Modeling the influence of acoustic loading on laryngeal self-sustained oscillations

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#2pSC4

OBJECTIVE

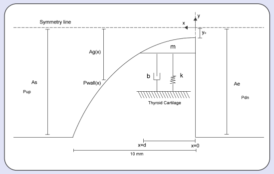
In this project, three-way interactions between sound waves in the subglottal and supraglottal tracts, the vibrations of the vocal folds, and laryngeal flow were investigated. The purpose was to determine if fluid-sound interactions were as significant as fluid-structure interactions during phonation. The effects of several acoustic loads on phonation were studied.

INTRODUCTION

- Different studies on voice production have demonstrated that forces that are in phase with the velocity of the tissue of the vocal folds are favorable to phonation (Rothenberg, 1981; Titze 1988; Fulcher *et al.*, 2006). These forces can be produced by:
  - ✓ A "mucosal wave" in the cover of the vocal folds. The driving force is produced by fluid-structure interactions.
  - ✓ An inertive impedance in the vocal tract (fo<<F1). The driving force is produced by fluid-sound interactions.
- The relative importance between fluid-structure and fluid sound interaction in phonation is still unknown.
- The role of other supraglottal loadings and the subglottal tract is not clear.
- Traditional one-mass models cannot reach self-sustained oscillations (SSO) without acoustic loading, since the effects of the mucosal wave are not included.
- For these models, the effects of the mucosal wave can be introduced in the flow instead of the structure using a orifice discharge coefficient (ODC).

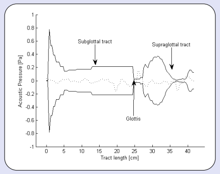
INTERACTIVE MODEL OF PHONATION

- Based on a previous one-mass model (Fulcher *et al.*, 2006), where negative Coulomb damping is used to drive the folds.
- Fluid-structure interactions, fluid-sound interactions and collision effects were added to the previous model.
- Bernoulli's equation and obstruction theory were used. A smooth time-varying ODC resembled the effects of the mucosal wave.
- The ODC for converging and diverging glottal shapes were taken from experimental data (Park et al., 2006).



Half of the symmetric representation of the vocal folds model

- The acoustic loads were modeled using a wave reflection analog approach (Story, 1995; Rahim ,1994).
- Contributions to this technique were made (see chart below).

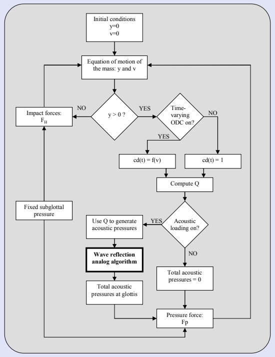


Representation of the complete system -source and acoustic loads- using a wave reflection analog approach

- Material properties were taken from previous studies (Titze, 2002; Story and Titze, 1995).
- Equation of motion of the mass is given by:

$$m\ddot{y} + b\dot{y} + k(y - y_o) = F_p + F_H$$

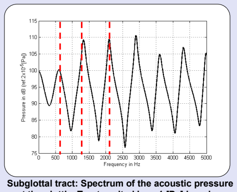
- F_p is the pressure force acting on the open cycle, including
  - ✓ Fluid-structure interactions
  - ✓ Fluid-sound interaction
- F_H are the forces acting during collision, including
  - ✓ Hertz impact forces
  - ✓ Change in damping properties
  - ✓ Upstream pressure force on the non-colliding surface



Simplified block diagram of the interactive source model

CONTRIBUTIONS TO THE WAVE ANALOG TECHNIQUE

- New subglottal attenuation factor: global attenuation as by Rahim (1994). Subglottal tract losses were larger by roughly a factor of 3 compared with that of the vocal tract.
- New subglottal tract design: Based on the area functions from Weibel (1963) with an adjusted termination. Results presented on the right.
- Complete set of tests to evaluate the scheme:
  - ✓ Comparison with theoretical complex solution
  - ✓ Effects of boundary conditions
  - ✓ Effects of radiation impedance
  - ✓ Effects of the global loss factor
  - ✓ Acoustic coupling between tracts



Subglottal tract: Spectrum of the acoustic pressure at the glottis. Tract excited by a 1 [Pa] impulse.

— : Acoustic Pressure
--- : Typical subglottal resonances from Harper, 2000.

NOTE: The figure was constructed measuring the impulse response of the tract at the glottis. Fs=44.1 KHz.

FLUID-STRUCTURE INTERACTIONS VS. FLUID-SOUND INTERACTIONS

Research questions:

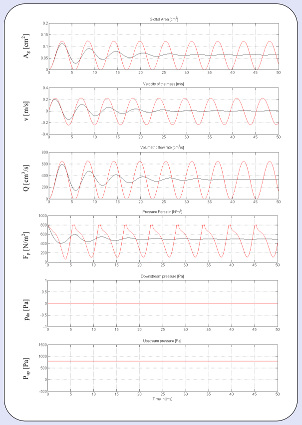
- What was the relative importance between fluid-structure interactions and fluid-sound interactions?
- What was the role of each tract?
- What were the effects of different acoustic loadings in SSO?

Methods:

- Fluid structure interactions were activated/deactivated through the time varying ODC
- Three different cases were tested: No acoustic loading, subglottal tract + an inertive supraglottal loading (vowel /A/), and subglottal tract + a less inertive supraglottal loading (vowel /i/).

— : ODC OFF (no fluid-structure interactions)
--- : ODC ON (with fluid-structure interactions)

NO ACOUSTIC LOADING



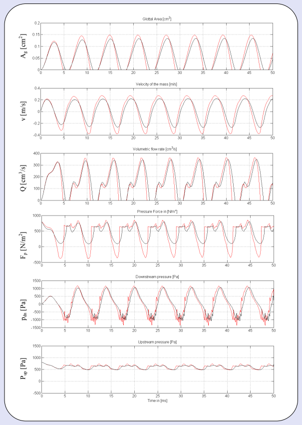
Time history with no acoustic loading

- As = Ae = infinity
- Supraglottal formants: F_1= n/a, F_2= n/a
- Subglottal formants: F_1= n/a, F_2= n/a

- Fundamental frequency: f_0=180Hz
- The time-varying ODC yielded to SSO
- Without the time-varying ODC the vocal folds did not reach SSO
- The presence of acoustic loading was not a required condition to reach a steady state
- Collisions effects were not significant, for which the spectral analysis showed only a few harmonics

Values were comparable with other models for all loading scenarios (Story and Titze, 1995; Alipour *et al.,* 2000).

MRI VOWEL /i/ + SUBGLOTTAL TRACT

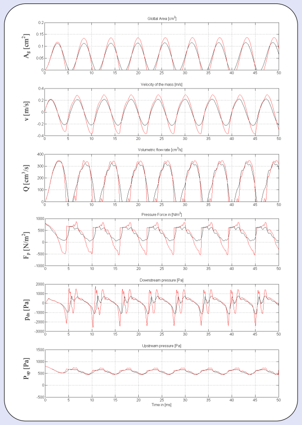


Time history with MRI vowel /i/ and subglottal tract

- As = 2.7 cm^3, Ae = 0.33 cm^2
- Supraglottal formants: F_1= 225 Hz, F_2= 2486 Hz
- Subglottal formants: F_1= 613 Hz, F_2= 1341 Hz

- Fundamental frequency: f_0=170Hz
- Acoustic loading yielded to SSO
- Large coupling between source and vocal tract
- Subglottal tract: less pronounced effects in the source
- Modified source properties (Q): Reduced amplitude, added depression on the opening phase and skewing.
- The presence of the time-varying ODC was not a required condition to reach a steady state
- When the time-varying ODC was introduced only minor differences were noted. The driving force showed the largest variation.

MRI VOWEL /A/ + SUBGLOTTAL TRACT



Time history with MRI vowel /A/ and subglottal tract

- As = 2.7 cm^3, Ae = 0.45 cm^2
- Supraglottal formants: F_1= 786 Hz, F_2= 1147 Hz
- Subglottal formantz: F_1= 613 Hz, F_2= 1341 Hz

- Fundamental frequency: f_0=190Hz
- Acoustic loading yielded to SSO
- Larger coupling between source and vocal tract
- Subglottal tract: did not vary significantly
- Modified source properties (Q): Reduced amplitude, added ripple on the opening phase and skewing
- The presence of the time-varying ODC was not a required condition to reach a steady state
- When the time-varying ODC was introduced, larger variations were observed in *Q*, F_p and P_{dn}
- The effect of collision were more significant.

CONCLUSIONS

COMPARISON BETWEEN INTERACTIONS

- Both fluid-structure interactions and fluid-sound interaction led to self-sustained oscillations
- Acoustic loading was more significant than the effects introduced by the orifice discharge coefficient.
- The influence of the subglottal tract appeared to be significant, but not as determinant as that of the vocal tract.

EFFECTS OF THE ACOUSTIC LOADING

- Important changes were observed in the source (through the volumetric flow rate Q): Ripples and depressions that increased spectral components, changes in f_0
- The less coupled with the loading, the more pronounced the effects were in the source.
- The supraglottal and subglottal tracts played different roles
- The inertance theory was met only in the vocal tract
- The vocal tract was more dominant than the subglottal tract
- The subglottal tract reduced the effects introduced by the vocal tract in Q

GENERAL

- The interactive one-mass model was able to illustrate the same effects only seen in high order models.
- Results comparable with other studies using finite elements (Alipour *et al.*, 2000) and higher order models (Story and Titze, 1995).

FUTURE WORK

- Improve subglottal tract design: enhance the current wave reflection analog design.
- Improvements in the source model: pressure distribution codebook, or interactive high order model (finite element model).
- Theoretical perspective: develop a complete impedance analysis and an interactive state model.
- Experimental perspective: use synthetic models of the vocal folds using the acoustic loadings. Digital image correlation is suggested.

OTHER ACOUSTIC LOADS

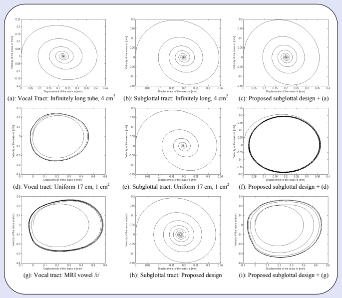
Objective:

- To evaluate what types of acoustic loadings lead to self-sustained oscillations (SSO).

Methods:

- Only fluid-sound interactions were considered (No time varying ODC was used)
- Phase plot only (displacement vs. velocity)
- Infinitely long tubes, uniform tubes with variable area and length, MRI vowels and subglottal tract designs were used.
- Cases tested: supraglottal tract, subglottal tract and both tracts simultaneously.

PHASE PLOTS



Phase plots (displacement vs. velocity) for different acoustic loads

- Effect of supraglottal loading in SSO
  - ✓ It met inertance theory (Titze, 1998).
  - ✓ It led to SSO for relatively narrow shapes (≤1cm^2).
  - ✓ The area was the most sensible variable.
- Effect of subglottal loading in SSO
  - ✓ It did not meet the inertance theory.
  - ✓ It did not reach to SSO, but it showed favorable.
  - ✓ Realistic shapes were comparable to an infinitely long tube.
  - ✓ The effects were combined when using both tracts.
  - ✓ Its design (shape, boundary conditions, losses) could severely affect phonation.

REFERENCES

- Zañartu, M. (2006), "Influence of Acoustic Loading on the Flow-Induced Oscillations of Single Mass Models of the Human Larynx," M.S. Thesis, School of Electrical and Computer Engineering, Purdue University.
- Fulcher, L. P. , Scherer, R. C., Melnykov, A. and Gateva, V. (2006), "Negative Coulomb damping, limiting cycles, and self-oscillation of the vocal folds," Am. J. Phys. **74** (5), pp. 386-393.
- Park, J. B. and Mongeau, L. (2006), "Instantaneous orifice discharge coefficient measurements of a physical, driven model of the human larynx," J. Acoust. Soc. Am., in press.
- Alipour, F., Berry, D. A. and. Titze, I. R (2000), "A finite-element model of vocal-fold vibration," J. Acoust. Soc. Am., vol. **108**(6), pp. 3003-3012.
- Harper, V. P. (2000), "Respiratory Tract Acoustical Modeling and Measurements, Ph.D. Dissertation", School of Electrical and Computer Engineering, Purdue University, 2000.
- Story, B. H., Titze, I. R. and Hoffman, E. A. (1996) "Vocal tract are functions from magnetic resonance imaging," J. Acoust. Soc. Am., vol. **100**(1), pp. 537-554.
- Story, B. H. and Titze, I.R. (1995), "Voice simulation with a body-cover model of the vocal folds," J. Acoust. Soc. Am., vol. **97**(2), pp. 1249-1260
- Story, B. H. (1995), "Physiologically-Based Speech Simulation using an Enhanced Wave-Reflection Model of the Vocal Tract", Ph.D. Dissertation, University of Iowa.
- Rahim, M. G. (1994), "Artificial Neural Networks for Speech Analysis/Synthesis", First edition, Kluwer Academic Publishers, New York.
- Titze, I. R. (1988). "The physics of small-amplitude oscillation of the vocal folds," J. Acoust. Soc. Am. **83**, pp.1536-1552.
- Titze, I. R. (2002), "Regulating glottal airflow in phonation: Application of the maximum power transfer theorem to a low dimensional phonation model," J. Acoust. Soc. Am., vol. **111**(1), pp. 367-376
- Rothenberg, M. (1981), "Acoustic interaction between the glottal source and the vocal tract," in Vocal Fold Physiology, K. N. Stevens and M. Hirano Eds, University of Tokyo Press, Tokyo.
- Weibel, E. R. (1963), "Morphometry of the Human Lung", First Edition, New York, Springer.

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