3D FINITE ELEMENT MODEL OF THE HUMAN THORAX TO STUDY ITS LOW FREQUENCY RESONANCE EXCITED BY AN ACOUSTIC HARMONIC EXCITATION ONTO THE CHEST WALL

Arife Uzundurukan*[1,2], **Philippe Micheau**†[1,2], **Sébastien Poncet**‡[1], **Pierre Grandjean**§[1,2], **and Daria Camilla Boffito**¶[3]
[1]Department of Mechanical Engineering, Université de Sherbrooke, Sherbrooke, Québec, Canada
[2]Centre de Recherche Acoustique-Signal-Humain de l'Université de Sherbrooke, Sherbrooke, Québec, Canada
[3]Department of Chemical Engineering, Polytechnique Montréal, Montréal, Québec, Canada

1 Introduction

Chest physiotherapy (CPT), the standard current treatment method, is known as effective for bronchial drainage. By development of the technology, CPT shows a tendency to be independent of physiotherapists in order to provide patient accessibility of the treatment, whenever and wherever they need an airway clearance therapy (ACT) at low cost [1]. A realistic mechanical and numerical models, which is created by a real Computerized Tomography (CT), could be used to enhance our understanding of relevant sound transmission phenomena in the examination of respiratory disease and render the study possible to go further.

The acoustic studies in the literature deal with thorax geometry generally focus on the lung parenchyma and by using the difference in the propagation of shear wave provides the detection of the vicinity of parenchyma [2]. The interest in the application of Biot theory for the determination of physical material properties of the lugs has been increased because of the restriction of validity of the medium effective theory.

Ong and Ghista [1] have investigated the average chest resonance frequency for healthy male and female volunteers as 26.7 Hz and 27.8 Hz, respectively, in the frequency range of 15-50 Hz. Resonance occurs when a system is able to store and easily transfer energy and tends to vibrate at a higher amplitude. For ACT devices used in CPT, vibrations effect on the viscoelastic, shear-thinning, and thixotropic properties of bronchial mucus, liquefying it to ease expectoration. The influence of the range of frequency and the viscoelasticity [3] and the thermophysical properties [4] of mucus have been determined previously. However, any studies have been conducted so far to examine 3D finite element model (FEM) of the human thorax, which renders it possible to see the effects on the inside of airways for living bodies, by an acoustic harmonic excitation in the low frequency range.

In this study, it is aimed to investigate the thorax response in the low frequency range, 20-60 Hz, by a realistic 3D FEM of the human thorax. The acoustic harmonic excitation is investigated by 28 mm radius cylindrical shape under 5 N, which equals to 160 dB_{SPL} onto the back chest surface wall.

2 Method

The dimensions of the geometries belong to a male were determined by using CT scans via 3D Slicer 4.10.2. After the simplification, repairment, and conversion to solid geometries, the finite element model (FEM) has been created. The created FEM model in front view, in back view, under .stl meshes and under real meshes in the back view are illustrated in Fig. 1a., Fig. 1b., Fig. 1c., and Fig. 1d., respectively.

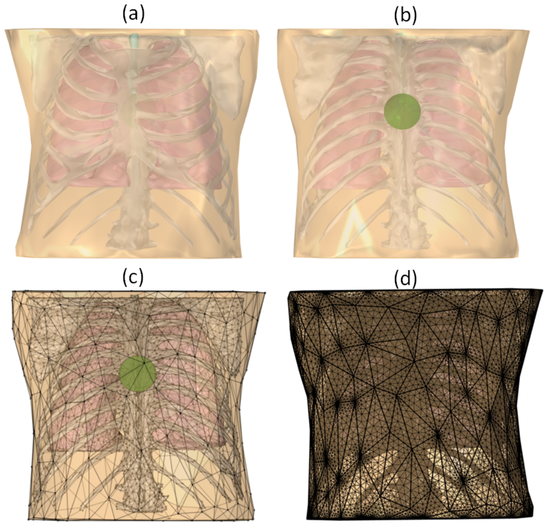

Figure 1: The modelled human thorax (a) in front view, (b) in back view, and in the back view (c) .stl meshes and (d) real meshes

The geometry shown in Fig. 1c. consists of 3x10^5 tetrahedral and 5.4x10^4 triangular meshes. The minimum and the maximum skewness quality of the geometry illustrated in Fig. 1d. are of 0.014 and 0.578, respectively. The result is taken within 2 h 32 min with the processor Intel(R) Core(TM) i7-9700 CPU @ 3.00 GHz with 16 GB RAM memory.

The physical properties of the airways was determined by ρ_a=1000 kg/m^3, E_{a1}=0.28 MPa, E_{a2}=0.124 $MPa.s$, ν_a=0.49998 [2]. For the soft tissue, which includes muscle, fat, and etc., and osseous region, which consists of rib cage, scapula, sternum, and etc., are considered as viscoelastic material. Therefore, Voight model is used. For the osseous region the material properties are taken as ρ_o=1500 kg/m^3, $\lambda_{1,o}$=2.6 GPa, $\lambda_{2,o}$=0 $GPa.s$, $\mu_{1,o}$=10x10^6 kPa, $\mu_{2,o}$=20 $Pa.s$ and for the soft tissue ρ_s=1000 kg/m^3, $\lambda_{1,s}$=2.6 GPa, $\lambda_{2,s}$=0 $GPa.s$, $\mu_{1,s}$=2.5 kPa, $\mu_{2,s}$=5 $Pa.s$ [5]. The physical properties of the lungs has been calculated by using Biot theory by using

---

*arife.uzundurukan@usherbrooke.ca
†philippe.micheau@usherbrooke.ca
‡sebastien.poncet@usherbrooke.ca
§pierre.grandjean@usherbrooke.ca
¶daria-camilla.boffito@polymtl.ca

following Eqn. 1 and in Eqn. 2.

$$\omega^2(-\rho+\beta\rho_f)u_i = \mu u_{i,jj} + (K_b+\mu/3)u_{j,ij} - (\alpha-\beta)p_i + F_i \tag{1}$$

$$\beta p_{ii} + (\phi^2/R)\rho_f\omega^2 p + \rho_f j\omega a = -\rho_f\omega^2(\alpha-\beta)u_{i,i} \tag{2}$$

where u is the steady-state dynamic oscillatory displacement, p represents the dynamic pressure of the air in the lungs in the frequency domain, α, β and R are the coupling parameters between the lung parenchyma and air, F_i shows the external inputs of force, ω is the angular velocity, and a is the rate of introduction of gas volume. When external excitation is negligible, Eqn. 1 forms as Eqn. 3, illustrates the shear behaviour.

$$\mu u_{i,jj} = -(\rho-\beta\rho_f)\omega^2 u_i \tag{3}$$

where

$$c_s = \sqrt{\mu/(\rho-\beta\rho_f)} \equiv \sqrt{\mu/\rho} \tag{4}$$

$$k_s = c_s/\omega \tag{5}$$

In here, c_s and k_s represent the shear wave and shear wave number, respectively. As for the compression waves, they are calculated from the slow compression wave numbers k_{ps} and fast compression wave numbers k_{pf} by using Eqn. 1 and Eqn. 2, where c_{pf} and c_{ps} are the fast and slow compression wave speeds. The density of the lungs is derived by Eqn. 8.

$$c_{pf} = \omega/k_{pf} \tag{6}$$

$$c_{ps} = \omega/k_{ps} \tag{7}$$

$$\rho = \phi\rho_p + (1-\phi)\rho_t \tag{8}$$

where lung tissue density is ρ_t=1000 kg/cm^3, air density in the lung ρ_p=1.21 kg/cm^3 and the air volume fraction of a healthy lung is ϕ=0.75. Therefore, the lung physical properties are calculated as ρ_l=250.9 kg/m^3, c_{sl1}=26.04 m/s, c_{sl2}=2.44 m/s, c_{pl1}=4.45 m/s, c_{pl2}=0.61 m/s.

3 Results

As a result of this study, 3D FEM of the human thorax is created and the acoustic harmonic excitation is investigated by 28 mm radius cylindrical shape under 160 dB_{SPL} onto the back chest surface as shown in Fig. 1b. The acceleration amplitude data is read from against the front of the chest wall surface as illustrated in Fig. 1a. under the frequency range of 20-60 Hz. As illustrated in Fig. 2, the acceleration amplitude, which reaches the peak point as 0.6332 m/s^2 at 28 Hz, is 0.4785 m/s^2 and 0.2021 m/s^2 at the lowest and highest frequencies in this frequency range.

4 Discussion

28 Hz is investigated as the resonance frequency with the inertance of 0.1266 $m/s^2.N$ in the frequency range of 20-60 Hz as shown in Fig. 2b. Even both of the resonance frequency and the inertance value depend on the chest size, gender, and body-mass index, the numerical results consistent with the reported average CPT experimental data with 23 volunteers in the literature [1].

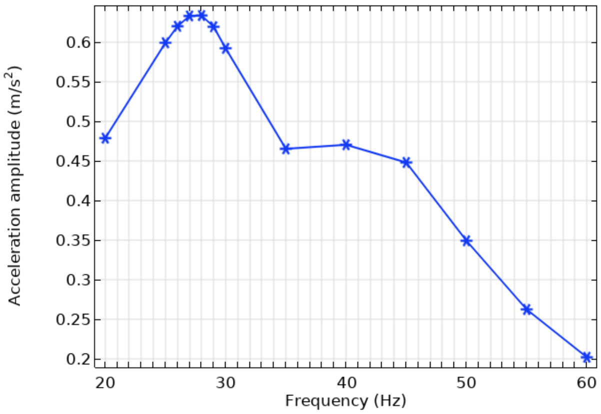

Figure 2: Acceleration amplitude in the low frequency

At 28 Hz, therefore, the thorax is able to store and easily transfer the energy and tends to vibrate at a higher amplitude. However, to determine the best CPT frequency, the viscoelastic, shear-thinning, and thixotropic properties of mucus has to be also investigated in this frequency range. Because even the maximum vibration occurs on the chest surface at 28 Hz frequency, it can differ for airways.

5 Conclusions

In the present study, the numerical results present the vibratory harmonic responses under the frequency range of 20-60 Hz onto the back surface of the thorax. The chest-resonance frequency under the excitation is obtained as close to 28 Hz. Despite the detailed complex human thorax geometry, the results are consistent with reported experimental CPT data in the literature. As a future study, a set of multidisciplinary experimental study for the viscoelastic, shear-thinning, and thixotropic properties of mucus will be conducted to go further in this acoustic study.

References

[1] J.H. Ong and D.N. Ghista. Applied chest-wall vibration therapy for patients with obstructive lung disease. *Human Respiration: Anatomy and Physiology, Mathematical Modeling, Numerical Simulation and Applications*, 3:157, 2006.

[2] Z. Dai, Y. Peng, B.M. Henry, H.A. Mansy, R.H. Sandler, and T.J. Royston. A comprehensive computational model of sound transmission through the porcine lung. *The Journal of the Acoustical Society of America*, 136(3):1419–1429, 2014.

[3] D. Schieppati, R. Germon, F. Galli, M.G. Rigamonti, M. Stucchi, and D.C. Boffito. Influence of frequency and amplitude on the mucus viscoelasticity of the novel mechano-acoustic Frequencer. *Respiratory Medicine*, 153:52–59, 2019.

[4] O. Lafforgue, N. Bouguerra, S. Poncet, I. Seyssiecq, J. Favier, and S. Elkoun. Thermo-physical properties of synthetic mucus for the study of airway clearance. *Journal of Biomedical Materials Research Part A*, 105(11):3025–3033, 2017.

[5] H.E. Von Gierke, H.L. Oestreicher, E.K. Franke, H.O. Parrack, and W.W. von Wittern. Physics of vibrations in living tissues. *Journal of Applied Physiology*, 4(12):886–900, 1952.