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Computational study of false vocal folds effects on unsteady airflows through static models of the human larynx

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ABSTRACT

Compressible large eddy simulation is employed to numerically investigate the laryngeal flow. Symmetric static models of the human larynx with a divergent glottis are considered, with the presence of false vocal folds (FVFs). The compressible study agrees well with that of the incompressible study. Due to the high enough Reynolds number, the flow is unsteady and develops asymmetric states downstream of the glottis. The glottal jet curvature decreases with the presence of FVFs or the ventricular folds. The gap between the FVFs stretches the flow structure and reduces the jet curvature. The presence of FVFs has a significant effect on the laryngeal flow resistance. The intra-glottal vortex structures are formed on the divergent wall of the glottis, immediately downstream of the separation point. The vortices are then convected downstream and characterized by a significant negative static pressure. The FVFs are a main factor in the generation of stronger vortices, and thus on the closure of the TVFs. The direct link between the FVFs geometry and the motion of the TVFs, and by extension to the voice production, is of interest for medical applications as well as future research works. The presence of the FVFs also changes the dominant frequencies in the velocity and pressure spectra.

1. Introduction

During human speech, the vocal folds are excited into self-sustained oscillations by the lung pressure that is applied to their inferior surfaces. The true vocal folds (TVFs) motion modulates the area between the vocal folds to an alternating convergent (during opening) and divergent (during closing) glottal duct. In computational models of normal phonation, it is usually assumed that the larynx is symmetric relative to the anterior-posterior mid-plane and the TVFs vibrate in a symmetric fashion. However, the intra-glottal flow structure can be asymmetric despite of geometrical symmetry (Scherer et al., 2001, 2002; Shinwari et al., 2003; Mihaescu et al., 2007). At low flow rates, the glottal flow is laminar and can be attached or skewed to one of the folds due to the Coanda effect (Cherdron et al., 1978; Tsui and Wang, 1995). This phenomenon is typically observed for steady flow conditions (Pelorson et al., 1994; Hofmans et al., 2003; Scherer et al., 2001; Shinwari et al., 2003; Kucinschi et al., 2006). Also, asymmetric flows can naturally occur during phonation due to asymmetries in the vocal fold geometry.

The impact of the FVFs, or the ventricular folds, on the trans-glottal flow has also been studied (Scherer et al., 1983; Ikeda et al., 2001). The FVFs redirect skewed flow from the glottis and cause enhancement of low pressure in the glottis (Miller et al., 1988; Pelorson et al., 1994; Mihaescu et al., 2013). The FVFs also influence the vortical structures and pressure in the larynx. Miller et al. (1988) observed significant pressure recovery and jet reattachment with the presence of FVFs. An experimental study in a rigid laryngeal model suggested that FVFs straighten the glottal jet flow and reinforce its quasi-two-dimensionality (Chisari et al., 2011). The visualization results obtained in a 3:1 up-scaled dynamic glottis model in a water circuit showed that pressure loss is decreased when a second constriction is added downstream the glottis and the glottal jet is stabilized in the divergent phase of the cycle (Triep and Brücker, 2010). Bailly et al. (2008) concluded that asymmetrical seem quite limited under unsteady flow conditions created by a dynamical vocal fold replica. McGowan and Howe (2010) found that the rigid ventricle folds have negligible effect on the voice source when the vocal fold movement is specified by a simple mathematical model. The reason might be that the flow unsteadiness caused by the wall

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movement appears to be only significant in the case of the straight uniform vocal fold replica (Deverge et al., 2003). Numerical studies showed that the glottal jet can impinge on the FVFs, leading to a high-frequency dipole sound source (e.g. Zhang et al., 2002). Using a rigid replica combining TVFs and FVFs, Agarwal (2004) linked the trans-laryngeal airflow resistance to the laryngeal geometry. However, Kucinschi et al. (2006) found that the pressure drop in the models with FVFs is very similar to those without FVFs at the same volumetric flow rate. Iijima et al. (1992) found that the effect of the FVFs was less significant for a convergent glottal shape than for a divergent or uniform shape.

With the development in computer technology and numerical methods, Computational Fluid Dynamics (CFD) has been used in a large range of applications. Unsteady CFD tools have investigated two-dimensional, axisymmetric, and three-dimensional glottal configurations with and without vocal fold motion (Zhao et al., 2002; Zhang et al., 2002; Hofmans et al., 2003; Alipour and Scherer, 2004; Suh and Frankel, 2007; Mihaescu et al., 2010). Only a few studies have been discussed on the effects of the FVFs. Farahani et al. (2013) investigated the incompressible laryngeal flow for a geometry including FVFs, but did not account for the divergent phase in the cycle of the TVFs. Also, other studies have considered the reconstruction of subject-specific geometries using computed tomography data such as the work by (Bakhshaee et al., 2013). Xue et al. (2014) analyzed the phonation cycle using flow structure interaction (FSI) and an incompressible solver for the Navier–Stokes equations. Nevertheless, most of the research to date has tended to focus on parametric models, which remains a way to isolate and understand better the contribution from specific parts of the larynx to the human phonation.

The present study numerically explores the unsteady trans-glottal flow structure during the divergent phase of the TVFs motion. In order to investigate the FVFs effects, static laryngeal models with and without the presence of the FVFs just downstream the TVFs are considered. Time-averaged velocity and pressure, as well as their fluctuations, are utilized in the discussion. Spectral analyses of frequency are performed to find the flows dominant frequency mode. The FVFs effects on the flow resistance and on the developed instabilities are also discussed.

2. Methods

Unsteady large eddy simulation (LES) (Fluent Inc.®) is employed to investigate the incompressible and the compressible laryngeal airflows. This solver has been validated in the previous studies (Mylavarapu et al., 2009; Mihaescu et al., 2011). Nine three-dimensional static and diverging larynx models with and without FVFs are considered. Fig. 1 shows the schematic of the two-dimensional cross-section of the baseline (without FVFs) (a) and of the symmetric larynx model with FVFs (b) as well as its main dimensions. A three-dimensional view of the baseline model is also shown (c). The length of the sub-glottal region is 10 mm. The TVFs shape is characterized by a 20° divergent angle corresponding to the closing phase of the phonation cycle. The $x-y$ plane represents the axial plane, the $x-z$ plane represents the sagittal plane and the $y-z$ plane represents the coronal plane. The computational domain consists of a square cross-section of 15.24 mm × 15.24 mm in the axial plane, and 60 mm in the stream-wise direction (z). The length of the glottis is the same as that of the false folds and of the computational cross-section, 15.24 mm. The glottal width (D_g), which is the minimum distance between the TVFs, is 1.6 mm. The FVFs shape is characterized by a 40° divergent angle. Two ventricle sizes (h_v) are considered to investigate the influence of the cavity resonance on the flow structures, so the FVFs are placed downstream from the glottal exit at 6 mm and 2.67 mm. The geometry and sizes are similar to Kucinschi et al. (2006). Four sets of flow gap between the FVFs (D_{FVF}) are considered in this study: 3 mm, 4.5 mm, 6.23 mm and 8.58 mm. These values fall in the range studied by Agarwal (2004). The length of the supra-glottal region varies from case to case because the total stream-wise length of the computational domain is kept constant at 60 mm. The computational domain is discretized into approximately 1.5×10^6 unstructured hexahedral mesh volumes.

Second order finite volume schemes are employed to discretize the flow governing equations on the computational domain. The time integration is performed using an implicit second order discretization scheme. The semi-implicit method for pressure-linked equation (SIMPLE) algorithm is applied to solve the coupling between the pressure field and velocity field (Patankar and Spalding, 1972). The wall-adapting local eddy-viscosity (WALE) model is employed as the subgrid-scale model in this study (Nicoud and Ducros, 1999). The simulations are conducted under uniform inlet and outlet pressure boundary conditions. To follow the study performed by Mihaescu et al. (2013), the trans-glottal pressure is 687 Pa (7 cm H_2O), which corresponds to a normal conversation level. The Reynolds number based on the glottal width is around 3600 at the narrowest location of the glottis. The compressible flow solver is employed for a complete characterization of the flow field in the tract. No-slip boundary conditions for velocity are set at the solid boundaries of the computational domain. A converged solution based on a steady state RANS solution with standard $k-\epsilon$ turbulence model is used to initialize the LES simulations. The time step used in the study is $\Delta t = 2.0 \times 10^{-5}$ s. The mean flow quantities are statistically averaged over a period of 10,000 time-steps. Based on the time step and the total running time, the frequencies can be computed in the range of 5–50,000 Hz.

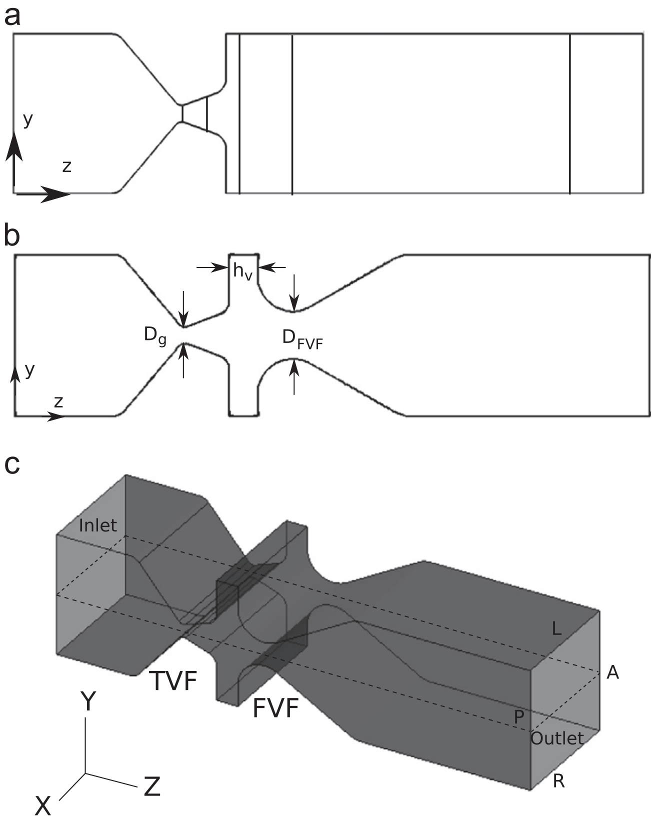

Fig. 1. Schematic of the cross-section of the larynx models. (a) Baseline geometry. (b) Model including FVFs. D_g: glottis width; h_v: ventricular height; D_{FVF}: gap between FVFs. (c) Three-dimensional larynx model.

3. Results

The general behavior of the flow in the baseline glottal configuration, without FVFs, is investigated. Then, the flow through different glottal configurations that include the FVFs is explored to establish a connection between the flow structures.

3.1. Baseline case: no FVFs

This study sets out to be a foundation to a broader range of investigations such as the acoustic effects of FVFs on the human phonation. The compressible flow solution includes acoustic information, since the unsteady compressible Navier–Stokes equations describe both the vortical field and the aerodynamically generated sound. Thus a compressible solver is preferred over an incompressible one. It is assumed that the Reynolds number is low enough to assume that incompressible and compressible solvers will show similar results, due to the low flow rates that occur in