for energy transfer**
- **Synchronization pattern (near field fluid-structure interaction) determines phonation threshold pressure, frequency, and vocal fold vibration**
- Acoustics-structure coupling with subglottal or supraglottal acoustics
  - Minor role, at onset of normal phonation

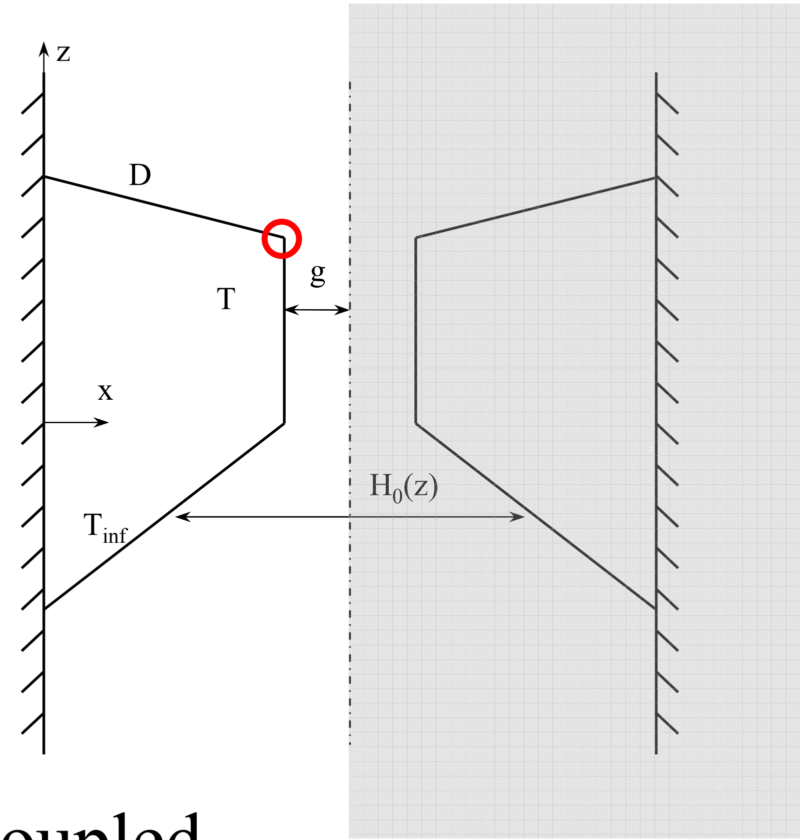
Motivation/Objective

- Glottal flow phenomena
  - Flow separation
    - 1. flow separation may oscillate along the vocal fold surface, depending on the glottal channel geometry (convergent, straight, and divergent)
    - 2. may be asymmetric
    - 3. Coanda effect
  - Downstream of the flow separation point:
    - unsteady vortex shedding
    - jet instabilities (symmetric, asymmetric)
    - Turbulence
- Effects of these flow phenomena on phonation onset mechanisms/vocal fold vibration are still not well understood.

→ Understand the influence of flow separation on phonation onset mechanisms in terms of eigenmode-synchronization.

Approach and Model Description

- A continuum model of the vocal fold
  - directly measurable model parameters
  - Physical description of the structure, the fluid flow, and their interaction.
  - Linear stress-strain relationship
- Flow:
  - 1D potential flow
  - Fixed separation point at superior edge
  - Neglect sub- and supra-glottal acoustic loading
- Imposed symmetry with the glottal channel centerline



Linear stability analysis of the coupled fluid-structure system.

Non-dimensional formulation

- Length: vocal fold thickness T
- Density: vocal fold density ρ
- Pressure: vocal fold Young's modulus E
- Velocity: wave velocity of the vocal fold structure $\sqrt{\frac{E}{\rho_{vf}}}$
- Time: $\frac{1}{T}\sqrt{\frac{E}{\rho_{vf}}}$
- Frequency: $T\sqrt{\frac{\rho_{vf}}{E}}$

Problem Formulation

- Lagrange's Equation for the vocal fold structure

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_r}\right)-\frac{\partial L}{\partial q_r}=Q_r,\ r=1,2,\dots,N$$

- Lagrangian $L=T\text{-}U$

$$T=\tfrac{1}{2}\iint_S(\dot{\xi}^2+\dot{\eta}^2)\rho dS;\quad U=\tfrac{1}{2}\iint_S(\varepsilon_x\tau_x+\varepsilon_z\tau_z+\gamma_{xz}\tau_{xz})dS$$

Displacement in x and z direction:

$$\xi(x,z,t)=\sum_{i=1}^{I}\sum_{k=0}^{K}A_{ik}(t)x^i z^k;\ \eta(x,z,t)=\sum_{i=1}^{I}\sum_{k=0}^{K}B_{ik}(t)x^i z^k$$

Generalized Coordinates:

$$[q]=[A_{10},A_{11},\cdots,A_{IK},B_{10},\cdots,B_{IK}]_{N=2\times I\times(K+1)}$$

Generalized Force:

$$Q_r=-\int_{l_{FSI}}\left(p\frac{\partial\xi}{\partial q_r}n_x+p\frac{\partial\eta}{\partial q_r}n_z\right)dl,\ r=1,2,\dots,N$$

p: Flow Pressure; l_{FSI}: fluid-structure interaction interface

Flow Model Assumptions

- One-dimensional potential flow up to the point of flow separation;
- Fixed flow separation point at the superior edge of the vocal folds.
  - This assumption is reasonable as this study concerns the linear stability of the coupled fluid-structure system.
- Zero pressure recovery for the flow downstream the flow separation point.
  - zero pressure fluctuation boundary condition at the vocal fold outlet;
- Constant flow rate at the vocal fold inlet
  - zero velocity fluctuation.

- Linearized 1D momentum and continuity equation around the mean state (mean vocal fold geometry)

$$\frac{\partial u}{\partial t} + U_0 \frac{\partial u}{\partial z} + u \frac{\partial U_0}{\partial z} + \frac{1}{\rho} \frac{\partial p}{\partial z} = 0$$

$$\frac{\partial h}{\partial t} + \frac{\partial (U_0 h)}{\partial z} + \frac{\partial (u H_0)}{\partial z} = 0$$

Flow Pressure on the FSI interface

$$\frac{p(z,t)}{\rho} = \int_{z\sup}^{z} \left(\frac{\partial}{\partial t} + U_0 \frac{\partial}{\partial z} + \frac{\partial U_0}{\partial z} \right) \left[\frac{1}{H_0} \int_{z\inf}^{z} \left(\frac{\partial}{\partial t} + U_0 \frac{\partial}{\partial z} + \frac{\partial U_0}{\partial z} \right) h dz \right] dz$$

$$= p_0(h) + p_1(h_t) + p_2(h_{tt})$$

Flow-induced stiffness

$$p_0(h) = \int_{z\sup}^{z} \left(U_0 \frac{\partial}{\partial z} + \frac{\partial U_0}{\partial z} \right) \left[\frac{1}{H_0} \int_{z\inf}^{z} \left(U_0 \frac{\partial}{\partial z} + \frac{\partial U_0}{\partial z} \right) h dz \right] dz$$

$$p_1(h_t) = \int_{z\sup}^{z} \left[\frac{1}{H_0} \int_{z\inf}^{z} \left(U_0 \frac{\partial}{\partial z} + \frac{\partial U_0}{\partial z} \right) h_t dz \right] dz + \int_{z\sup}^{z} \left(U_0 \frac{\partial}{\partial z} + \frac{\partial U_0}{\partial z} \right) \left[\frac{1}{H_0} \int_{z\inf}^{z} h_t dz \right] dz$$

$$p_2(h_{tt}) = \int_{z\sup}^{z} \frac{1}{H_0} \int_{z\inf}^{z} h_{tt} dz dz$$

added mass, present even for zero flow rate

Flow-induced damping

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

Eigenvalue problem

- Control equations

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

- Constant loss factor σ

$$C = \sigma\omega M$$

- Eigenvalue Formulation

$$\begin{bmatrix} \dot{q} \\ \ddot{q} \end{bmatrix} = \begin{bmatrix} 0 & I \\ -(M - Q_2)^{-1}(K - Q_0) & -(M - Q_2)^{-1}(C - Q_1) \end{bmatrix} \begin{bmatrix} q \\ \dot{q} \end{bmatrix}$$

- Solve for eigenvalues/eigenvectors as a function of jet velocity/subglottal pressure
- Phonation onset occurs at the jet velocity for which the growth rate of one eigenvalue first becomes positive

Solution Procedure

- Two-step procedure:
  - 1. Solve for steady state for a certain imposed subglottal pressure
  - 2. Solve the eigenvalue problem, checking for phonation onset. If no onset, repeat step 1 for a larger value of subglottal pressure. If onset, stop.

- For simplicity, the first step was skipped in this study.
  - Assume the mean steady-state vocal fold geometry does not change with subglottal pressure
  - Start with given steady-state (pre-phonatory) vocal fold geometry
  - Linear stability of the given pre-phonatory vocal fold geometry.

Model Parameters Used

	Non-dimensional values	Physical value
Structural Damping Loss factor	0.1 (weak)	0.1
VF Thickness	1	7 mm
VF Depth	1.4	10 mm
VF Entrance Slop	45°	45°
Glottal Channel Gap	0.1428	1 mm
VF Density	1	1030 kg/m^3
Young's Modulus	1	3 kPa
Scaling velocity	1	1 m/s
Flow Density	0.0012	1.2 kg/m^3

Effects of Flow-induced Stiffness

- Control equations

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

- Effects of Flow-induced damping and inertia were studied and reported in another study*.

- Effects of Flow-induced Stiffness:

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

* Zhang, Z., Neubauer, J., Berry, D.A., (2007) "Physical mechanisms of phonation onset: a linear stability analysis of an aeroelastic continuum model of phonation," in review, J. Acoust. Soc. Am.

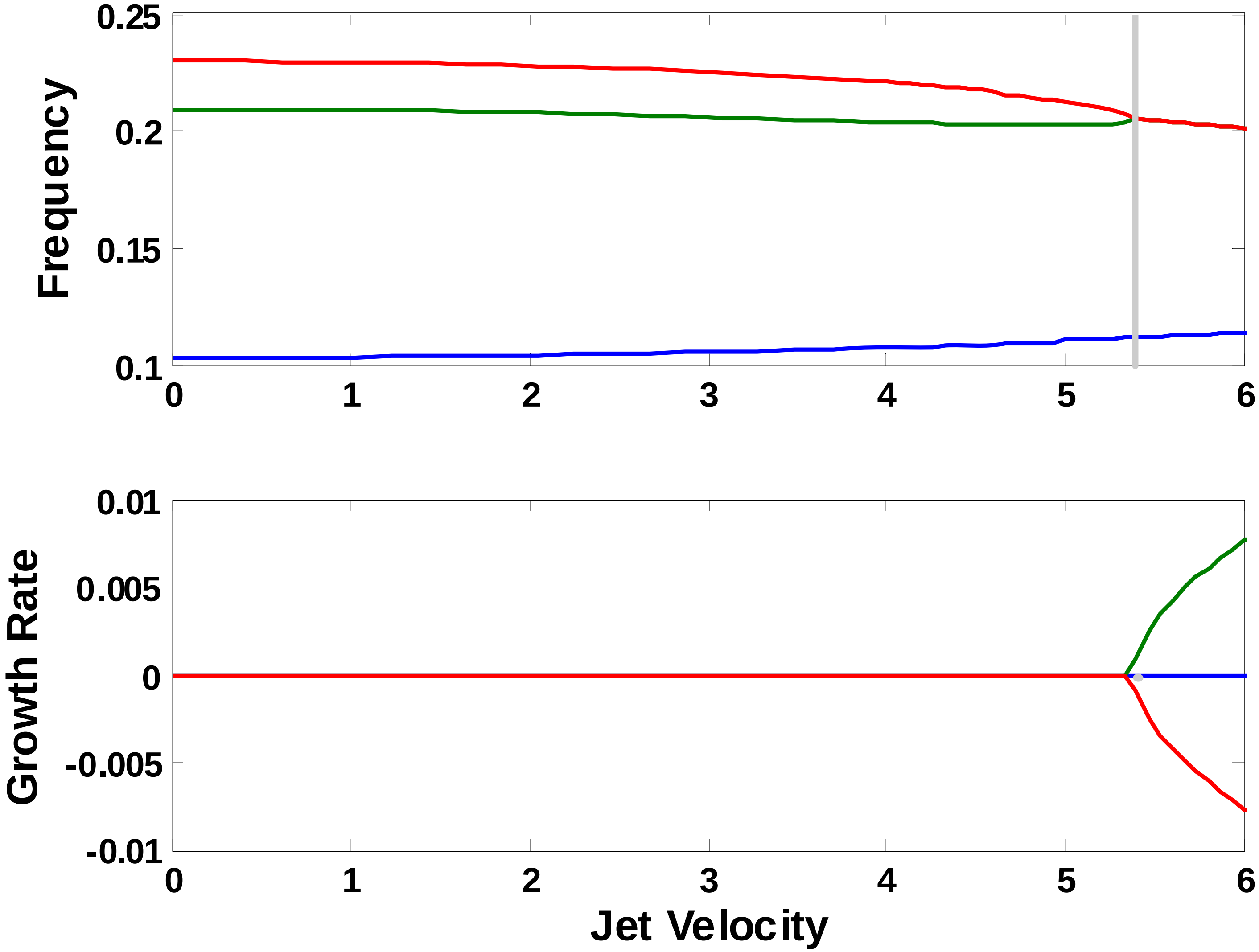
Possible instabilities of $M\ddot{q} + (K - Q_0)q = 0$

- Static Divergence: zero-frequency instability
  - Flow-induced stiffness exceeds the structural stiffness
  - Q_0 is symmetric: the system is a conservative system, in which limit cycle solutions are impossible (see, e.g., Strogatz, 1994)
  - One-eigenmode instability

- Coupled-mode flutter: phonation onset
  - Q_0 is asymmetric, non-conservative system
  - Synchronization of two structural modes

Synchronization of two eigenmodes

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

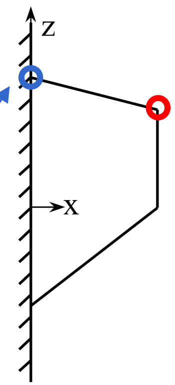


- Eigenmodes move toward each other due to the flow coupling effects
- Two eigenmodes merge and lead to phonation onset
- Similar behavior has been reported in the two-mass model (Ishizaka, 1981; 1986)

Role of Flow separation in phonation onset

- The flow-induced stiffness matrix is asymmetric due to imposed flow separation

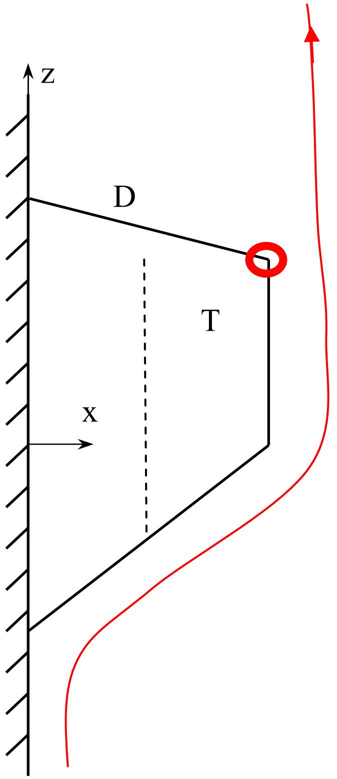
$$Q_0(i,k) = \frac{U_0^2}{H_0} \int_{z\inf}^{z\sup} \varphi_i \varphi_k dz - \frac{U_0^2(z_{sp})}{H_0(z_{sp})} \int_{z\inf}^{z\sup} \varphi_i(z_{sp}) \varphi_k(z) dz$$



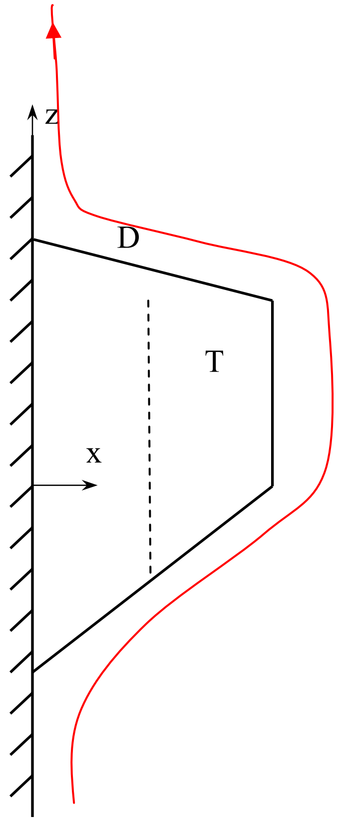
$\varphi_i = x^m z^n$ is the basis function of the Ritz method

  – Q_0 is symmetric only when $\varphi_i\ (z_{sp}) = 0$ for all the basis functions.

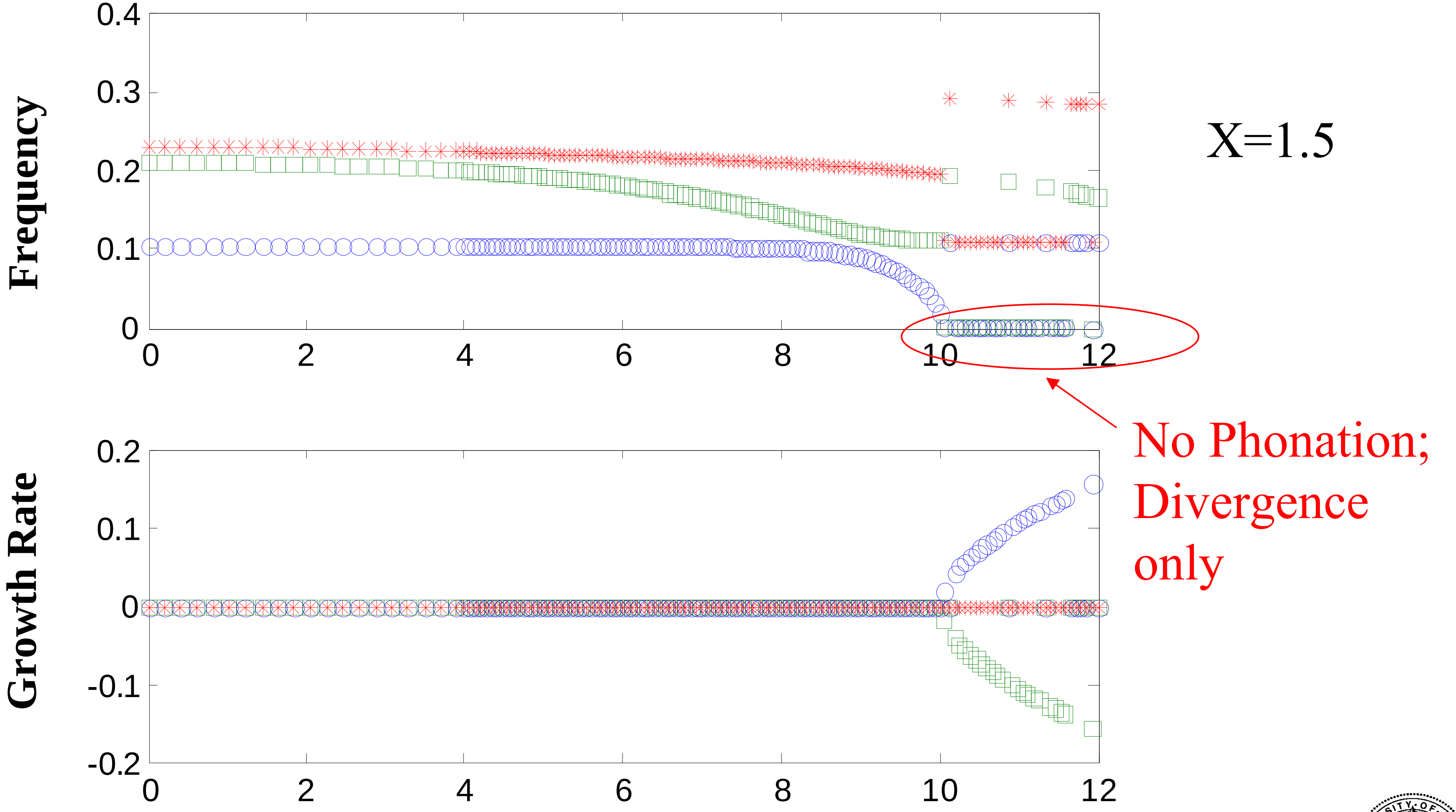
Separated Flow



Potential Flow

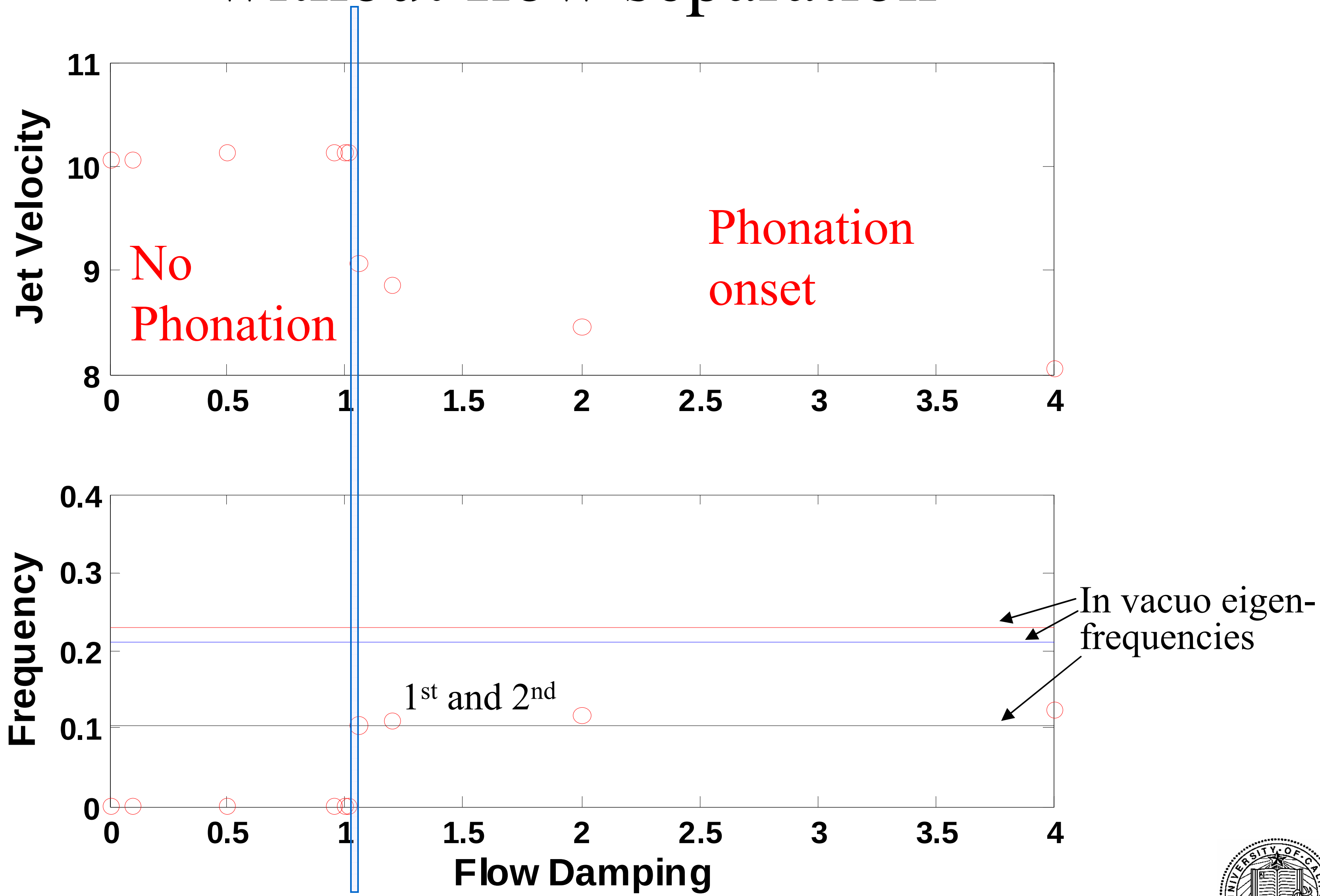


Potential flow: No Flow Separation



- Any non-conservative mechanisms would contribute to the asymmetric nature of the Q_0 matrix, and facilitate phonation onset:
  - e.g., sufficiently large viscous flow resistance

Effects of Flow Damping without flow separation



Effects of flow separation location

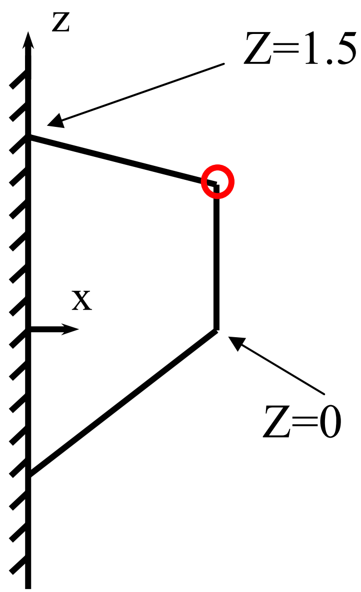
- Flow separation > asymmetric flow-induced stiffness matrix Q_0 > eigenmode-synchronization > phonation onset
- Variation of the flow separation point may affect the degree of asymmetry of the Q_0 matrix, and therefore affect the eigenmode-synchronization pattern.

Effects of flow separation location

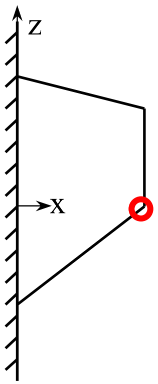
Influence on:

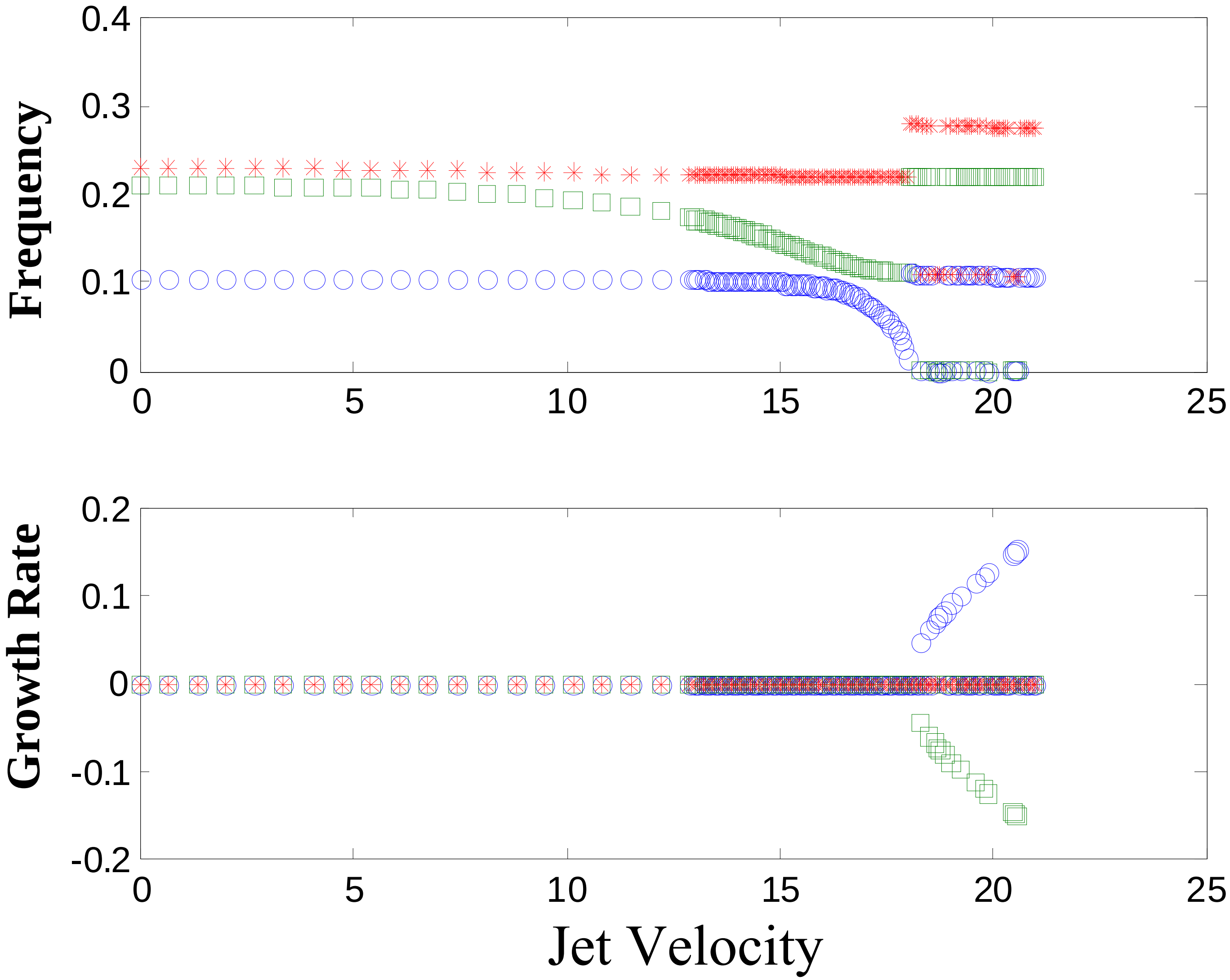
- Eigenmode synchronization pattern
- Phonation threshold
- Phonation frequency at onset

- Move the fixed flow separation point along the medial surface
  – $0 <= Z_{sp} <= 1.5$



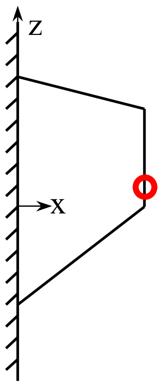
Effects of Flow Separation Location



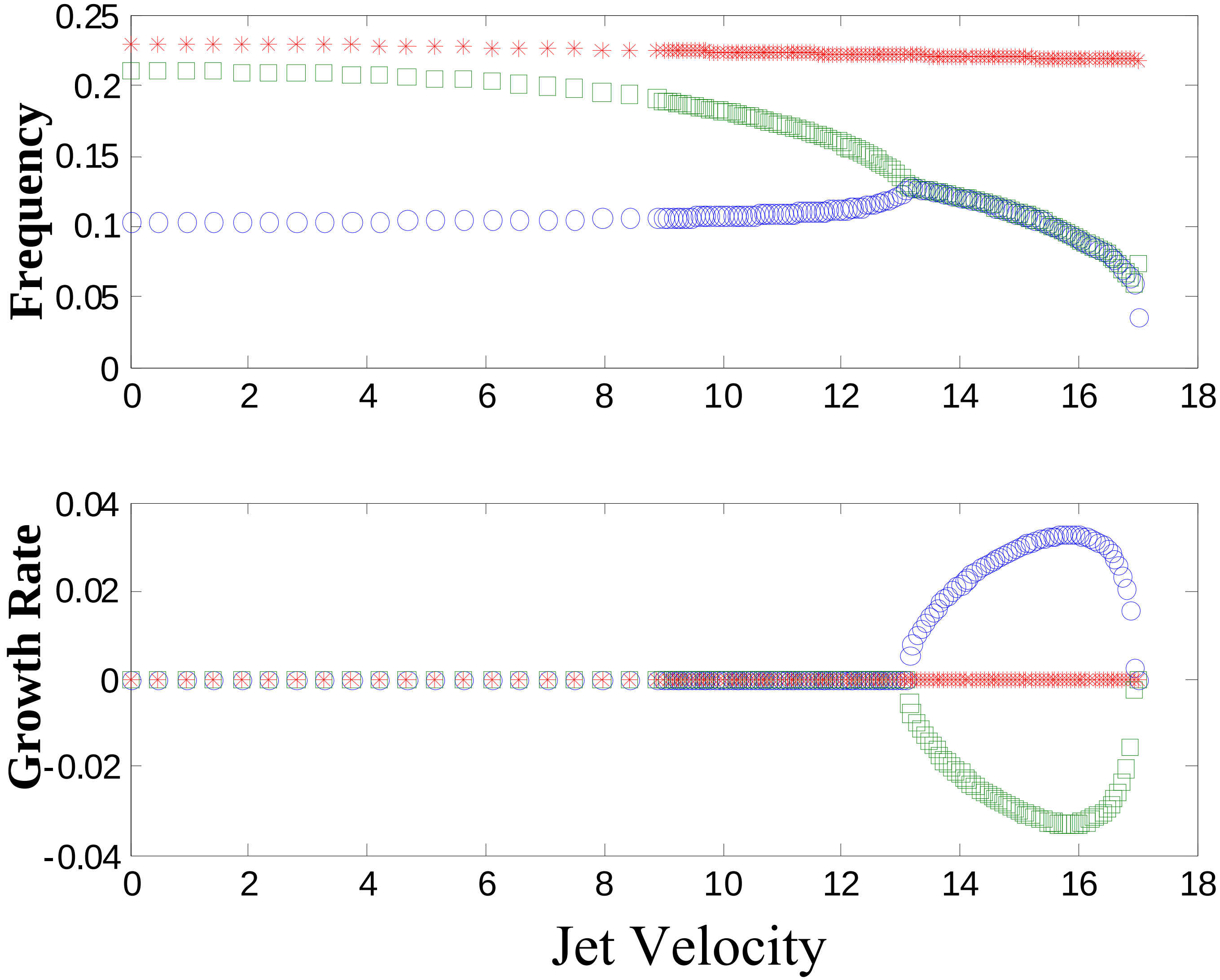


$Z_{sp} = 0$

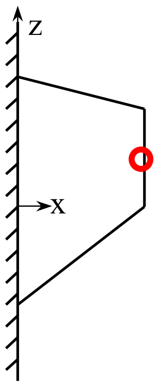
Effects of Flow Separation Location



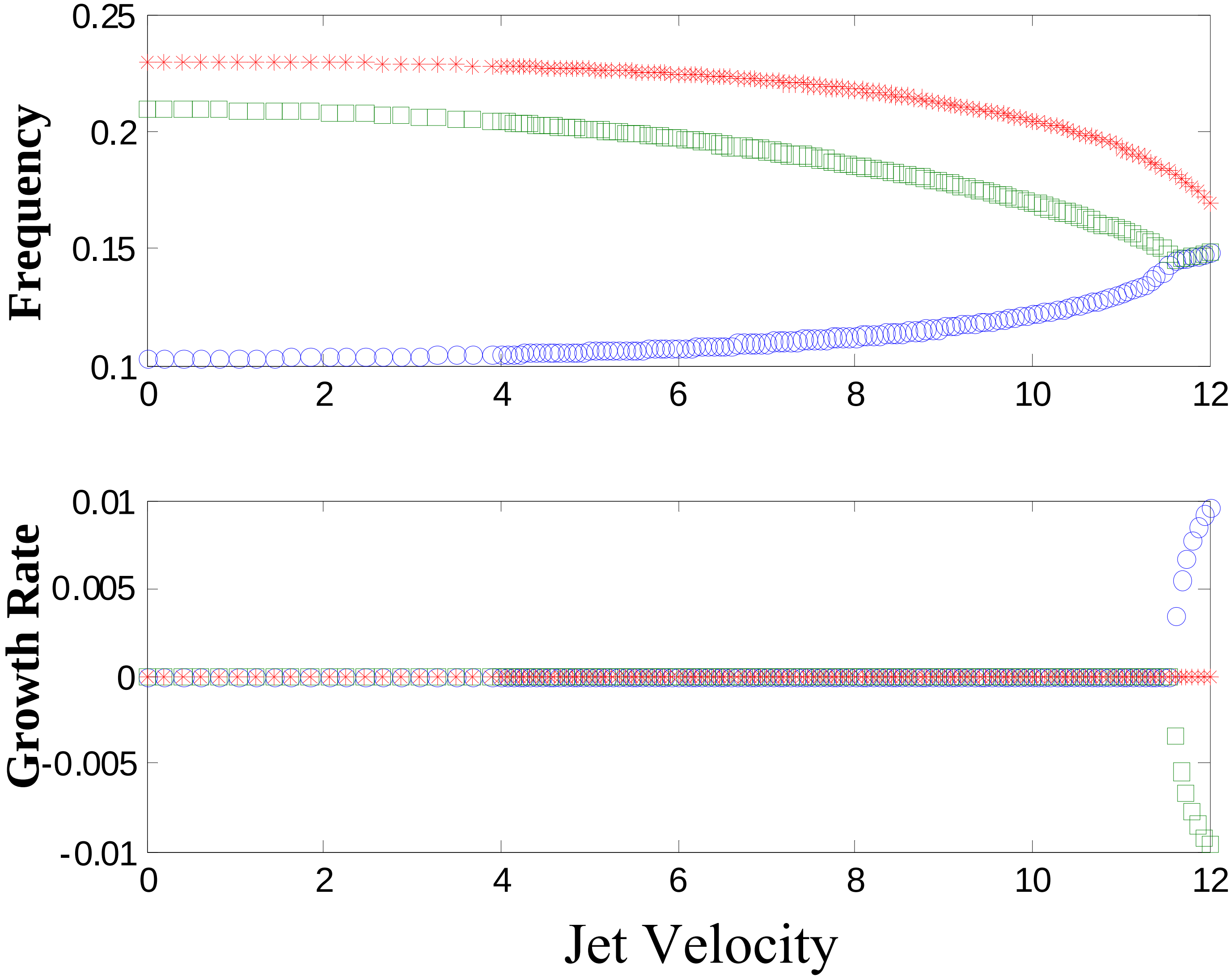
$Z_{sp} = 0.1$



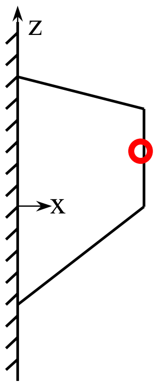
Effects of Flow Separation Location



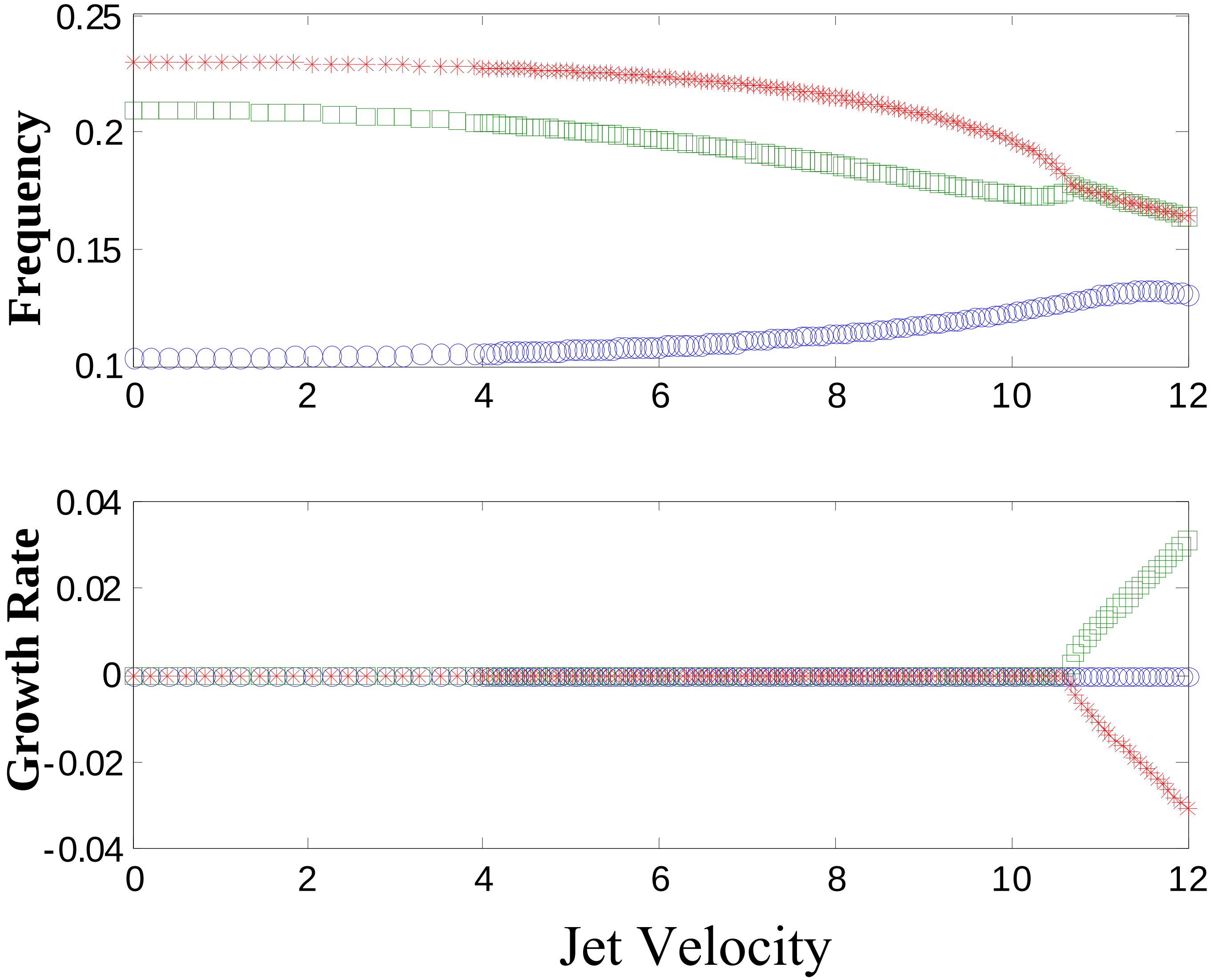
$Z_{sp} = 0.45$



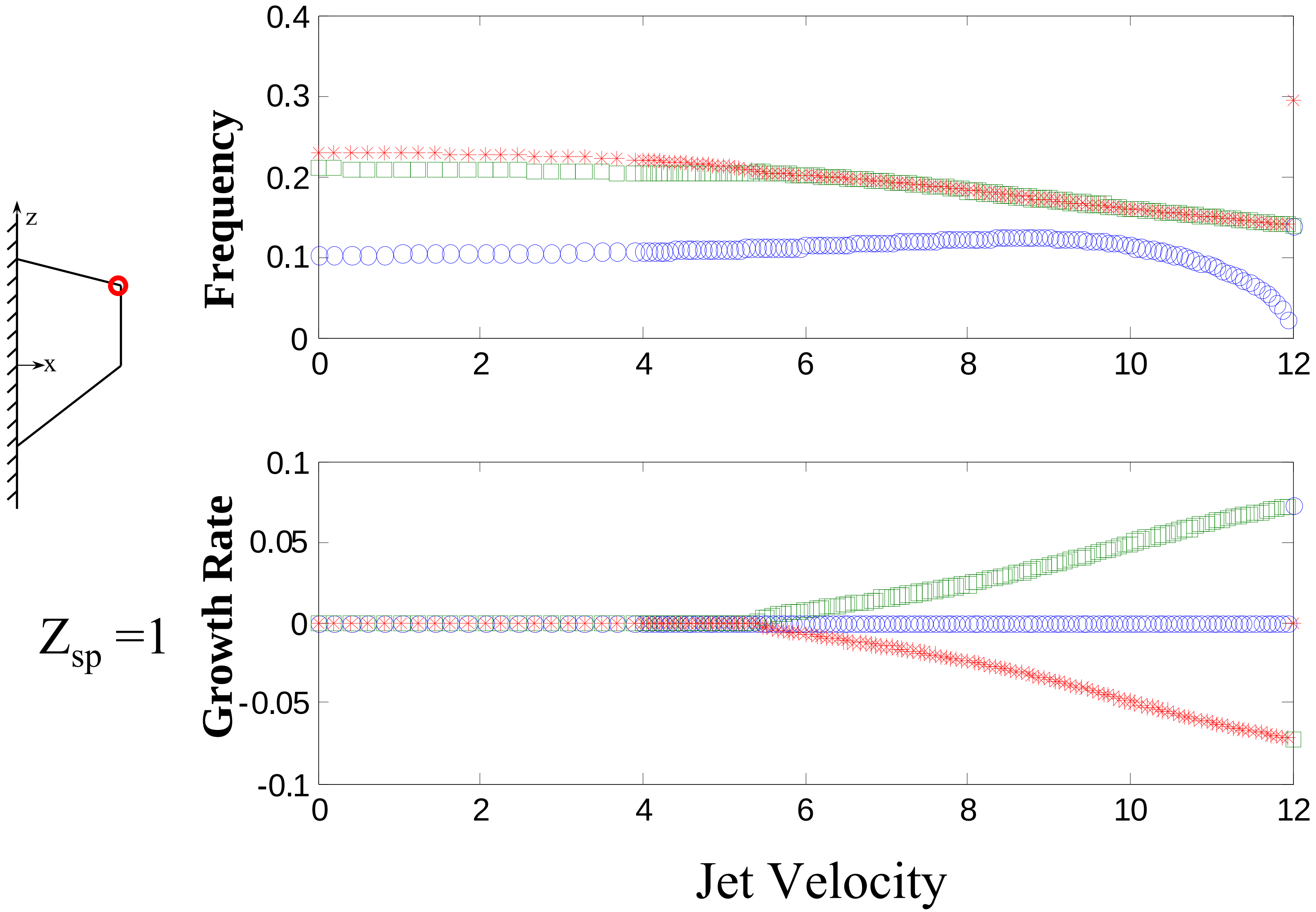
Effects of Flow Separation Location



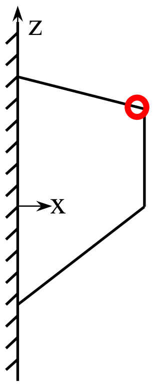
$Z_{sp} = 0.5$



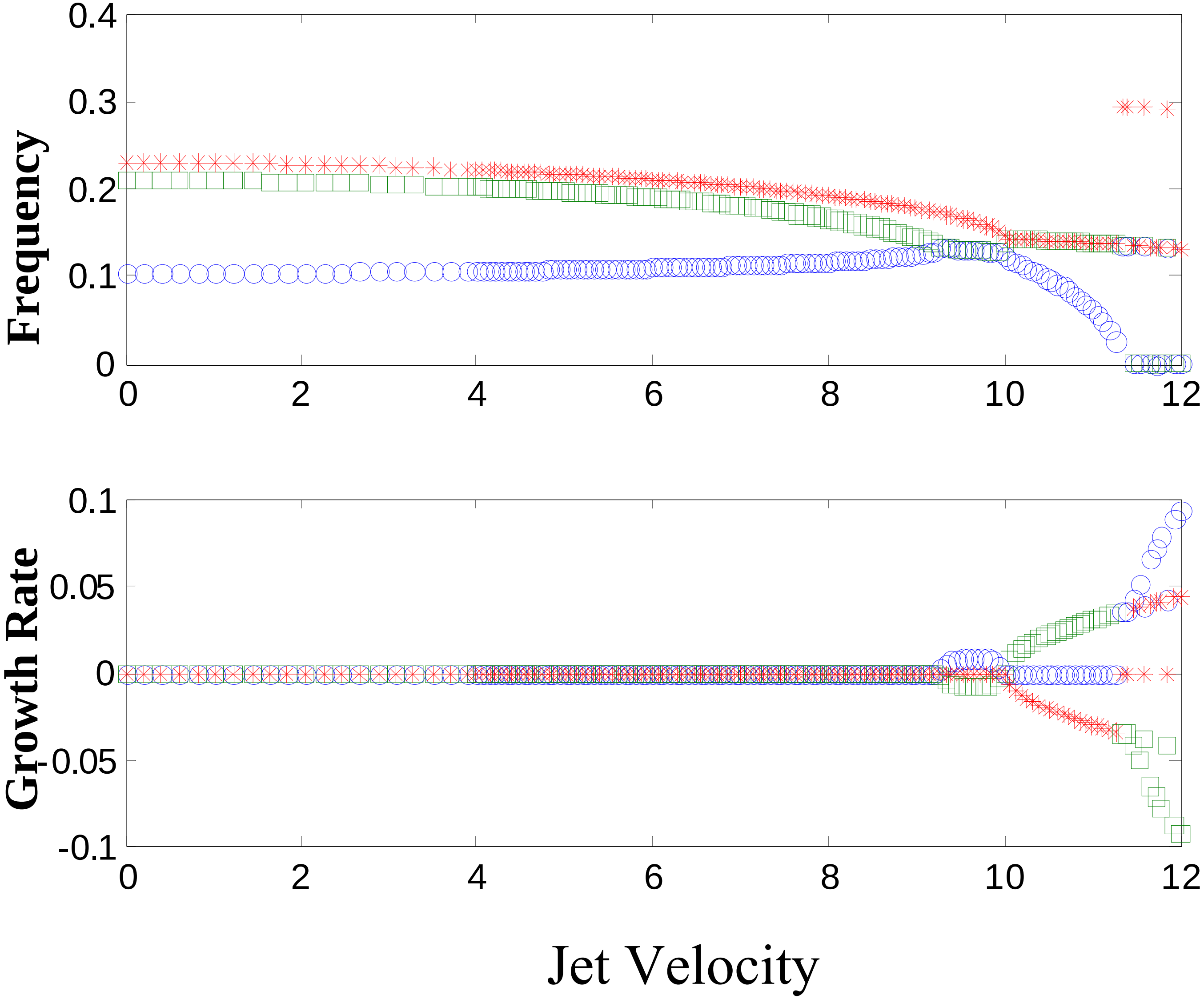
Effects of Flow Separation Location



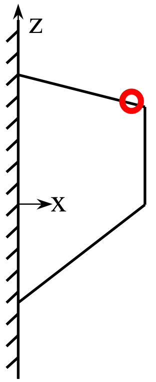
Effects of Flow Separation Location



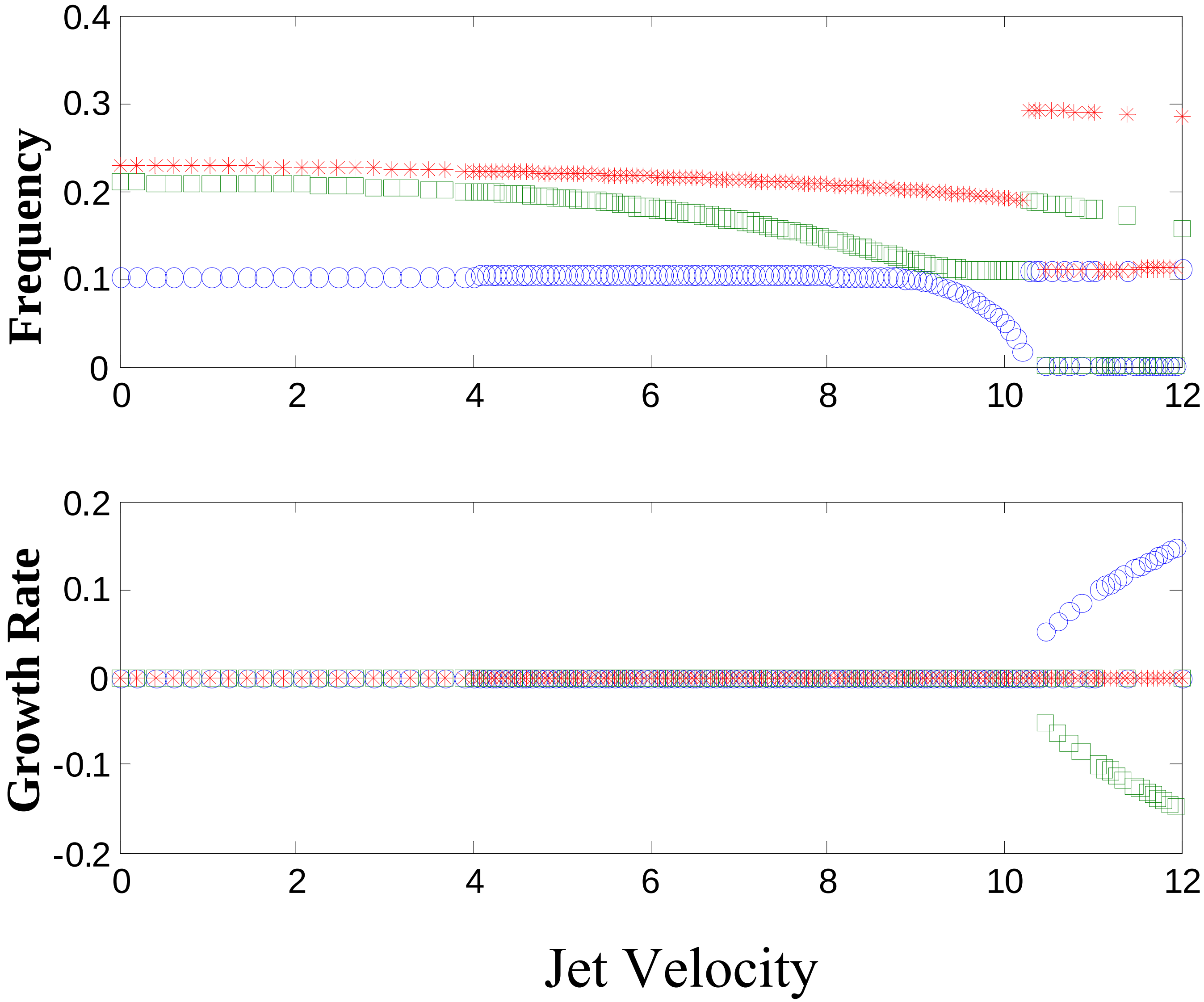
$Z_{sp} = 1.005$



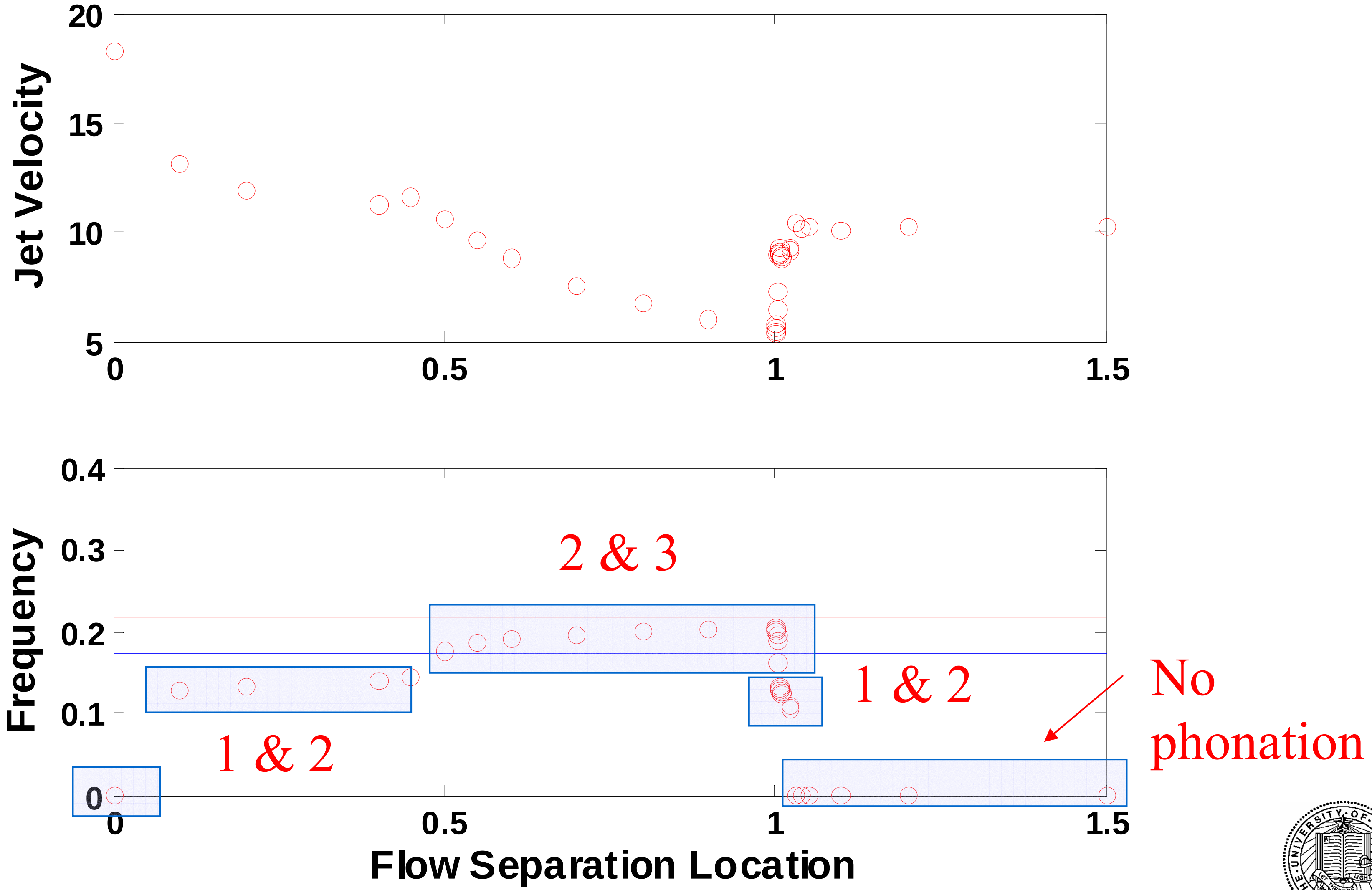
Effects of Flow Separation Location



$Z_{sp} = 1.03$



Effects of Flow Separation Location



Effects of Flow Separation Location - II

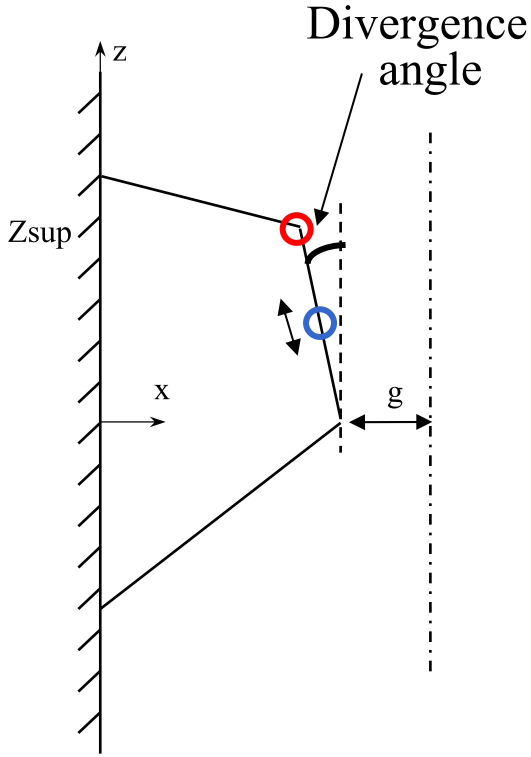
- Movement of the flow separation location changes the eigenmode interaction pattern (or movement of eigenmodes in the phase space), leading to different types of instabilities and eigenmode-synchronization patterns:
  - 1st & 2nd, 2nd & 3rd, and divergence.
- Eigenmode synchronization does NOT always occur between two closely-spaced in vacuo eigenmodes.

Effects of glottal channel geometry

(convergent, straight, and divergent)

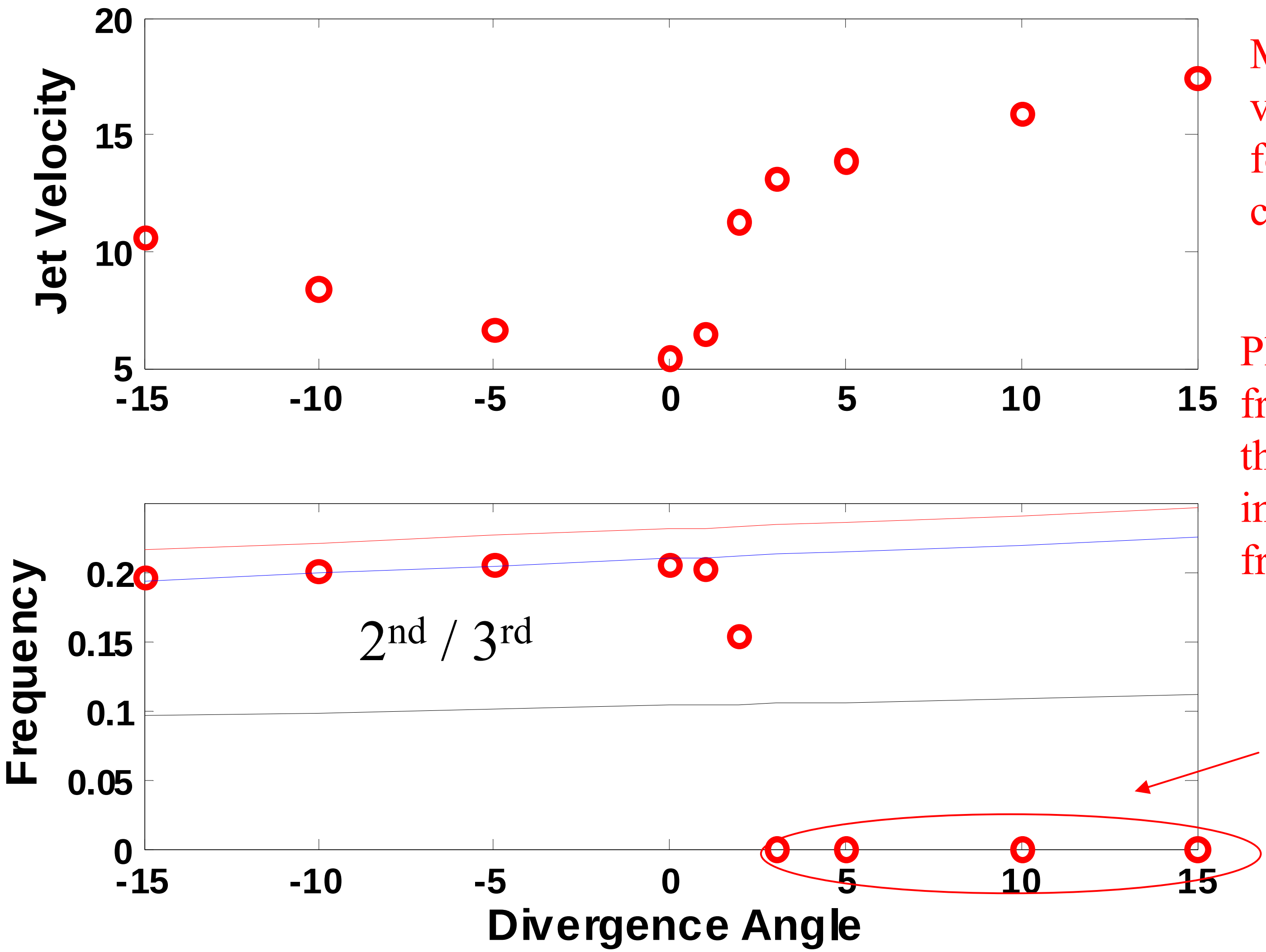
Vocal fold with varying divergence angle

- Varying divergence angle
- Minimum glottal half-width (*g*) remains constant
- Flow separation location determined in two ways:
  - 1. Fixed flow separation location at the superior edge of the medial surface.
  - 2. Flow separation location dependent of divergence angle.
    - Criterion for determination of the flow separation location (the $A_{sp}/A_{min}=1.2$ criterion):
    - Convergent: $Z_{sp}=Z_{min}$
    - Straight: $Z_{sp}=Z_{sup}$
    - Divergent:
      - If $Z_{sup}<Zmin*1.2$, $Z_{sp}=Z_{sup}$
      - Otherwise $Z_{sp}=Z_{1.2}$, where $A(Z_{1.2})=1.2*Z_{min}$



Effects of Divergence Angle -- I

flow separation fixed at superior edge of medial surface

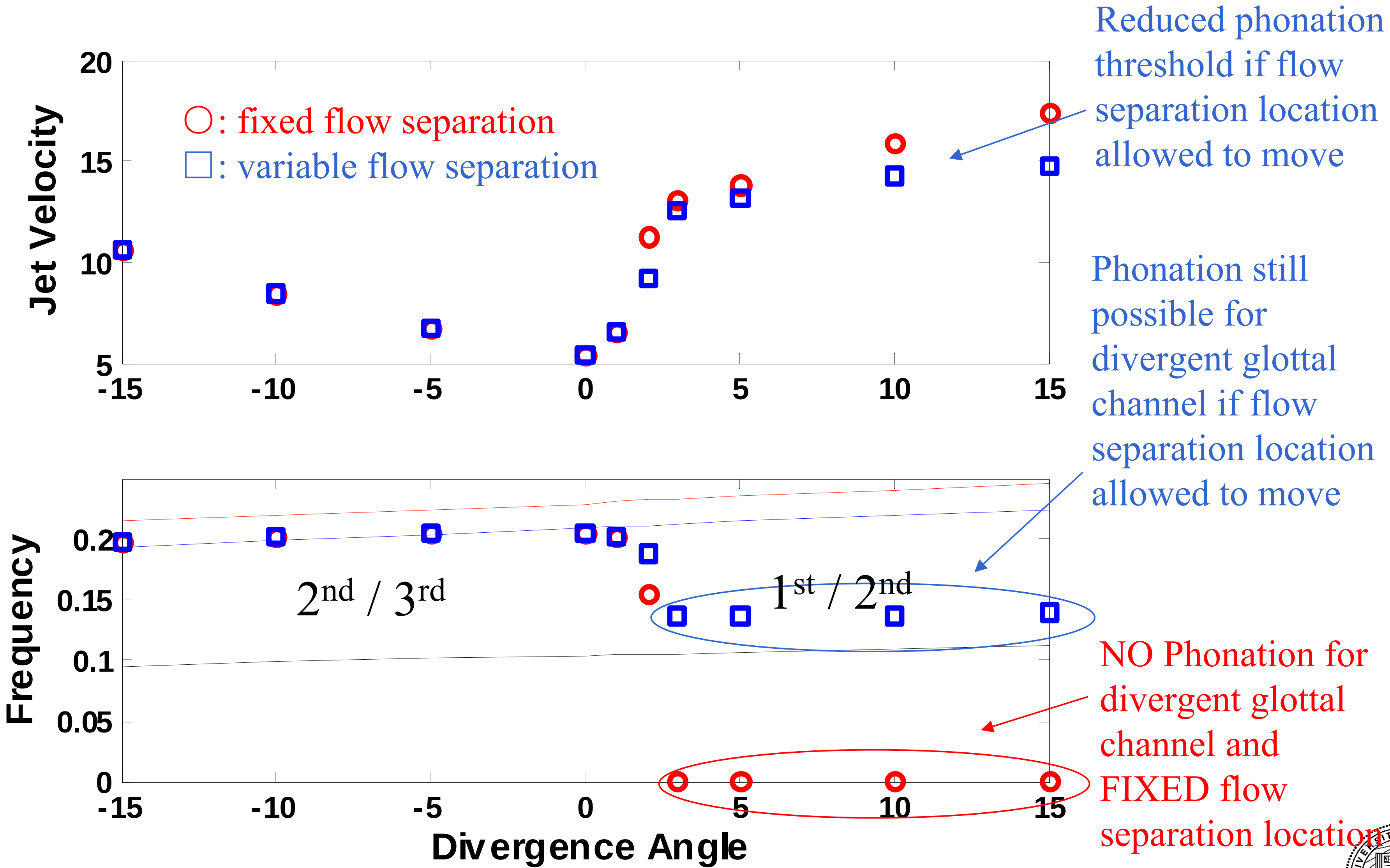


Minimum onset velocity occurred for straight glottal channel geometry.

Phonation frequency lower than the 2nd and 3rd in vacuo eigen-frequencies.

NO Phonation for divergent glottal channel and FIXED flow separation location

Effects of Divergence Angle - II
Flow separation location dependent on VF geometry



Summary

- Phonation is due to the synchronization of two eigenmodes.
- Synchronization pattern affects the phonation threshold pressure, frequency, and vocal fold vibration
- Which eigenmodes synchronize is determined by the structure of the flow-induced stiffness matrix
  - many factors such as flow separation location, flow damping, and vocal fold geometry.
  - Synchronization does NOT always occur between two closely-spaced in vacuo eigenmodes
- Models needed to accurately predict the flow separation point
- At least two degrees-of-freedom need to be retained in reduced-order models of phonation
  - One-mass model or degenerate two-mass model can not capture the synchronization mechanism
  - Three degrees-of-freedom are recommended

Future Work

- More realistic flow models:
  - Navier-stokes equations: effects of viscosity, presence of the boundary layer
- Subglottal and supraglottal tract acoustic loading
- Finite-amplitude analysis
- *Experimental verification.*