ICVPB 2020

12th International Conference on Voice Physiology and Biomechanics
March 18-20, 2020, Grenoble, France

Energy-consistent modelling of the fluid-structure interaction in the glottis

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Keywords : Fluid-structure-sound interactions, voice production modeling

Introduction

The physics of voice has been fruitful in producing a wide variety of models, from full-featured numerical ones (mostly based on FEM for tissues and FVM for airflow) to reduced-order models focusing on the predominant phenomenon. A large body of work in the second category relies on the description of the glottal aerodynamics from the late 1950, based on Bernoulli theorem, thus ignoring rapid or large-amplitude motions of the vocal folds. This is justified on experiments in rigid static larynx-like ducts. However, those simplified models contain an intrinsic paradox where the tissues are driven by the power received by the flow, whose description assumes it does not provide power to tissues.

The main objective of the current communication is to propose a minimal model of the full vocal apparatus that restores a consistent description of the power exchange between the glottal airflow and the vocal folds.

Methods

The model is formulated using the port-Hamiltonian systems (pHS) theory, a framework emphasizing the separation between the intrinsic behavior of components and their interconnection through ports (see Ref. [1] for an introduction). The detailed description of the proposed model is given in Ref. [2]. Its main characteristics is that it includes the simplest kinematics of an incompressible potential flow of inviscid air in the glottis that ensures the continuity of the normal velocity on the surface of the vocal folds (assumed planar for sake of simplicity, see Fig. 1)

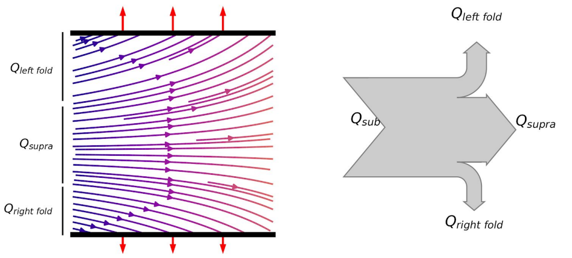

Fig. 1: Example of the velocity field during the glottal opening (on left) and representation of the volume flow division (on right).

The capabilities of the proposed model are explored by means of time-domain simulations (notably using the passive guaranteed numerical scheme derived from the pHS theory) and numerical continuation (giving access to bifurcation and limit cycles, i.e., phonation thresholds and steady-state oscillating regimes).

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Results

Several cases were explored numerically to investigate the effect of the pre-phonatory configuration and of the asymmetry of the vocal folds.

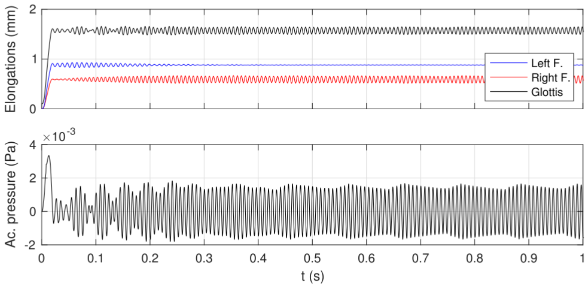

Fig. 2: Example of time-domain simulation in a strongly asymmetric configuration (here, right fold stiffer than left fold)

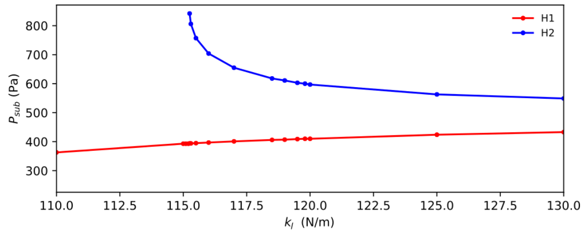

Fig. 3: Bifurcation diagram showing the existence of a second limit cycle beyond some asymmetry threshold

Discussion

Accounting for the transverse component of the glottal flow leads to a more consistent modeling of the fluid-structure interaction that drives phonation. The results obtained with the proposed model already evidence interesting outcomes such as the contact stresses that apply to the superficial layers of tissues during glottal closure, the production of raucous sounds (quasi-periodic regimes) or the existence of a second possible limit cycle for asymmetric folds that can lead to intermittency and thus to pathological voice.

Increasing the complexity of the model will remain easy thanks to the modularity provided by the pHS framework.

Acknowledgements

We acknowledge the support of the INFIDHEM ANF-DFG project (ANR-16-CE92-0028).

References

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