A FINITE ELEMENT SCHEME FOR FULLY-COUPLED FLUID-STRUCTURE INTERACTIONS AND ITS APPLICATION TO HUMAN VOCAL FOLDS VIBRATION DURING PHONATION

By

Xingshi Wang

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Examining Committee:

Prof. Lucy Zhang, Thesis Adviser
Prof. Timothy Wei, Member
Prof. Assad A. Oberai, Member
Dr. Michael H. Krane, Member

Rensselaer Polytechnic Institute
Troy, New York

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ABSTRACT

The focus of this thesis is to develop a numerical scheme for fully-coupled fluid-structure interaction problems and apply it to numerically studying the vibration of human vocal folds during phonation. The vocal folds vibration is a fully-coupled fluid-structure interaction problem, the motion and deformation of the structure strongly affecting the fluid flow, and a fluid induced self-oscillating procedure, the system sustain self-oscillated by a constant pressure driven flow. Due to the nature of the problem, the numerical model used has to fulfill the following requirements. First, the numerical model has to be completely coupled fluid-structure interaction system. Second, the numerical model should perform well when there exists large density ratio between the fluid and structure because the density of the vocal fold muscle is close to water and the density ratio between the vocal fold muscle and the airflow is about 1000. Third, the motion and deformation of the structure have to be predicted accurately even with complicated geometry and material descriptions since the vocal folds have complex shape and layer-structure, and are governed by viscoelastic material description.

So far, most of the numerical models currently used do not satisfy all these requirements. The modified Immersed Finite Element Method (IFEM) is developed and introduced in this thesis, which perfectly fulfills all the requirements above. The Immersed Finite Element Method is a fully coupled fluid-structure interaction numerical scheme. The fluid and solid domains are solved independently using finite element method, and coupled with each other within one time step. For most of the numerical schemes solving fluid-structure interaction problems, the fluid and solid solutions are coupled with each other explicitly. The modified IFEM is able to couple the fluid and solid solutions semi-implicitly, meaning all the effects due to the density difference between solid and fluid are taken into account implicitly. The semi-implicit coupling extends the stability region of the numerical scheme and allows us to consider the fluid-structure interaction problems when the fluid and solid properties are very different from each other, for example high density

ratio between the solid and fluid, and the solid with relatively large stiffness. For the modified IFEM, the solid solution is solved based on the boundary conditions applied on the fluid-structure interface and the solid constitutive laws using the finite element method. The solid does occupy volume in the numerical model and its volume change is no longer neglected. It provides more accurate solid solution comparing to most of other numerical algorithms. Based on all these numerical features, the modified IFEM is appropriate to be applied to numerical study the vocal folds vibration during phonation. Indeed, it is a robust and efficient numerical algorithm for various fully-coupled fluid-structure interaction problems.

Self-oscillated vocal folds vibration is successfully captured by the modified IFEM. The numerical results agree pretty well with the experimental data and other numerical studies. A parameter study is performed to show how the vocal folds vibration is affected by the lung pressure, the material description and geometry of the vocal folds. Further analysis shows that the glottal flow is inherently unsteady and the viscous effect of the vocal folds wall is not negligible. The asymmetric glottal jet due to the instability of the fluid flow, commonly referred as the Coanda effect, is observed and its effects on the vocal folds vibration are also examined. The reason why the vocal folds are able to sustain self-oscillated is sort out by characterizing the vocal folds vibration pattern and evaluating the energy flow between the vocal folds and the glottal flow. All these findings help us to obtain a better understanding of the dynamics of the voice production procedure of human being.