CERN SUMMER STUDENT REPORT

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Abstract

This summer, I spent eight weeks as a student at the European Organization for Nuclear Research (CERN), which was an amazing experience in my academic and professional development. CERN, known for its groundbreaking contributions to particle physics and nurturing environment for scientific research, gave me an unparalleled opportunity to participate in advanced scientific work and contribute to one of its proposed projects, the SHiP (Search for Hidden Particles) experiment.

This report summarizes my experiences, challenges, and accomplishments while at CERN. It describes the processes involved in my primary work, which is to ***investigate the structural dynamics of the decay vessel for the SHiP experiment***. From the first phase of modeling the optimum design using CAD software to the subsequent modal analysis for extracting vibration characteristics and producing dispersion curves, this report provides a thorough overview of the work done and the insights acquired.

Contents

Chapter One: Introduction

Overview of CERN and the SHiP Experiment

The European Organization for Nuclear Research, or CERN, was founded in 1954 and is a leading particle physics research laboratory located on the Franco-Swiss border near Geneva. It has contributed to important discoveries such as weak neutral currents in the 1970s and, most notably, the Higgs boson in 2012, which was found using the Large Hadron Collider (LHC), the world's most powerful particle accelerator. CERN's early accelerators, such as the Proton Synchrotron (PS) and Super Proton Synchrotron (SPS), paved the way for these breakthroughs. Additionally, CERN transformed global communication with Tim Berners-Lee's conception of the World Wide Web in 1989.

CERN continues to advance scientific knowledge with projects like the SHIP experiment, probing hidden particles and dark matter, and plans to upgrade the LHC for even greater capabilities. It remains a beacon of international scientific cooperation and a leader in exploring the universe's fundamental mysteries.

The SHiP experiment is a proposed fixed target experiment connected to the SPS (Super Proton Synchrotron) accelerator to search for "hidden" particles that have been predicted by various scientific models. These particles could help explaining mysteries such as dark matter, neutrino oscillations and the imbalance of matter in the Universe. The aim of the experiment is to find long-lived, weakly interacting particles. The SPS’s high-intensity proton beam is used to search for these particles at different energy levels by using two different detection methods, either by observing their visible decays, or by detecting their scattering effects on electrons or nuclei.

Fig.1 shows SHiP detector layout. On the lower left side is the beam target surrounded by a hadron absorber. From this target, the collision at $\approx$ 400 GeV follows the white dashed line trajectory and goes through different systems before entering the decay volume. Somewhere in the latter, according to the theory, particles will decay (green and brown curves) before reaching the spectrometer and other detectors. All these phenomena need to happen in complete vacuum to avoid hitting other non-desired particles that would distort the experiment. The entire system detector measures approximately 130 m in length, where the decay vessel is 50 m long. It is this structure I am to study.

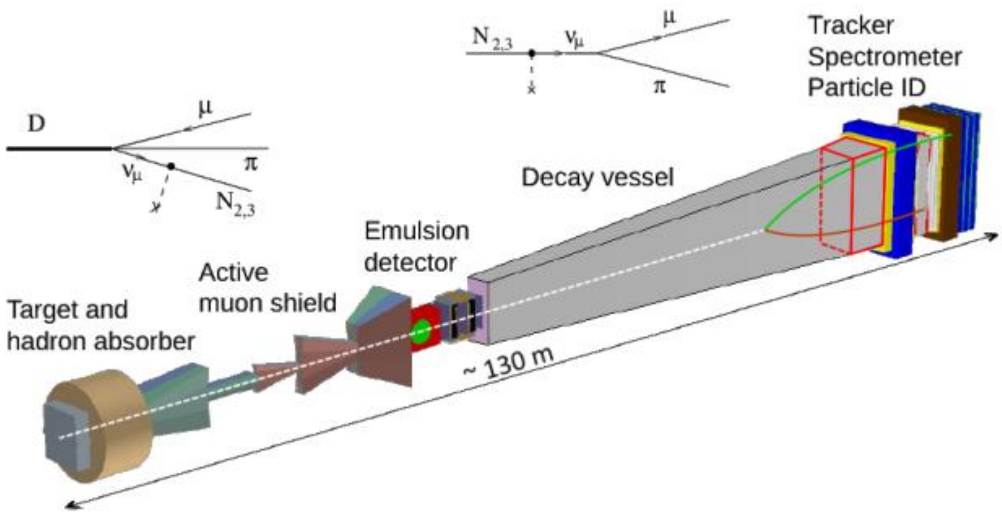


Figure 1: Concept of the SHiP Experiment

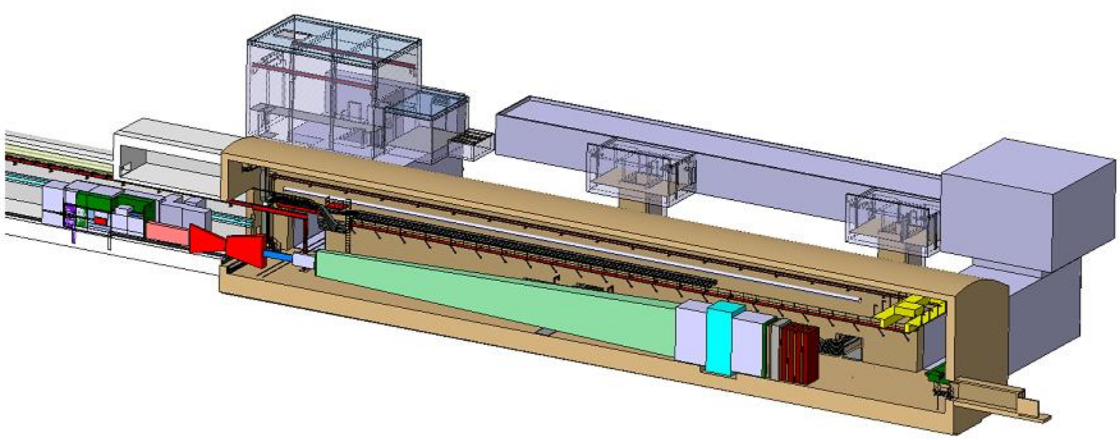


Figure 2: The SHiP Experiment

Objectives and Scope of my Summer Activities

The primary objective of my internship is to investigate the structural dynamics of the decay vessel, a task crucial for ensuring the vessel's stability and functionality during the experiment. This investigation involved several key tasks:

1. Modeling the Optimized Design: Using Ansys® SpaceClaim, I was tasked with creating a detailed 3D model of the decay vessel. This phase required a thorough understanding of the 2D configuration, material properties, and design constraints.

2. Modal Analysis: An approximate cross-section of the decay vessel was subjected to modal analysis to determine its vibration characteristics. This analysis aimed to identify the natural frequencies and mode shapes, which are essential for understanding how the vessel will respond to various operational conditions.

3. Dispersion Curves: Plotting the vibration characteristics obtained from the modal analysis were used to plot dispersion curves. These curves are vital for predicting how vibrations propagate through the structure, thereby informing the design adjustments needed to mitigate potential issues.

Significance of the Project

The structural integrity of the decay vessel is critical to the success of the SHiP experiment. Any undetected weaknesses or resonant frequencies could compromise the vessel's performance, leading to inaccurate results or even failure during high-energy particle interactions. By rigorously analyzing the vessel's dynamics, this project contributes to the overall reliability and precision of the SHiP experiment.

Chapter Two: Details of My Summer Activities

Overview of the Decay Vessel

The decay vessel is a hollow squared base pyramid where the decays occur during the experiment operations. To provide a highly accurate result in the detectors, the vessel is evacuated to eliminate the background from neutrinos interaction. As neutrinos and muons are very small elementary and interacting particles, they induce signal acquisition in the spectrometers. To prevent this interaction, the decay vessel is surrounded by a 30 to 40 cm thick liquid scintillator that emits light when interacting with unwanted particles. This technique, allows the physicists to know when a signal is produced by a searched decay, or only by surrounding unwanted particles.

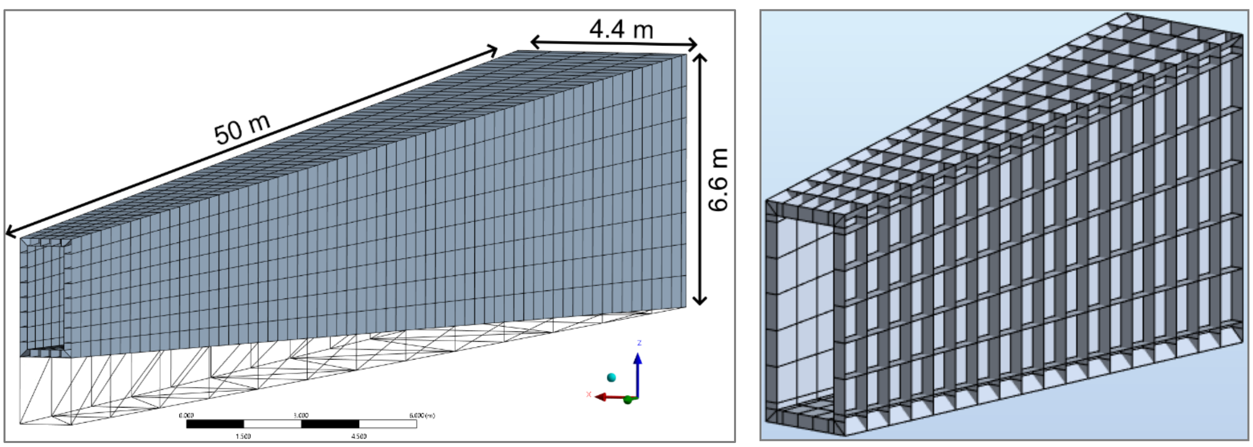


Figure 3: Previous model of the Decay Vessel

3D Modelling

My first task was to model the optimized design of the decay vessel from the given 2D configuration shown in figure 4. For this task, I chose to use Ansys® SpaceClaim due to its flexibility in making modifications and its compatibility with Ansys® Mechanical for subsequent modal analysis. The optimized design reduces the number of horizontal and vertical stiffening members compared to the previous model (Fig. 3), enhancing structural efficiency while minimizing material use. A key improvement was the introduction of a detachable aluminum liquid scintillator container, replacing the static one from the previous concept proposal. This change facilitates easier maintenance, cleaning, and replacement or upgrading of the scintillator material, providing enhanced flexibility for experimental setups and modifications. Additionally, the optimized design incorporated a new support type, the HE-A profile, which offers improved load-bearing capacity, enhanced stability, and better distribution of internal stress and forces throughout the structure.

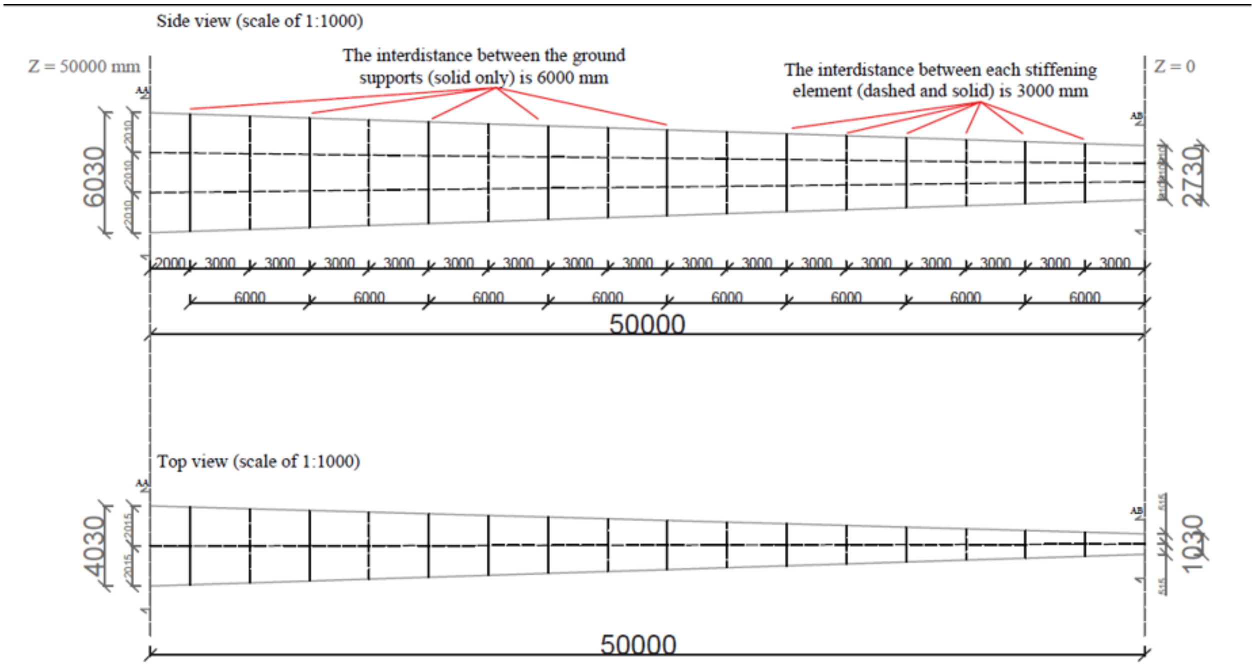


Figure 4: 2D Configuration of the Optimized Decay Vessel

In Ansys® SpaceClaim, I integrated these design improvements, ensuring that each modification aligned with the given specifications and goal of enhancing structural efficiency. The result is a significantly improved decay vessel design that achieves better structural efficiency and flexibility.

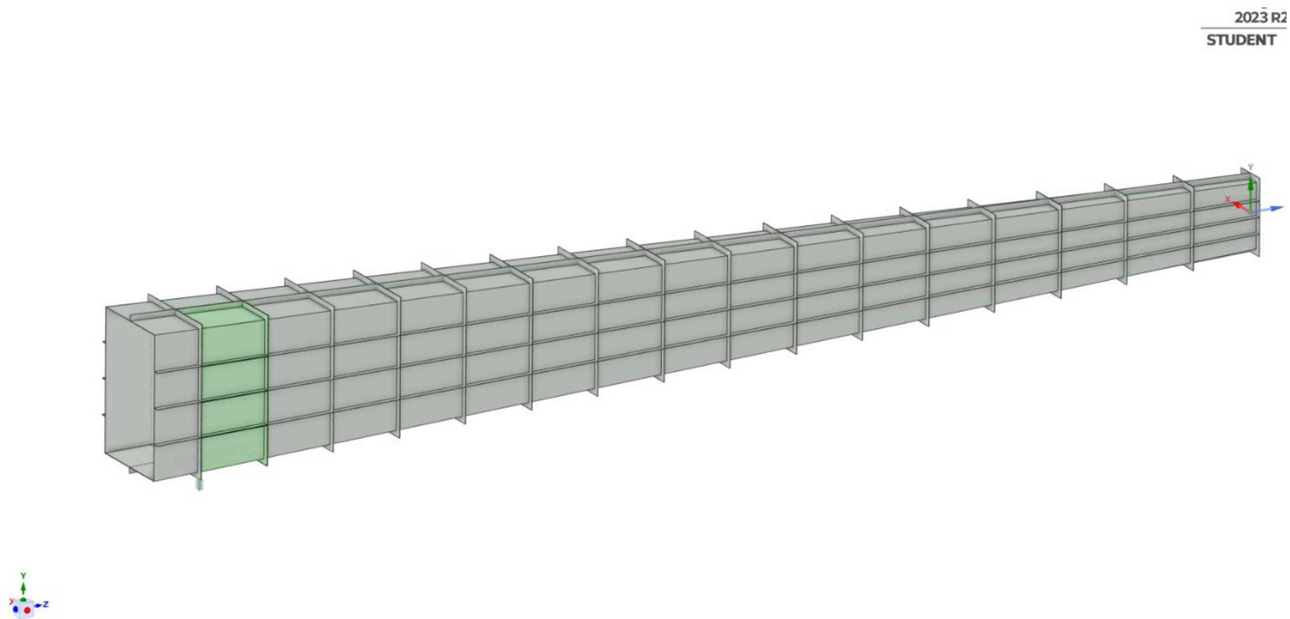


Figure 5: 3D Model of the Decay Vessel without Support

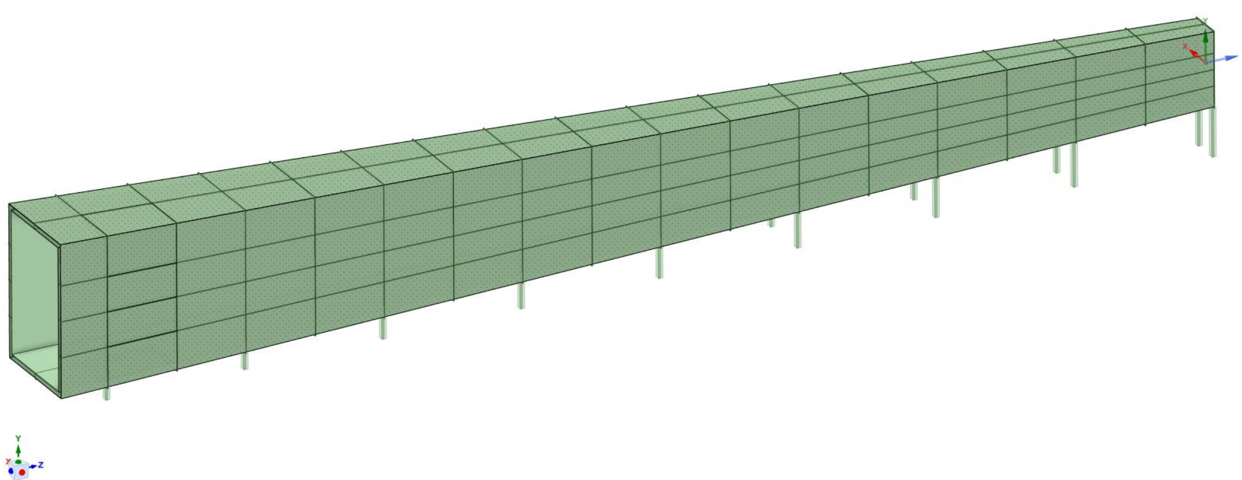


Figure 6: 3D Model of the Decay Vessel with Support

Modal Analysis & Dispersion Curve

The project's final goal is to create dispersion curves for the decay vessel, which can be accomplished using a variety of methods, including time-domain and frequency-domain approaches. This study used the frequency-domain method (modal analysis). This entailed modeling the decay vessel's geometry and material properties, setting appropriate boundary conditions, and conducting a modal analysis to establish its natural frequencies and related mode shapes. The eigenfrequencies and wave lengths were derived from the modal analysis results, enabling for the creation of dispersion curves by graphing the natural frequencies against the wave numbers. These curves provide important insights into the wave propagation characteristics of the decay vessel, which is necessary for understanding its dynamic behavior.

Finite Element Formulation for Modal Analysis

The starting point for modal analysis is the equation of motion for a linear, time-invariant system, which can be represented as:

$$\boldsymbol{M}\ddot{\boldsymbol{u}}(t) + \boldsymbol{C}\dot{\boldsymbol{u}}(t) + \boldsymbol{K}\boldsymbol{u}(t) = \boldsymbol{F}(t) \qquad (1)$$

where $\boldsymbol{M}$ is the structural mass matrix, symmetric and positive definite, $\boldsymbol{C}$ is the structural viscous damping matrix, $\boldsymbol{K}$ is the structural stiffness matrix, symmetric and positive or semipositive definite, $\boldsymbol{F}(t)$ is the vector of applied load time histories, and $\boldsymbol{u}$, $\dot{\boldsymbol{u}}$, $\ddot{\boldsymbol{u}}$, are the displacement vector and its time derivatives, respectively.[1]

To simplify the mathematical model a linear elastic solid is considered and no damping is added, i.e. C = 0 in Equation ***(1).*** The elemental matrix then becomes

$$\left(\begin{bmatrix} \boldsymbol{K}_{11} & \boldsymbol{K}_{1i} & \boldsymbol{K}_{12} \\ \boldsymbol{K}_{1i}^{T} & \boldsymbol{K}_{ii} & \boldsymbol{K}_{i2} \\ \boldsymbol{K}_{12}^{T} & \boldsymbol{K}_{i2}^{T} & \boldsymbol{K}_{22} \end{bmatrix} - \omega^2 \begin{bmatrix} \boldsymbol{M}_{11} & \boldsymbol{M}_{1i} & \boldsymbol{M}_{12} \\ \boldsymbol{M}_{1i}^{T} & \boldsymbol{M}_{ii} & \boldsymbol{M}_{i2} \\ \boldsymbol{M}_{12}^{T} & \boldsymbol{M}_{i2}^{T} & \boldsymbol{M}_{22} \end{bmatrix}\right) \begin{Bmatrix} \boldsymbol{U}_1 \\ \boldsymbol{U}_i \\ \boldsymbol{U}_2 \end{Bmatrix} = \begin{Bmatrix} \boldsymbol{F}_1 \\ \boldsymbol{F}_i \\ \boldsymbol{F}_2 \end{Bmatrix}, \qquad (2)$$

When a free wave propagates through an infinite structure, $\boldsymbol{F}_i$. The nodal forces at the end nodes of the cell, $\boldsymbol{F}_1$ and $\boldsymbol{F}_2$, are not zero, since these forces are responsible for transmitting the wave motion from one cell to the next. Thus, according to [1] the problem will incorporate a coupling relationship between left and right displacements. The elemental matrix then becomes:

$$\begin{bmatrix} \boldsymbol{K}_{11} + 2\boldsymbol{K}_{12} + \boldsymbol{K}_{22} & \boldsymbol{K}_{1i} + \boldsymbol{K}_{i2} \\ \boldsymbol{K}_{1i} + \boldsymbol{K}_{i2} & \boldsymbol{K}_{ii} \end{bmatrix} \begin{Bmatrix} \boldsymbol{U}_1 \\ \boldsymbol{U}_i \end{Bmatrix} = \omega^2 \begin{bmatrix} \boldsymbol{M}_{11} + 2\boldsymbol{M}_{12} + \boldsymbol{M}_{22} & \boldsymbol{M}_{1i} + \boldsymbol{M}_{i2} \\ \boldsymbol{M}_{1i} + \boldsymbol{M}_{i2} & \boldsymbol{M}_{ii} \end{bmatrix} \begin{Bmatrix} \boldsymbol{U}_1 \\ \boldsymbol{U}_i \end{Bmatrix}. \quad (3)$$

Test Case

My first task for the modal analysis was to replicate a sample analysis described in [1] using Ansys® to validate the analysis approach before proceeding to the decay vessel's approximate case. The referenced analysis was performed using Finite Element Analysis (FEA) codes as detailed in [1]. This validation task involved conducting a modal analysis on an isotropic plate with dimensions 60 mm in length, 4 mm in breadth, and 4 mm in thickness, following the methodologies and mathematical formulations specified in the reference.

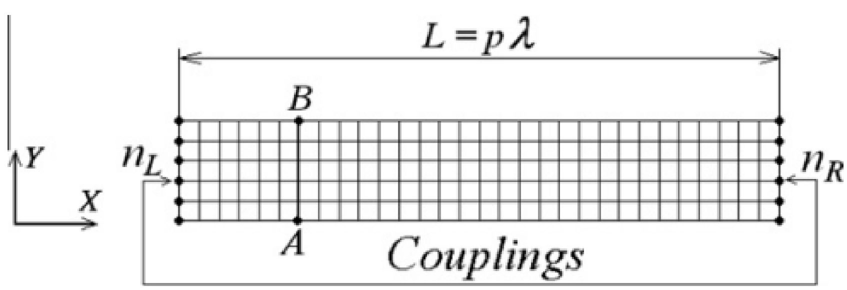


Figure 7: Isotropic plate example from [1]

In this process, I used Ansys® Mechanical – Modal analysis to obtain mode shapes similar to those presented in [1]. These mode shapes were then categorized based on symmetry and anti-symmetry. Following this categorization, I plotted dispersion curves derived from the data obtained during the modal analysis. This step was crucial to ensure the accuracy and reliability of the analysis methodology before applying it to the more complex case of the decay vessel.

Approach used in Ansys® Mechanical

1. Modeling the Structure

- Geometry: Defining the geometry specified in [1] using Ansys® SpaceClaim.

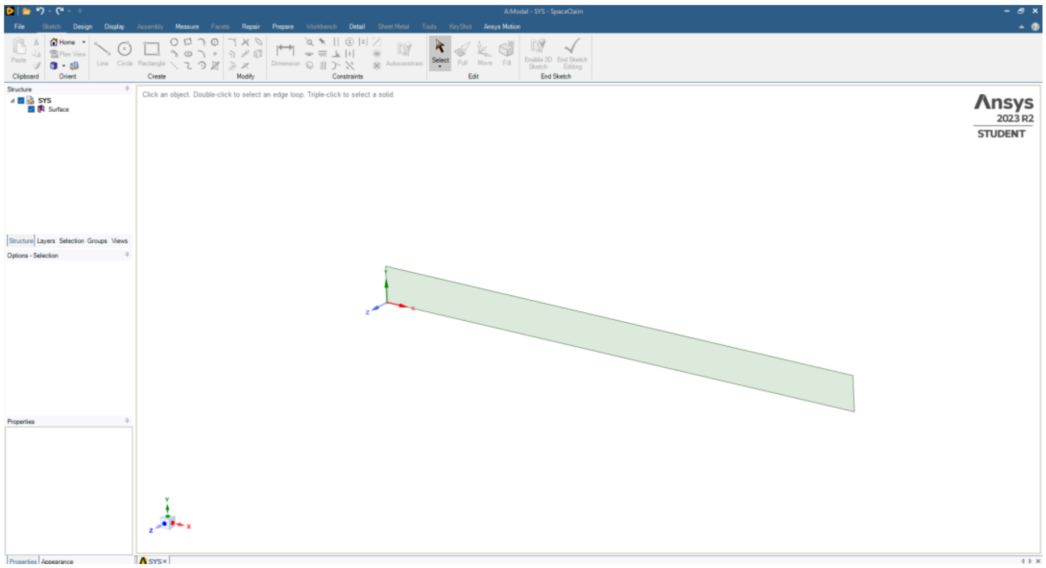
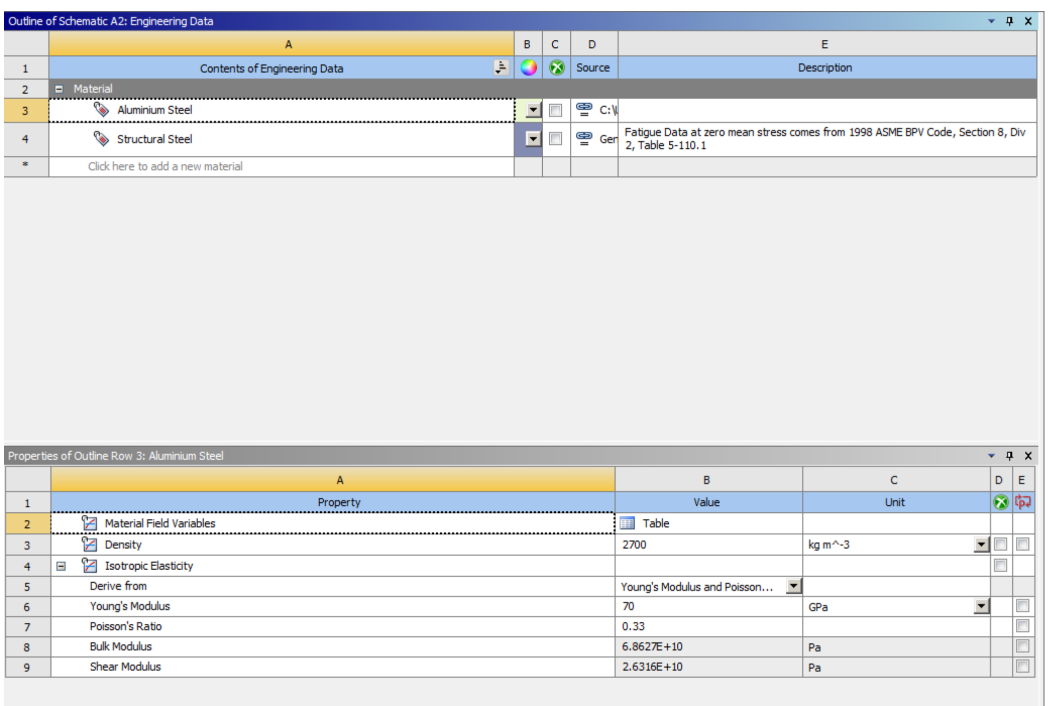


Figure 8: Geometry creation in Ansys® SpaceClaim

- Material Properties: Input material properties such as density, Young's modulus, and Poisson's ratio as specified in [1].



Outline of Schematic A2: Engineering Data

	A	B	C	D	E
1	Contents of Engineering Data			Source	Description
2	Material				
3	Aluminium Steel			C:\	
4	Structural Steel			Ger	Fatigue Data at zero mean stress comes from 1998 ASME BPV Code, Section 8, Div 2, Table 5-110.1
*	Click here to add a new material				

Properties of Outline Row 3: Aluminium Steel

	A	B	C	D	E
1	Property	Value	Unit		
2	Material Field Variables	Table			
3	Density	2700	kg m^-3		
4	Isotropic Elasticity				
5	Derive from	Young's Modulus and Poisson...			
6	Young's Modulus	70	GPa		
7	Poisson's Ratio	0.33			
8	Bulk Modulus	6.8627E+10	Pa		
9	Shear Modulus	2.6316E+10	Pa		

Figure 9: Material property assignment in Ansys® Workbench

2. Finite Element Analysis (FEA)

- Mesh Generation: A mesh for the structure was generated as specified in [1], Quad shell elements with four nodes and size 0.2 mm was used, ensuring it is fine enough to capture the necessary details of wave propagation.

- Coupling Constraint: The coupling constraint on the nodes was done using named selections and remote points. The displacements for each pair of symmetric nodes were coupled in the X and Y directions as shown below in Figure 10.

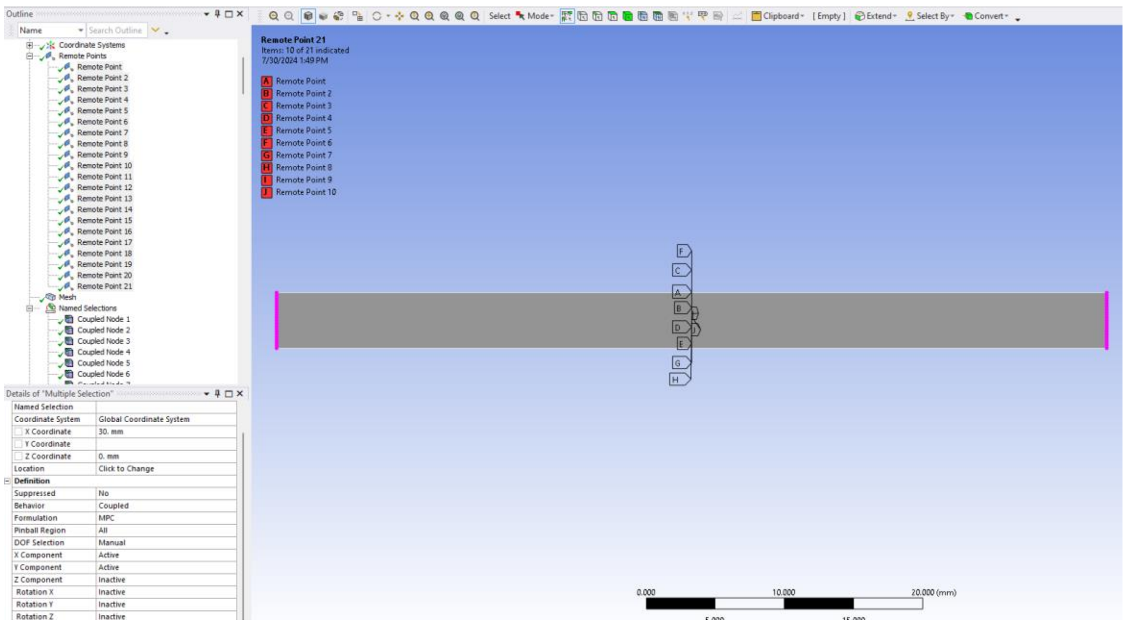


Figure 10: Applying Coupling constrain in Ansys® Mechanical

- Modal Analysis: A modal analysis was conducted to determine the natural frequencies and mode shapes of the structure. This involves solving the eigenvalue problem:

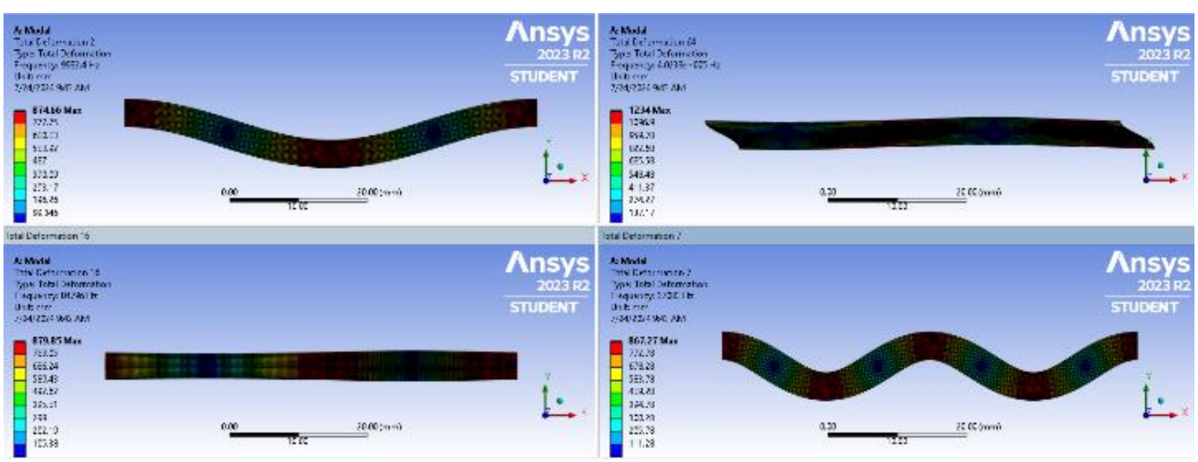


Figure 11: Test Case Mode Shapes

4. Post-processing to Obtain Dispersion Curves

- Frequency vs. Wave Number: The eigenfrequencies (natural frequencies) were extracted from the modal analysis (Fig. 11) and for each classification of mode shapes the corresponding wave length is determined. This was achieved by analyzing the spatial distribution of the mode shapes. Using the wavelengths, wavenumbers were calculated using the formular:

$$\mu = 2\pi/\lambda \qquad (4)$$

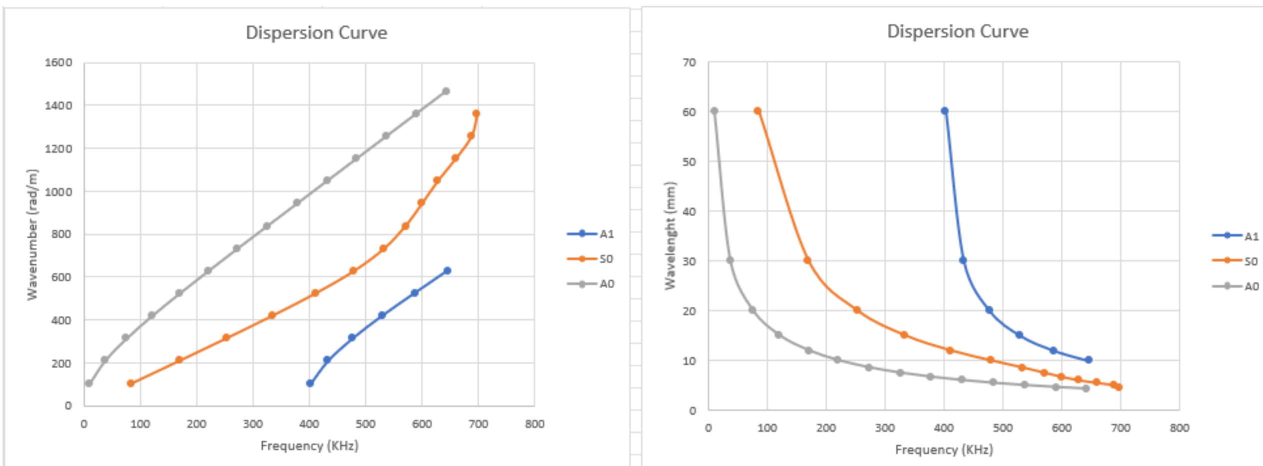


Figure 12: Test Case Dispersion Curves

Decay Vessel Approximate Case

After validating the analysis approach with the test case, I applied the same modal analysis methodology to an approximate cross-section of the decay vessel. This involved altering the material properties to steel S355, ensuring the analysis accurately represents the vessel's actual condition. Using Ansys® Mechanical, the modal analysis was conducted to obtain mode shapes, these shapes were then categorized based on symmetry and anti-symmetry, and the corresponding dispersion curves were plotted.

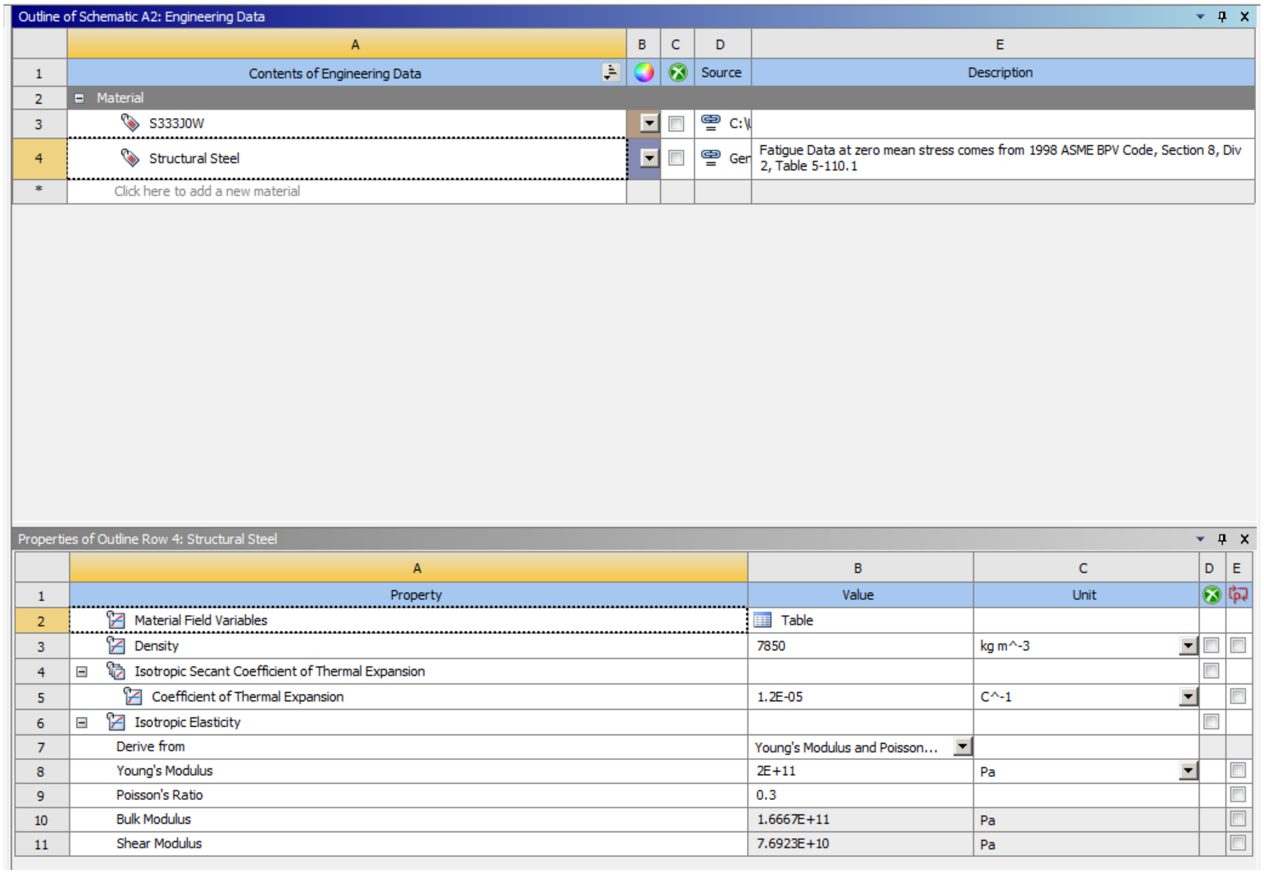


Figure 13: Material Reassignment

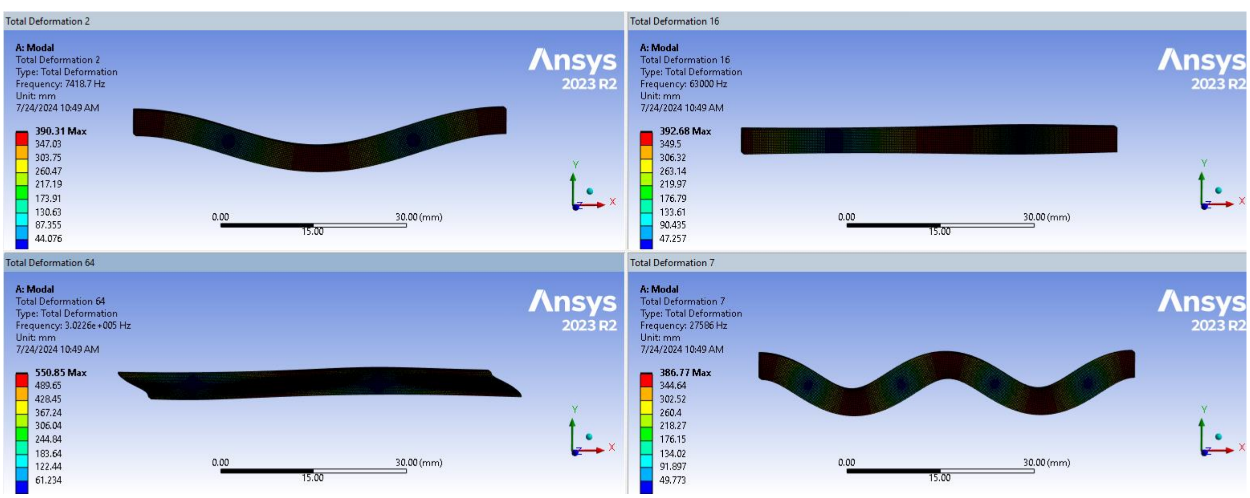


Figure 14: Decay Vessel Approximate Cross Section Mode Shapes

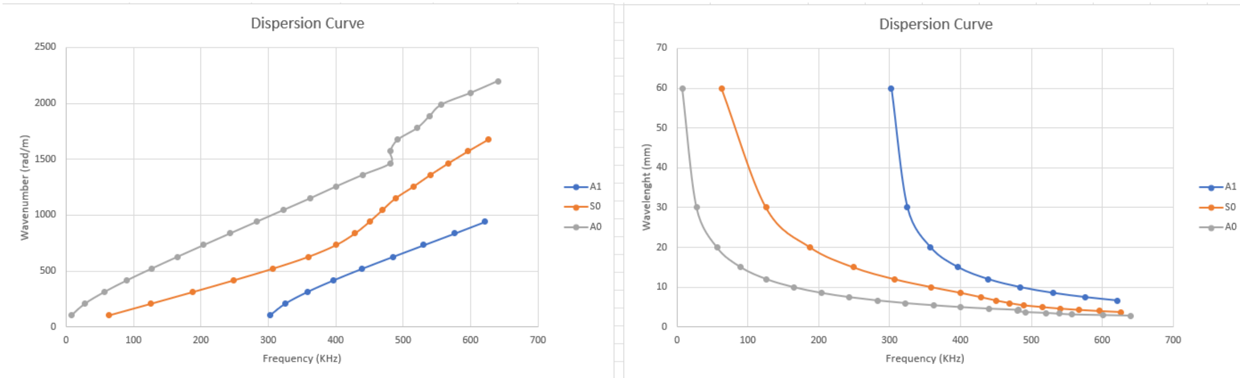


Figure 15: Decay Vessel Approximate Cross Section Dispersion Curves

Conclusion and Outlook

The modeling and approximation study of the decay vessel provided insights for further analysis and research. Initially, the decay vessel was modeled in 3D using Ansys® SpaceClaim from a 2D configuration provided. This modeling included various changes, including a reduction in the number of horizontal and vertical stiffening elements, the addition of a detachable aluminum liquid scintillator container, and the use of the HE-A profile for support. These modifications made maintenance easier, increased experimental setup versatility, and improved load distribution, all of which contributed to a more durable and adaptable design.

Following this, a modal analysis was performed to validate the structural integrity and dynamic behavior of the vessel. This began with replicating a sample analysis from [1] using Ansys® to ensure the accuracy of the methodology. A modal analysis on an isotropic plate with specified dimensions was conducted, with mode shapes categorized based on symmetry and anti-symmetry, and dispersion curves plotted from the data. This validation confirmed the reliability of the analysis approach.

Subsequently, the validated modal analysis methodology was applied to an approximate section of the decay vessel, with material properties adjusted to reflect those used in the vessel. Mode shapes were obtained, categorized, and dispersion curves were plotted, providing critical insights into the vessel's dynamic behavior.

Further analysis will involve conducting the same modal analysis on a more detailed FE model of the decay vessel, incorporating the stiffening members and the changing cross-section for a comprehensive assessment. Additionally, seismic analysis can be performed to evaluate the vessel's response to earthquake-induced forces, and fluid-structure interaction analysis can be undertaken to understand the interplay between the vessel's structure and the liquid scintillator. These further studies will enhance the robustness and reliability of the decay vessel design, ensuring its suitability for the SHiP experiment.

Acknowledgments

I would like to sincerely thank the following people and institutions for their important assistance and direction during my visit:

Above all, I would want to express my gratitude to my supervisors, Andrea Miano, Fabrizio Aloschi, and Marco Andreini. I would especially want to thank Fabrizio Aloschi and Marco Andreini for their time, patience, and willingness to share their vast knowledge. I have gained a great deal of knowledge from our conversations, and their explanations and advice have been inspirational.

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I am also grateful to Richard Jacobsson, the lead physicist of the SHiP experiment, for allowing me to work on this significant project.

Additionally, I would like to thank my fellow summer students for their camaraderie and support. The shared experiences and mutual assistance have been invaluable.

Lastly, I would like to express my deep appreciation to my family for their continuous encouragement and support.

Sincerely,
Daniel.

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