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MODAL ANALYSIS OF CRANIUM VIA EXPERIMENTAL AND NUMERICAL APPROACHES

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Abstract: *This paper presents a comprehensive study on the modal analysis of the cranium (also the Latin term for the human skull) using both experimental and numerical approaches. The primary objective is to determine the natural frequencies and modal shapes of the cranium, which characterize its dynamic behavior under various conditions. Understanding these properties is essential in fields such as biomechanics and forensic science, as well as medical applications, including surgical planning and trauma analysis. The study details the methodology for conducting experimental measurements and numerical simulations, highlighting the techniques used to capture the cranium's vibrational characteristics. Additionally, the paper discusses the equipment and software employed in the analysis, ensuring accuracy and reliability in the obtained results. By combining experimental data with computational models, this research contributes to a deeper understanding of the biomechanical properties of the human cranium.*

Keywords: Biomechanics, Cranium, Experiment, Modal analysis, Numerical simulations

1. Introduction

In medical terminology, "cranium" specifically refers to the portion of the skull that encloses the brain, while the "skull" includes both the cranium and the facial bones. Traumatic brain injury (TBI) is a major health concern that can result from high-rate loading, such as impacts or blasts. due to the limitations of experimental approaches in replicating extreme loading conditions, computational methods are increasingly used to simulate and quantify the mechanical properties of the skull. These simulations help researchers analyze how the cranium responds to different forces, contributing to advancements in medical diagnostics, injury prevention, and protective equipment design; see (Eiba et al., 2024; Eslaminejad et al., 2020; Frydrýšek, 2019; Frydrýšek et al, 2023; McElhaney et al, 1970) and (Vlčková et al., 2022).

Experimental studies have shown that the human skull exhibits nonlinear mechanical behavior and is significantly strain rate dependent. This means that its response varies depending on the speed and magnitude of the applied force, making it essential to integrate both experimental and numerical approaches for accurate modeling. Modal analysis, which identifies natural frequencies and modal shapes, provides a framework for studying these biomechanical properties. In our measurements, we have identified 15 natural frequencies, with two dominant ones observed at 488 Hz and 874 Hz. These frequencies are critical in characterizing the cranium's vibrational response and can offer valuable insights for medical and engineering applications, such as improving surgical techniques and designing better protective headgear. For more information see (Eiba et al., 2024; Gao, 2007; Eslaminejad et al., 2020; Frydrýšek, 2011; 2019) and (McElhaney et al, 1970).

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2. Experimental modal analysis

Experimental modal analysis is a technique used to determine modal parameters, which provide a mathematical representation of a structure's dynamic behavior. The method we have used for our measurement is called MISO (multiple-input, single-output).in this case the accelerometer is fixed at reference point, and a roving hammer is used for excitation; see Figure 1. A triaxial accelerometer (B&K 4524B) receives the analog signals, and a transformer (B&K 3160-A-042) is used to digitize the signals. To perform the experiment, excitation points had to be defined. This was done by meshing the geometrically complex skull and creating a simplified regular grid of 151 nodes on its outer surface; see Figure 2 and Eiba et al. (2024).

Fig. 1:Impact hammer

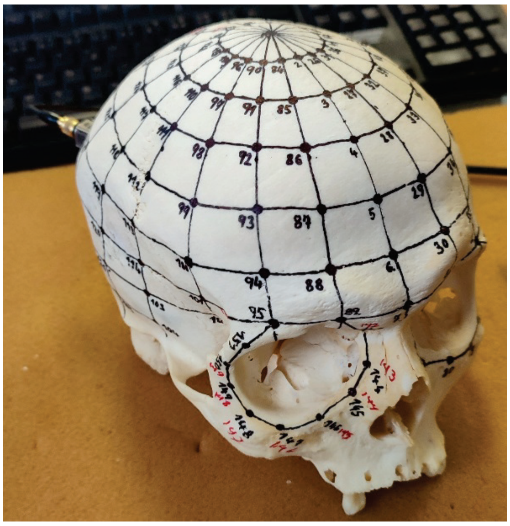

Fig. 2: Cranium mesh

Fig. 3: Coordinate measuring machine

To simulate the physics of the skull in the software (Bruel & Kjaer R2022, which we used), it was necessary to record the coordinates of nodes in space. In our case, a CMM (3D CMM LH 65 X3 measuring device (WENZEL, Germany) with a Renishaw PH10M rotated head and a SP25M-1 measuring probe) was used for this purpose. CMMs use a probing system to detect discrete points on the surfaces of objects; see Figure 3. The excitation was done three times for each point and the mean value is considered automatically by the software; see (Eiba et al., 2024).

Frequency response function graph as output of the experiment could be seen below; see Figure 4.

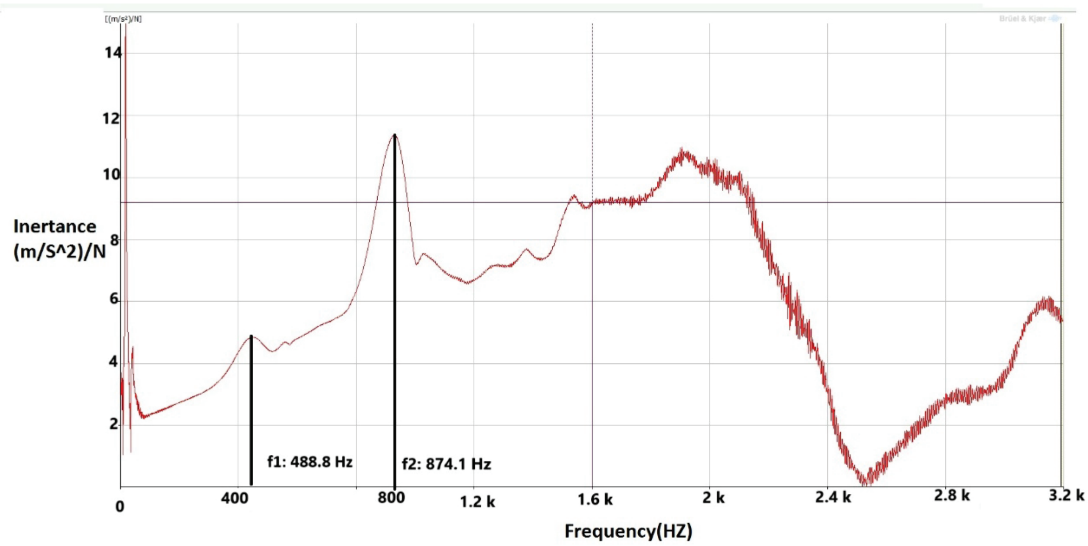

Fig. 4: Frequency response function

It could be seen that two main resonances occur at 488.8 HZ and 874.1 HZ. Modal shapes corresponding to these natural frequencies can be seen below; see Figure 5.

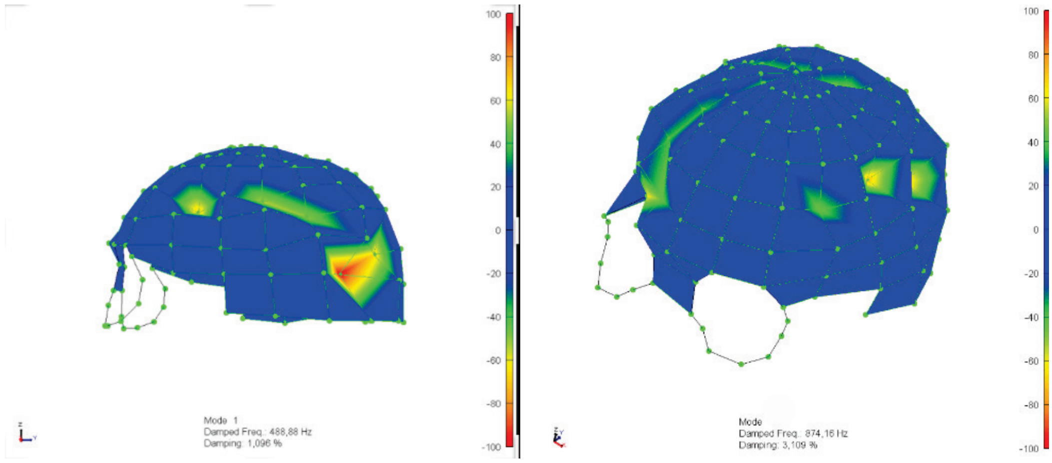

Fig. 5: Modal shapes at 488.8 Hz & 874.1Hz

3. Numerical modal analysis

Below formula can be used to solve the eigen value problem in mechanics or biomechanics.

$$\left(\boldsymbol{K} - \boldsymbol{\Omega_i}^2\boldsymbol{M}\right)\boldsymbol{\phi_i} = \mathbf{0} \tag{1}$$

where $\boldsymbol{K}$ represents stiffness matrix, $\boldsymbol{M}$ represents consistent mass matrix, $\boldsymbol{\Omega_i}$ eigen frequency corresponds to $\boldsymbol{\phi_i}$ eigen vector, the solver LS-DYNA R13, Share Memory Parallel (SMP) with double precision (Ansys, Canonsburg, United States of America) is used. Based on the complexity of the task, the solver uses BCSLIB-EXT 4.1 Library (Boeing Co., Arlington, United States of America) to search first two eigen frequencies and eigen vectors.

The stiffness and mass matrices were generated using the image processing software Materialize Mimics (Materialize NV, Leuven, Belgium), which created a finite element mesh from images acquired via a Computed Tomography (CT) scanner; see Figure 6.

Fig. 6: Finite element mesh

Young's modulus and density are considered based on the radio density. Poisson's ratio is the same for all regions with the value μ = 0.19 taken from the paper published by McElhaney et al.

The results obtained from this simulation and its comparison with experimental results can be seen in Tab 1.

Tab. 1: Numerical and experimental eigenfrequencies

	Numerical result	Experimental result	Variance from experiment
1st eigen frequency	688.3 Hz	488.8 Hz	40.8 %
2nd eigen frequency	734.3	874.1 Hz	-15.9 %

4. Conclusions

This study highlights the difficulty of accurately measuring the skull's properties because of its complex shape. Eigen frequency differences between experimental and numerical approaches are evident. To improve accuracy, more samples should be tested, and better tools, like a frequency exciter, could be used. The results can help develop computer models of the skull, but differences between experiments and calculations show that more work is needed. Despite these challenges, the findings could be useful in medicine, forensic science, and biomechanics, helping with implant design, injury assessment, and new treatment methods including experiments, numerical and probabilistic methods; see (Eiba et al., 2024; Frydrýšek, 2011; Frydrýšek et al., 2022; Hlinka et al, 2023) and (Vlčková et al., 2022).

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