A Preliminary study on deriving optimal low-order vocal fold models from high-order finite element models

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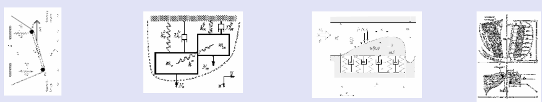
Lumped Mass Models of Phonation

A standard approach in the field of vocal fold modeling is the use of simple lumped mass models (Flanagan and Landgraff, 1968; Ishizaka and Flanagan, 1972; Horacek and Svec, 2002a, 2002b; Kob, 2002; LaMar et al., 2003). These models approximate the essential attributes of human phonation, including vocal fold motion, fluid flow, and acoustic interactions between the source and filter (Zanartu, 2006). These models are computationally efficient, and have proven to be useful in modeling the human vocal folds. However, the values of masses, spring constants, and damping elements vary (sometimes widely) from model to model. This research aims to develop accurate, objective methods for obtaining lumped element parameters of the vocal folds.



Benefits and Drawbacks of Lumped Element Models of Phonation

Benefits	Drawbacks
• Simple	• Finer details of phonation not modeled
• Basic mechanisms captured	• Relationship between actual vocal folds and lumped element parameters still unclear
• Computationally inexpensive	

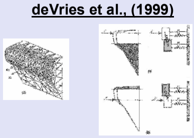
Objectives:

1) To develop accurate, objective methods for obtaining lumped element parameters of the vocal folds.
2) To test these methods through simulations and comparisons with a synthetic physical model of the vocal folds.

Previous Studies

Two previous studies have presented methods for determining the mass and stiffness values of vocal fold models: deVries et al., (1999); and Titze and Story, (2002).

deVries et al., (1999)



1. Forces (F) applied to both FE and lumped mass models
2. Resulting displacements equated to obtain stiffness values (k_1, k_2, k_c).
3. Mass values (m_1, m_2) obtained by equating natural frequencies

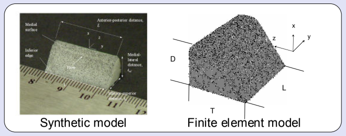
Titze and Story, (2002)

1. Tissue stiffnesses and primary geometric parameters used to obtain spring values (k1,k2, kc).
2. Density and geometric assumptions used to obtain mass values (m1, m2)
3. Boundary effects were neglected, simple rectangular geometries were assumed
4. Method for converting between one and two mass models of two degrees of freedom presented:

METHODS: order reduction

Objectivity in the method was a primary concern. To test the method, a synthetic physical model of the vocal folds was analyzed.

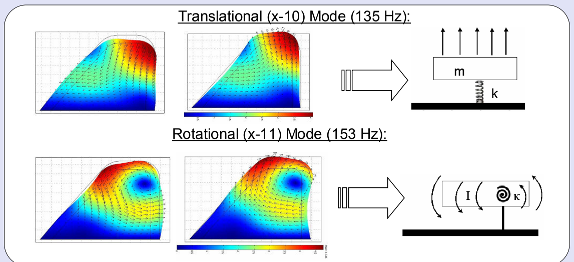
1. Create a finite element model of the vocal folds and perform modal analysis.



Synthetic model Finite element model

2. Identify relevant modes of vibration

The sustained oscillation of the human vocal folds is generally viewed as a fluid-induced coupling of translational rotational vibration modes (Berry, 2001). These modes are illustrated below:



3. Equate the kinetic energy of vibratory modes to obtain mass values.

Translational Mode:

i) Estimate average translational velocity:

$$\bar{x}_i = \left[\frac{\int_V X_i \cdot u_i\, dV}{\int_V u_i\, dV}\right] + \left[\frac{\int_V u_i^2\, dV}{\int_V u_i\, dV}\right] A\sin(\omega t)$$

ii) Equate kinetic energy of the continuum with kinetic energy of a single mass:

$$\int_V \frac{1}{2}\rho|\dot{x}|^2\, dV = \frac{1}{2}mv^2$$

Rotational Mode:

i) Estimate average angular velocity by neglecting x- and z- components of rotation:

$$\bar{\varpi}_{3(y)} = \frac{\int_V -\frac{\dot{u}}{r_y}\, dV}{V} \quad , \quad \bar{\varpi}_{3(x)} = \frac{\int_V \frac{\dot{v}}{r_x}\, dV}{V}$$

ii) Equate kinetic energy of the continuum with kinetic energy of a single mass:

$$\int_V \frac{1}{2}\rho|\mathbf{v}|^2\, dV = \frac{1}{2}I\bar{\varpi}^2$$

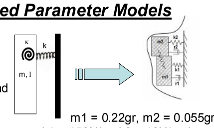
4. Equate modal frequencies to obtain stiffness parameters.

$$\omega_{FEM\,trans} = \sqrt{\frac{k}{m}}$$

$$\omega_{FEM\,rot} = \sqrt{\frac{\kappa}{I}}$$

Lumped Parameter Models

m = 0.275 g
I = 8.3 e -9 kg m²
κ = 7.7 e -3 Nm/rad
k = 198 N/m

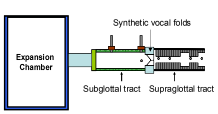


m1 = 0.22gr, m2 = 0.055gr
k1 = 158N/m, k2 = 40N/m, kc = 9N/m

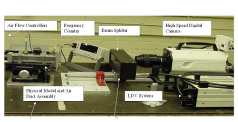
METHODS: validation of the order reduction

Previously reported experiments:

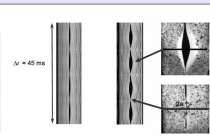
- Yielding self-sustained oscillation with a synthetic physical model (silicone rubber)
- Different supra and subglottal acoustic loading conditions can be used (Chen et al. 2008)
- High speed imaging of the oscillating model: kymography and digital image correlation (Spencer et al. 2008)



Basic experimental setup (Chen et al. 2008)



High speed imaging setup (Spencer et al. 2008)

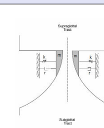


Video post processing (Spencer et al 2008)

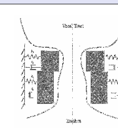
Lumped mass simulations:

- Two source models were created using the proposed order reduction technique: a single-mass model (translational mode only) and a two-mass model (translational and rotational modes). Single-mass model used only parameters from m1.

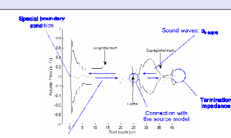
•Effect of acoustic coupling and experimental conditions were considered.



Single-mass model (Zañartu et al., 2007)



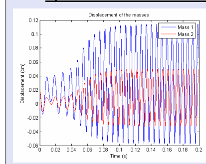
Two-mass model (Steinecke & Herzel, 1995)



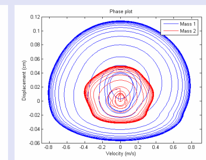
Acoustic coupling using wave reflection analog (Zañartu et al. 2007)

PRELIMINARY RESULTS

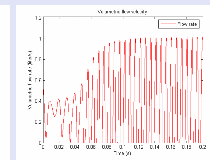
1) Self-sustained oscillation with the FEM reduced order parameters



Two-mass model: vowel /a/
Mass displacements



Two-mass model: vowel /a/
Phase plots



Two-mass model: vowel /a/
Volumetric flow velocity

OBSERVATIONS:

- The parameters used for the simulations yield self-sustained oscillation within the expected frequency range
- Oscillation frequency increased with pressure loading (as observed in human phonation)
- Very slow onset of about 100 ms that is similar to that of the rubber model (but differs from real phonation)

2) Comparison between simulations and experiment:

Configuration	Subglottal Pressure (kPa)	Experimental results*		Single-mass model simulations		Two-mass model simulations	
		Mean flow (l/s)	Pitch (Hz)	Mean flow (l/s)	Pitch (Hz)	Mean flow (l/s)	Pitch (Hz)
No acoustic loading	2.06	1.03	107.5	N/A	N/A	0.42	153
Vowel /i/	1.60	0.23	113.5	0.65	140	0.40	156
Vowel /a/	1.61	0.28	120	0.75	159	0.35	154

* From Chen et al., 2008

OBSERVATIONS:

- Lower pitch in the experiments suggests that other (lower) modes are excited on the single layer silicone model
- High-speed imaging shows a strong out-of-plane mode not present in the selected lumped mass models or in real human phonation
- Higher mean flow in the simulations is due to the rectangular opening in the lumped mass model (roughly twice as big as the one in the physical model).
- Acoustic loading effects are more pronounced on the single-mass model
- The increased volumetric flow velocity due to the orifice geometry explains the stronger acoustic coupling observed in the single-mass model

DISCUSSION

✓ The proposed method yields parameters that lead to self-oscillation typical of two-mass models
✓ The current scheme is restricted to low frequency modes which have simple displacement patterns.
✓ The proposed order reduction method does not account for damping
✓ The single-layer silicone vocal folds model does not exhibit the modes observed during phonation:
- It cannot be represented using traditional lumped mass models of the vocal folds
- It is not adequate to evaluate the order reduction technique

✓ It is anticipated that a more realistic physical model (such as a two-layer silicone model) would be a better choice for future work in this area.
✓ Further developments consider validation using excised larynx experiments and human phonation

Preliminary results suggest that the proposed scheme is a consistent approach for obtaining lumped element parameters of the vocal folds. Further developments and validations are needed.

REFERENCES

- Chen, L.J. , Zañartu, M., Cook D.D, and Mongeau, L. "Effects of acoustic loading on the self-oscillations of a synthetic model of the vocal folds "9th International Conference on Flow-Induced Vibrations, FIV2008, 30 JUNE – 3 JULY 2008, Prague, Czech Republic.
- de Vries, M.P., Schutte, H.K., and Verkerke, G.J., (1999), "Determination of parameters for lumped parameter models of the vocal folds using a finite-element method approach," J. Acoust. Soc. Am. 106, pp. 3620-3628.
- Ishizaka, K. and Flanagan, J. L., (1972) "Synthesis of voiced sounds from a two mass model of the vocal cords," Bell Syst. Tech. J.51, pp. 1233-1268.
- Steinecke, I., Herzel, H. (1995) "Bifurcations in an asymmetric vocal-fold model", J. Acoust. Soc. Am., 97(3), pp. 1874-1884.
- Stevens, K. N., (2000), "Acoustic Phonetics", First edition, The MIT Press, Massachusetts.
- Spencer, M, Siegmund, T., Mongeau, L., "Determination of superior surface strains and stresses, and vocal fold contact pressure in a synthetic larynx model using digital image correlation", J Acoust Soc Am. 2008 Feb ;123 (2), pp.1089-103
- Titze, I.R., Story, B.H.,(2002), "Rules for controlling low-dimensional vocal fold models with muscle activation," J Acoust. Soc. Am.112 (3), pp.1064–1076.
- Zañartu, M., Mongeau, L. and Wodicka, G. R. (2007), "Influence of acoustic loading on an effective single mass model of the vocal folds", J. Acoust. Soc. Am., 121(2), pp. 1119-1129.

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