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Interaction between a simplified soft palate and compressible viscous flow

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ABSTRACT

Fluid–structure interaction in a simplified 2D model of the upper airways is simulated to study flow-induced oscillation of the soft palate in the pharynx. The goal of our research has been a better understanding of the mechanisms of the Obstructive Sleep Apnea Syndrome and snoring by taking into account compressible viscous flow. The inspiratory airflow is described by the 2D compressible Navier–Stokes equations, and the soft palate is modeled as a flexible plate by the linearized Euler–Bernoulli thin beam theory. Fluid–structure interaction is handled by the arbitrary Lagrangian–Eulerian formulation. The fluid flow is computed by utilizing 4th order accurate summation by parts difference operators and the 4th order accurate classical Runge–Kutta method which lead to very accurate simulation results. The motion of the cantilevered plate is solved numerically by employing the Newmark time integration method. The numerical schemes for the structure are verified by comparing the computed frequencies of plate oscillation with the associated second mode eigenfrequency in vacuum. Vortex dynamics is assessed for the coupled fluid–structure system when both airways are open and when one airway is closed. The effect of mass ratio, rigidity and damping coefficient of the plate on the oscillatory behavior is investigated. An acoustic analysis is carried out to characterize the acoustic wave propagation induced by the plate oscillation. It is observed that the acoustic wave corresponding to the quarter wave mode along the length of the duct is the dominant frequency. However, the frequency of the plate oscillation is recognizable in the acoustic pressure when reducing the amplitude of the quarter wave mode.

1. Introduction

Fluid structure interaction (FSI) refers to a phenomenon where a flow field interacts with compliant or elastic structures. The behavior of many dynamic systems is influenced by the interaction between the fluid flow and structural components that are involved in the system. This interaction happens in a wide range of phenomena such as flapping of insect wings, the flutter of flags, the vibration of bridges and structures and the aeroelasticity of aircraft wings. With growing interest in the multidisciplinary field of biomedical and biomechanical engineering, a vast amount of research has been conducted to comprehend fluid–structure interaction in physiological systems in the human body (Tian et al., 2014; Wu and Cai, 2014; Larsson and Müller, 2012).

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One of the prime examples of FSI in biomechanical systems is the dynamics of the upper airways where the interaction between inspiratory and expiratory airflow with soft tissues may lead to flow-induced instabilities. Disorders of the upper airways are often associated with respiratory syndromes. Among these, obstructive sleep apnea (OSA) and snoring are closely related to the flow conditions in the upper airways. Obstructive sleep apnea syndrome (OSAS) is one of the most prevalent types of sleep-disordered breathing caused by repetitive collapse of the soft tissues in the upper airways. Estimates show that OSAS affects 2–4% of the adult population (Young et al., 1993). The significant consequence of OSAS is sleep fragmentation which can lead to increased daytime sleepiness, fatigue-related accidents and risk of cardiovascular diseases (Malhotra and White, 2002). Even though snoring does not necessarily mean that one has sleep apnea, estimates show that 10% of snorers are at risk of OSAS (Bertram, 2008).

In recent years, the fluid flow over a cantilevered plate has been a reliable theoretical model not only for many engineering applications but also for many biomechanical systems like human palatal snoring (Kuhl and DesJardin, 2012; Huang and Zhang, 2013). Computational models have been increasingly employed to model upper airways. In most of the investigations, inviscid flow has been assumed to develop numerical models for flow-induced instabilities (Guo and Païdoussis, 2000; Howell et al., 2009; Shoele and Mittal, 2016). A cantilevered beam immersed in a channel flow has been investigated by Auregan and Depollier (1995) both analytically and experimentally to understand snoring. They employed linear small deflection beam theory and neglected frictional losses. Quasi-parallel flow was assumed and the pressure on the beam was estimated by mass conservation and the Bernoulli equation. Huang (1995) modeled a cantilevered elastic plate immersed in an axial flow, and also conducted wind tunnel experiments to verify theoretical results for palatal snoring. The governing equation for linear plate bending was solved by using finite expansion of orthogonal in vacuum modes. Although the viscous effect of circulation was implicitly imposed by the Kutta–Joukowski condition at the free trailing edge of the plate, viscosity was neglected and potential flow theory was used. He found that fluid loading resulting from the interaction of the wake vortices is responsible for the irreversible energy transfer in the flow-induced instability.

Linear instability of thin elastic plates with different leading and trailing edge conditions in 2D channel flow was investigated by Guo and Païdoussis (2000). Similar to the work done by Auregan and Depollier (1995), the 1D linear plate equation was solved by applying the Galerkin method where plate deflections were recast in the form of an expansion series of orthogonal beam functions. A Fourier transform technique was applied to solve the perturbation pressure from the potential flow equations. They found that single-mode and coupled-mode flutter are dominant modes for plates with a free trailing edge and free-free edge, respectively. However, the instability of plates with either clamped or pinned boundary condition at edges may occur through first-mode divergence exceeding other types of instability modes (Guo and Païdoussis, 2000).

Tang and Païdoussis (2007, 2008) performed computational investigations of non-linear large deflection of cantilever plates using the inextensibility condition surrounded by axial flow. The flow was assumed purely inviscid even if a separate viscous drag was coupled into the plate equation, and the imposed pressure difference on the plate was estimated using an unsteady lumped vortex model. Their analytical results show that if critical flutter velocity and frequency increase, the drag coefficient will increase. Furthermore, in experimental results they observed sudden flutter vibration at critical velocities. However, the onset of oscillation will be more unlikely, if the flow velocity is reduced from an initial plate flutter. They demonstrated the possibility of a hysteresis phenomenon by including an unsteady von Kármán vortex street in their simulation. Conducting more theoretical investigations on the effect of trailing edge wakes on plate instability, they concluded that longer plates together with higher critical frequencies cause higher ratios of plate vibration velocity to wake-induced flow velocity, and thus a smaller effect of wake-induced flow velocities on the plate.

In contrast to the studies mentioned above, Balint and Lucey (2005) and Tetlow and Lucey (2009) included viscous effects directly in their instability analysis by solving the Navier–Stokes equation in a 2D channel surrounding a cantilever plate. Whereas Balint and Lucey (2005) modeled the motion of a thin plate using linear plate theory under differential pressure, Tetlow and Lucey (2009) added a tension term defined as the skin friction force acting on both the upper and lower sides of the plate. In both studies, the finite element method was employed in order to solve the unsteady, laminar Navier–Stokes equations in a channel geometry with inlet boundaries above and below the flexible plate and to estimate fluid loads interfacing with the plate. Their fluid solver was explicitly coupled to the structural finite difference solver. Based on their numerical results, when both upper and lower inlets are open, a flutter-type instability is initiated at a critical Reynolds number, while if one of the inlets is closed, a divergence-type instability occurs at a critical velocity. Although Tetlow and Lucey (2009) imposed a constant pressure drop along the channel rather than assuming velocity-driven flow, flutter instabilities similar to those found by Balint and Lucey (2005) were observed.

In this paper, we use a compressible viscous flow model to simulate the flow-induced oscillation of the soft palate in the pharynx by a simplified 2D model (cf. Fig. 1). We couple the compressible flow in the pharynx to a cantilevered thin plate model of the soft palate in an arbitrary Lagrangian–Eulerian (ALE) formulation by using a two-way explicit coupling. A high order finite difference method based on summation by parts (SBP) (Strand, 1994; Svärd and Nordström, 2014) is used for the spatial discretization of the compressible Navier–Stokes equations. The classical fourth order explicit Runge–Kutta scheme is applied for time integration for the sake of accuracy and easy parallelization. The Newmark time integration method and central finite difference method are used to solve the linearized Euler–Bernoulli thin beam model. To achieve geometric flexibility with high order operators for this simplified model in the upper airways, the multi-block structured grid approach is employed. We investigate the effect of material properties on the oscillation behavior of the flexible plate. Using compressible fluid flow permits us to investigate the acoustic waves inside the channel and also the effect of flexible plate oscillation on sound generation.

The paper is organized as follows. In Section 2, the models for fluid flow, structure and their coupling by FSI are presented. In Section 3, first the verification of the structure scheme is performed. Next, the numerical simulation of the plate