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Snoring as Markers for Obstructive Sleep Apnea – A Computational Multiphysics Investigation

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Abstract

Obstructive Sleep Apnea (OSA) influence daytime sleepiness and is linked with hypertension and cardiac problems. Diagnosis of obstructive sleep apnea involving sleep tests are expensive, cumbersome and not practical for large scale diagnosis. Therefore, this article presents a computational investigation of snoring as potential markers for identifying patients with obstructive sleep apnea. To that end, a coupling between the fluid and structural physics of a cantilevered plate inside an obstructed channel flow is undertaken, to idealize soft palate instability within an obstructed oropharynx. Unlike previous approach, a pressure-specified inlet and velocity-specified outlet boundary conditions in the channel are applied to closer replicate actual conditions. A parametric study on the effect of channel obstruction to cantilever plate instability suggest onset and variability in onset of snoring as potential markers to detect obstructive sleep apnea. This may be exploited for development of mass diagnosis of obstructive sleep apnea in the general population.

Keywords: Obstructive sleep apnea, Fluid-structure interaction, Snoring, CFD, FEM

Introduction

Recurrence of complete or partial obstruction of the upper airway during sleep is associated with a condition called obstructive sleep apnea (OSA). This condition has the adverse affect of compromising sleep quality and reduction of oxygen saturation. Thus, leading to daytime sleepiness and has been linked to more serious disorders including hypertension and heart problems (Bertram, 2008).

Standard diagnosis of OSA through sleep tests are expensive, cumbersome and not practical for mass diagnosis in the general population. Therefore, this paper aims to explore a potential for cheaper and more practical detection of OSA by analyzing onset of soft palate snoring. Snoring is associated with flutter of the soft tissues in the upper airway (Huang et al., 1995). In order to investigate this soft palate flutter, following an approach by Balint and Lucey (2005), a simulation was undertaken where the upper airway was idealized as a 2-D channel and the soft palate was idealized as a cantilever plate. A multiphysics modeling was adopted by coupling the flow physics in the channel with the transient dynamic of the cantilever plate.

In this article, the governing fluid-structural physics and coupling approach are first presented in the following section. Next, simulation results for some obstructed cases are presented. Finally, the results are discussed in regards to difference in onset of snoring with severity of obstruction.

Computational Method

Fluid and Structural Equations

The fluid physics was modeled using standard laminar, incompressible, unsteady Navier-Stokes and continuity equations, described in the Arbitrary Lagrangian-Eulerian frame of reference:

$$\frac{\partial u_i}{\partial t} + \left(u_j - \hat{u}_j\right)\frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\nu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] \tag{1}$$

$$\frac{\partial\left(u_i - \hat{u}_i\right)}{\partial x_i} = 0 \tag{2}$$

where density and dynamic viscosity for air is respectively, ρ = 1.185 kg/m^3 and μ = 1.831 x 10^{-5} kg/ms, and $\hat{u}_j$ represents the mesh velocity in an Arbitrary Lagrangian-Eulerian framework.

In addition, the transient dynamic of the cantilever plate was modeled using Cauchy's equation:

$$\nabla.\sigma_{ij} + \boldsymbol{f} = \rho_s \frac{\partial^2 d_i}{\partial t^2} \tag{3}$$

where σ_{ij} is the stress tensor, d_i denote displacement of the cantilever plate and $\boldsymbol{f}$ represents the aerodynamics forces applied on the cantilever plate, as calculated from the fluid computations. Density and Young's modulus of the cantilever plate is set to ρ_s = 2272.2 kg/m^3 and E = 880 MPa respectively, giving a second mode frequency of 100 Hz (Balint and Lucey, 2005).

Coupling and Numerical Approach

Soft palate flutter was investigated by introducing an initial perturbation in the form of initial deformation, corresponding to the second mode shape of the cantilever plate. Onset of flutter was predicted by examining growth (indicating instability) or reduction (indicating stability) of this cantilever plate deformation. The interaction between fluid and structure was implemented by successively transferring the aerodynamic forces calculated in the channel flow computation to the structural computation and then transferring the cantilever deformation to redefine the fluid domain in the fluid computation (ANSYS, 2010).

Model and Boundary Conditions

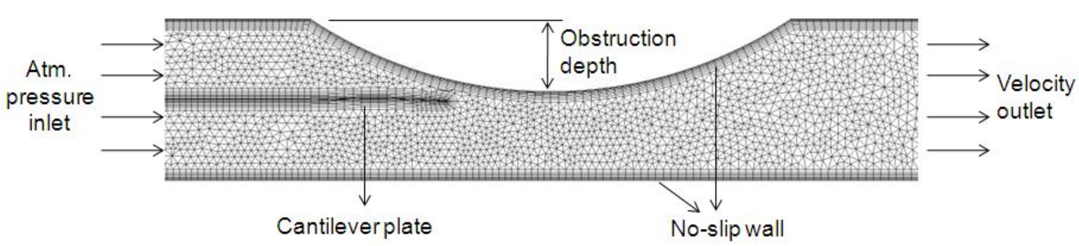
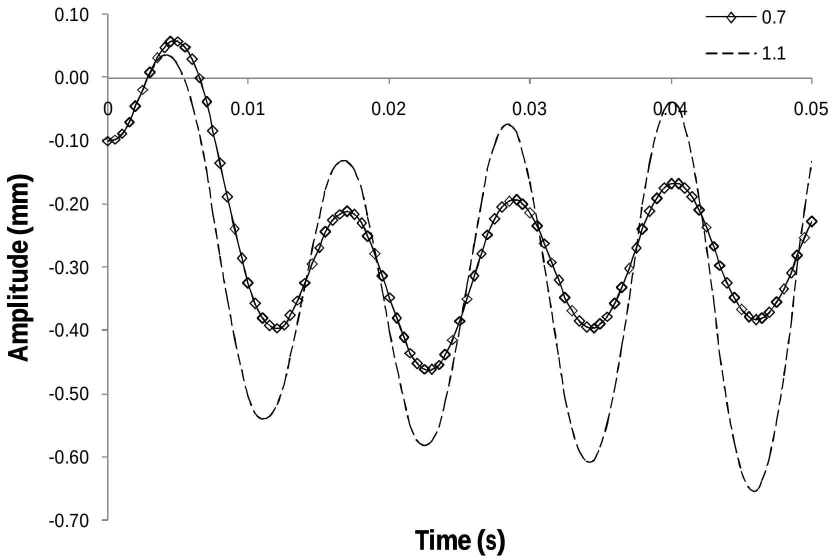


Figure 1. Close-up of channel model (with mesh) and boundary conditions.

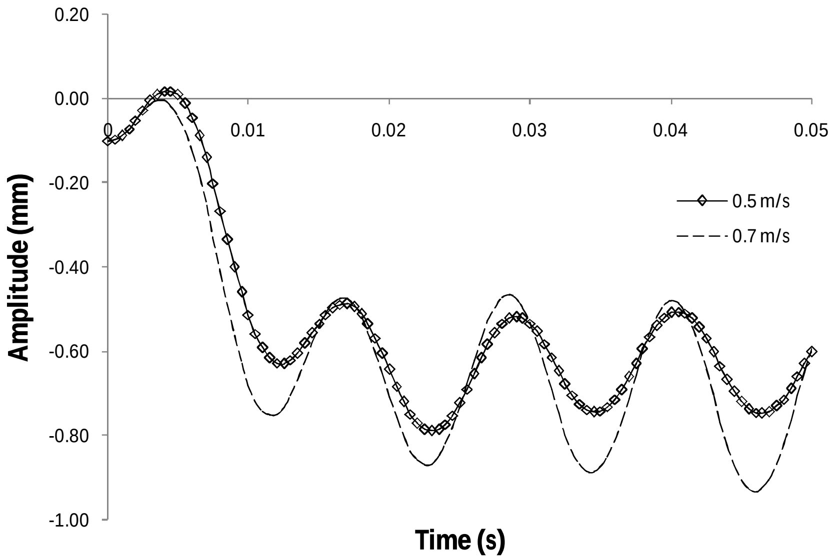
An obstruction was introduced in the 2-D channel to replicate partial obstruction of the upper airway. Two different obstruction depths (i.e. 2.0 mm and 4.5 mm) corresponding to respectively 20% and 45% obstruction of the channel, was simulated. The inlet of the channel was prescribed with atmospheric pressure, while the outlet of the channel was prescribed with velocities corresponding to typical inhalation flow rates. The remaining boundaries of the channel was set to no-slip walls. Fig. 1 shows geometry and boundary conditions of this model.

Results

In the following, several plots of cantilever tip deformation over time, corresponding to different outlet velocities, are presented for each obstruction case. Fig. 2a and 2b shows the tip deformation history for channel with obstruction of 2.0 mm and 4.5 mm depth, respectively.



(a)



(b)

Figure 2. Tip oscillation history for cantilever plate inside a channel with (a) 20% obstruction (b) 45% obstruction.

For case with 20% obstruction, Fig. 2a shows that for outlet velocity = 0.7 m/s, the cantilever tip deformation decays over time, suggesting stable oscillation of the cantilever plate. While for outlet velocity = 1.1 m/s, the cantilever tip deformation grows with time, indicating instability in the cantilever plate oscillation. Therefore, we may conclude that the critical velocity for onset of flutter in this case, falls between 0.7 and 1.1 m/s of the outlet velocity.

Similarly, for case with 45% channel obstruction, Fig. 2b shows that cantilever tip deformation decays and grows for outlet velocities of respectively, 0.5 m/s and 0.7 m/s. As a result, in this case, critical velocity for onset of flutter is between 0.5 and 0.7 m/s of the outlet velocity.

Discussion

Table 1 summarizes all our simulation results for each of the 20% and 45% channel obstruction cases.

Table 1: Simulation results for each case
(‘x’ **indicates instability, ‘✓’ indicates stability and** ‘o’ **indicates not performed)**

Outlet velocities (m/s)	20% obstruction	45% obstruction
0.5	o	✓
0.7	✓	x
0.9	o	o
1.1	x	o

The critical outlet velocity for onset of flutter is different for each obstruction case. A lower critical velocity is predicted for case with more severe channel obstruction. This indicates that onset of flutter occurs at lower flow rates in obstructed channels.

As inhalation flow rates cycle somewhat sinusoidally over time during sleep (see for example, (Fenn and Rahn, 1964)), lower critical velocity means that flutter occurs earlier in the inhalation cycle. This may suggest that for more obstructed airways, the onset for soft palate snoring occurs earlier during the inhalation. As a result, the time lapse before start of soft palate snoring, may indicate the severity of obstruction in the vicinity of the soft palate region in the upper airway. It is proposed that this measured time to onset of snoring, may be exploited to detect localized obstruction during apnea.

Furthermore, OSA patients may experience varying degrees of airway collapse or occlusion during sleep. With varying severity of obstruction, onset of snoring is also expected to vary from inhalation to inhalation. As a result, the time lapse between snoring episodes may also be highly variable in OSA patients, which is consistent with previous clinical studies (see for example, (Cavusoglu et al., 2008)).

Conclusions

In the present work, we investigated the onset of cantilever plate flutter in a partially obstructed channel. This was intended to idealize soft palate snoring in an obstructed upper airway, for a preliminary study on onset of snoring with respect to partial obstruction inside an upper airway. A multiphysics approach, coupling fluid and structural computations, suggest lowering of critical velocity for onset of flutter with respect to increasing degree of channel obstruction. This may be linked to varying onset of snoring with respect to severity of OSA in patients, which may be further exploited as non-invasive markers of OSA.

Currently, the critical velocity for onset of flutter was determined by graphically identifying upper and lower bounds of plate stability. An improved method to accurately estimate this critical velocity is recommended for future work. It is recognized that current 2-D model is a very crude representation of the upper airway. Investigations using anatomically-accurate upper airway models should be undertaken in the future. Finally, clinical experiments to evaluate and validate this approach as markers for OSA would also need to be performed.

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