Numerical method to simulate vibrational behaviour and resulting sound emission of biological systems

(extended abstract)

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ABSTRACT

Nowadays, in the process of developing technical systems the main focus is on lightweight design, noise reduction and smooth and efficient operation. Many biological systems are dealing with similar issues and already present powerful solutions. Understanding the mechanisms and functionality of biological systems enables us to transfer and apply them to technical systems.

The vibrational behaviour and the resulting sound emission of biological as well as technical systems depend on several aspects, such as the material of the components, the damping mechanisms, the type of dissipation, the kind of surrounding media and whether the media is static or moving as well as the interaction between fluid and structure. Therefore, we combine different numerical methods and use experimental data for validation. The fluid flow is considered in the frequency domain, enabling us to consider a realistic model. Additionally, the computation time is reduced significantly compared to time domain computations. Applying finite and infinite element method enables us to analyse the sound radiation in unbounded domains. Fluid and structure are coupled using the finite element method of fluid-structure interaction.

Preliminary computational results are discussed and implications for future directions of research are addressed.

Keywords: noise reduction, FSI, damping I-INCE Classification of Subjects Number(s): 26.1.2, 38.5.1, 61.1, 75.3

1. INTRODUCTION

Our project aims at simulating a biological system, which is well studied experimentally. We want to numerically investigate a human vocal tract, concerning the sound evolution, sound propagation and sound radiation. The vibrational behaviour and the resulting sound emission depend on the material of the vocal tract, the damping mechanisms, the type of dissipation, whether the air is static or moving and the interaction between fluid and solid. We will analyse the entire system, using the finite element method. To validate the numerical results, experimental data is used.

2. VOCAL TRACT

In the vocal tract, the source signal is tuned by a geometrical highly adaptable acoustical cavity between glottis and lip region. While the first two resonance frequencies are responsible for the uniqueness of the vowel, the higher harmonics are the basis for the timbre and the individuality of each voice. While the first two resonance frequencies are in the range of 80 Hz to 220 Hz, the higher harmonics reach up to 6 kHz (1). The viscous solid structure is completely covered with mucosa (2). In consequence, the vocal tract is a highly damped systems, which functions very efficiently. A three-dimensional model of a human vocal tract was developed by one of the authors, see (3), and is available for the numerical computations.

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3. NUMERICAL PRINCIPLES

Different numerical methods have to be combined to simulate the entire system. The fluid flow will be considered in the frequency domain. Solving the system in frequency domain requires significantly smaller models than time domain computations. Additionally the solution has only to be obtained once, and not in every time step. This saves a high amount of computation time.

Fluid flow in frequency domain computations can be considered using Galbrun equation. For the derivation of Galbrun equation it is assumed, that the fluid motion is caused by an ambient flow with time-independent parameters and a superimposed wave with small amplitude. After several computations the equation of momentum (1), the continuity equation (2) and the equation of state (3) are obtained, linearly dependent on the displacement $\mathbf{w}$, the pressure p_1 and the density ρ_1

$$\frac{d^2\mathbf{w}}{dt^2} - \mathbf{w}\cdot\nabla\frac{d\mathbf{v}_0}{dt} = -\frac{\nabla p_1}{\rho_0} + \frac{\rho_1\nabla p_0}{\rho_0^2} \tag{1}$$

$$\frac{d}{dt}\left(\nabla\cdot\mathbf{w} + \frac{\rho_1 + \mathbf{w}\cdot\nabla\rho_0}{\rho_0}\right) = 0 \tag{2}$$

$$p_1 + \mathbf{w}\cdot\nabla p_0 = c_0^2(\rho_1 + \mathbf{w}\cdot\nabla\rho_0). \tag{3}$$

Rearranging the equations and transforming into frequency domain by assuming a harmonic time dependency of $e^{-i\omega t}$ leads to the mixed, pressure and displacement based, Galbrun equation

$$-\rho_0\omega^2\mathbf{w} - 2i\omega\rho_0(\mathbf{v}_0\cdot\nabla)\mathbf{w} + \rho_0\mathbf{v}_0\cdot\nabla((\mathbf{v}_0\cdot\nabla)\mathbf{w}) + \nabla p_1 = \mathbf{0} \tag{4}$$

$$\rho_0 c_0^2(\nabla\cdot\mathbf{w}) + p_1 = 0. \tag{5}$$

This derivation can also be found in (4). The sound radiation is considered using infinite elements (5) and the interaction between fluid and structure is taken into account applying the finite element method of fluid-structure interaction.

4. CONCLUSIONS

The authors present preliminary investigations to simulate the vibrational behavior and resulting sound emission of a vocal tract under consideration of the fluid flow, the fluid-structure interaction, the damping mechanisms and the sound radiation in the unbounded domain.

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