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Validation of a flow–structure-interaction computation model of phonation

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ABSTRACT

Computational models of vocal fold (VF) vibration are becoming increasingly sophisticated, their utility currently transiting from exploratory research to predictive research. However, validation of such models has remained largely qualitative, raising questions over their applicability to interpret clinical situations. In this paper, a computational model with a segregated implementation is detailed. The model is used to predict the fluid–structure interaction (FSI) observed in a physical replica of the VFs when it is excited by airflow. Detailed quantitative comparisons are provided between the computational model and the corresponding experiment. First, the flow model is separately validated in the absence of VF motion. Then, in the presence of flow-induced VF motion, comparisons are made of the flow pressure on the VF walls and of the resulting VF displacements. Self-similarity of spatial distributions of flow pressure and VF displacements is highlighted. The self-similarity leads to normalized pressure and displacement profiles. It is shown that by using linear superposition of average and fluctuation components of normalized computed displacements, it is possible to determine displacements in the physical VF replica over a range of VF vibration conditions. Mechanical stresses in the VF interior are related to the VF displacements, thereby the computational model can also determine VF stresses over a range of phonation conditions.

1. Introduction

The myoelastic–aerodynamic theory of phonation (van den Berg, 1958; Titze, 2006) states that phonation is a result of two sources of oscillatory behavior. The first source (myoelastic) is based on the muscular nature of the VF tissue. It causes self-sustained oscillations in a similar manner as the elasticity in a spring causes the spring to vibrate (indefinitely in the absence of friction) when displaced from its resting state. The second source (aerodynamic) is based on the variation in fluid pressure associated with flow passing through a duct of varying cross-sectional geometry. This source causes the VFs to vibrate by creating regions of varying wall-pressure – and thus regions of relative push/pull – which in turn are cause by the airflow undergoing significant constriction in the glottis and a sudden expansion in the supra-glottal tract. Thus phonation is a result of cyclic imbalance between glottal air flow pressure and muscular tension in the vocal folds (VFs). Computational models of this flow–structure interaction (FSI) between glottal air flow and VFs are becoming increasingly realizable

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(de Oliveira Rosa et al., 2003; Alipour and Scherer, 2004; Thomson et al., 2005; Decker and Thomson, 2007; Luo et al., 2008, 2009; Zheng et al., 2009, 2010; Mittal et al., 2011; Bhattacharya and Siegmund, 2014) with the rapid advance in computation power and availability of sophisticated numerical algorithms. As an attractive alternative to excised and synthetic VF models, computational models provide unique advantages: (i) models are non-destructive and non-interfering, (ii) can be used to remove confounding factors (by abstraction) and (iii) can be used in sensitivity analysis (by parametric variation). A particular advantage is that computational models can be used to directly determine mechanical stresses in the VF interior. This unique capability is very important in understanding VF health, which depends on the state of stress within the VF (Titze, 1994; Chan and Tayama, 2002; Leydon et al., 2009). Design of VF implants (Zeitels et al., 2003) and investigation of glottal tract abnormalities e.g. subglottic stenosis (Smith and Thomson, 2013) would also benefit significantly from validated results. Notwithstanding the advances in the state-of-the-art of computer models, the validation of such models with experiment has been largely qualitative. The detailed quantitative validation of a computer model of VF vibration is the focus of the present study.

In FSI computations, the main challenges are (i) the dissimilar conventions in the description of the flow and VF domains (Eulerian and Lagrangian respectively), (ii) the necessity of tracking the flow–structure interface requiring complex discretization strategies and management of physical variables on the interface, (iii) the three-dimensionality of both domains, (iv) the complex constitutive behavior of VF tissue, and (v) the stability and accuracy issues in transient solvers of both physical domains. Though the preceding list applies strictly to implementations with separate fluid and structural solvers (segregated implementations), in alternative implementations with a single solver (monolithic implementations) some of the above challenges are overcome but only at the cost of additional complexities. Further, in both segregated and monolithic implementations, simulation of the minimum interval of interest in physical time typically requires computations to run for times that are larger than the physical time by orders of magnitude.

The foregoing computational challenges necessitate simplifications or restrictive assumptions in order to ensure the feasibility of the computational effort. Since simplifications will limit the validity of a particular model, the relevance of each restriction or simplification must be evaluated in the context of the study. For instance, two-dimensional studies, though computationally inexpensive, cannot provide insights into the three-dimensional (3D) nature of the glottal jet. Another motivation to include a particular simplification is to remove confounding factors within the physical problem. There are several aspects to the interaction between the airflow and the VFs (e.g. acoustics, glottal jet dynamics, VF wall motion, stresses within VF, VF hydration, etc.). Depending on the focus of a particular research study, the formulation of certain aspects will be more detailed than others. Though it is obvious that different aspects of the problem interact, it is not always clear to what degree they do. Therefore, approximations made to simplify a certain aspect (computational or physical) must be carefully analyzed for the effect they have on the focus of the study.

The aim of the present paper is to validate VF deformations computed from a 3D computational model of self-sustained VF vibrations. It has been shown that the model can be extended to include aspects of VF collision and complex constitutive behavior of the VFs (Bhattacharya and Siegmund, 2014). Commercially available solvers are employed to facilitate model development (complex geometry, constitutive properties, discretization and coupling) and to leverage post-processing capabilities. The model can be deployed on parallel processors, thereby increasing computation speed.

Existing experimental techniques do not allow the determination of mechanical strains in the VF interior vibration (Mittal et al., 2013). However, optical measurements of the superior surface displacements during free vibration are readily possible and used here in the computation–experiment comparison. This choice of validation strategy has the following motivation. In an elastic-viscoelastic solid continuum like the VFs, the stresses are completely determined if the strains and strain-rates are known. Therefore, validation of displacements, which determines strains and strain-rates, is sufficient to validate stresses within the VFs. Detailed displacement measurements have been obtained during free vibration on the VF superior surface (Wittenberg et al., 2000; Spencer et al., 2008; George et al., 2008; Chen, 2009).

The validation strategy is further enhanced by separately considering flow studies. The underlying rationale for this approach is that the airflow is the sole source of energy available to the VF for generating motion. The interaction between the VFs and glottal flow takes place through the energy transfer across the glottal surface. Both normal tractions (or flow pressures) and shear tractions arise on the glottal surface (Alipour and Scherer, 2004), but there is sufficient evidence that the predominant mode of energy transfer is due to the flow pressures (Thomson et al., 2005). Therefore a validation of computed flow pressures is included. However, no experimental data on flow pressures on the VF surface during FSI are available due to the challenges in obtaining such measurements. Thus, a direct validation of computed flow pressures in vibrating VFs is infeasible. Accordingly, the flow validation strategy is adapted as follows. Firstly, the flow-domain model within the segregated FSI model is separately exercised for the case of rigid VFs. Computed flow pressures are then compared with those obtained from a rigid VF experiment. Secondly, a comparison is made between flow pressures obtained from experiments on rigid VFs resembling instantaneous deformed VF shapes and those obtained from the full FSI computation with vibrating VFs. In previous experimental studies with rigid VF glottal shapes resembling instantaneous deformed VF shapes (Guo and Scherer, 1993; Scherer et al., 2001, 2002; Shinwari et al., 2003; Scherer et al., 2010; Fulcher et al., 2010) flow pressure on the VF walls have been reliably obtained. Such studies were motivated by the quasi-steady approximation (McGowan, 1993), which states that the instantaneous flow field though a vibrating glottis is not significantly altered if the deformation of the glottis is frozen in time. It must also be remarked that a considerable body of work exists on computation of glottal airflow past rigid VFs. With respect to VF wall pressures, these studies have shown excellent correspondence with experimental measurements, even when including significant variation in VF geometry (Guo and