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## **Development of Digital Twin of the Herøysund Bridge using Finite Element Model Updating**

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## **Abstract**

The aging of civil infrastructure presents significant challenges in a global scale, necessitating innovative research techniques for effective solutions. Governments are increasingly compelled to allocate additional time and budgetary resources towards maintenance, repairs, or the construction of new structures to replace deteriorated or damaged ones. This allocation is essential to ensure the provision of adequate services to citizens. Implementing a digital twin of any structure can help for Structural health monitoring. This thesis is aimed to build a digital twin of Herøysund Bridge. Vibration data obtained from the field work is used for finite element model updating. Updated finite element model is more similar to the real world behaviour of the bridge. In this thesis, a comprehensive literature review is carried out on various methodologies, including experimental modal analysis, operational modal analysis, and finite element modal updating. Furthermore, a genetic optimization algorithm is used for the finite element model updating of the shell-based model of the Herøysund Bridge using Matlab. The process of finite model updating, using a genetic algorithm, demonstrates promising results for the parameters updated.

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# 1 Introduction

In this section a detailed discussion is made on the master thesis task. Further, a literature review is carried out on various techniques that will be useful for this master thesis. Finally, the problem and the questions, which this thesis is focused on, will be discussed

## 1.1 Background

This thesis, titled "Development of Digital Twin of the Herøysund Bridge using Finite Element Model Updating" is a part of a larger innovative project focused on the Herøysund Bridge in Herøy municipality. The overall project is funded by Nordland Fylkeskommune and Statens Vegvesen. NTNU, UIT Narvik and SINTEF are the partners responsible for various packages [3].

The research subject of this thesis is the old bridge in Herøy municipality, constructed in 1966. This structure is a post-tensioned concrete bridge. A new bridge is under construction and it is expected to be finished in 2024 after the problems in the present bridge were discovered [4]. Herøy FoU started a research project in the year 2022. Notably, a monitoring system has been installed on the bridge and various research activities has been conducted over the course of time.

The main aim of the broader study is to offer a comprehensive overview of the bridge's present structural state and facilitate efficient structural health monitoring (SHM). Additionally, it seeks to analyze the post-tensioning system's aging process and develop optimal maintenance and repair strategies. These efforts are planned in four main work packages.

1. WP1: Structural health monitoring
2. WP2: Corrosion inspection, assessment, and repair
3. WP3: Structural assessment with damaged post-tension
4. WP4: Reliability and uncertainty quantification

This master thesis is part of WP1, which aims to calibrate the shell-based finite element model of the bridge created by Zeeshan Azad in 2023 [2]. The vibration data obtained during the operational modal analysis campaign is used to find the modal parameters. High sensitivity accelerometers were used to obtain this data. Additionally, the thesis explores other aspects, such as the impact of environmental factors (temperature, wind speed and humidity) on modal parameters.

## 1.2 Monitoring of the bridge

For the purpose of SHM, some sensors were placed on the bridge specifically for research purposes to capture vibration data of the bridge when the bridge



is excited by environmental factors (temperature, traffic and etc). The sensors were installed according to two plans: a long-term plan and a short-term plan. The short-term plan involved placing 30 sensors across the entire length of the bridge. After this period, some of the sensors were removed, leaving only a portion of the bridge under monitoring. This thesis focuses on data collected from the long-term monitoring plan, which only includes data from parts of the bridge where sensors remained and it includes 12 sensors. Figure 1.1 illustrates the locations of sensors on the bridge for short-term plan. Additionally, Table 1.1 provides detailed information on the measurement axes of these sensors.

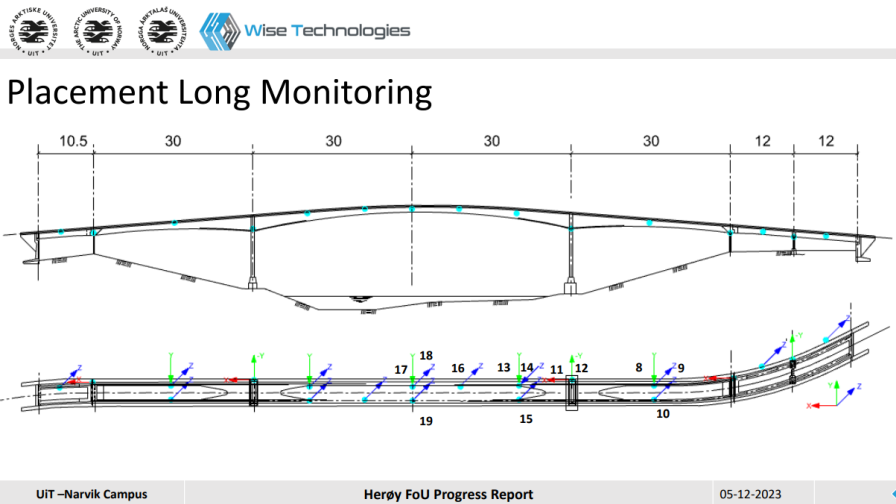


Figure 1.1: Sensor configuration on bridge for monitoring

Number of sensor	Axes of measurement
8	+Y
9	+Z
10	+Z
11	+X
12	-Y
13	+Y
14	-Z
15	+Z
16	+Z
17	+Y
18	+Z
19	+Z

Table 1.1: Distribution of sensors by measurement axes

### **1.3 Literature review**

In this chapter, the emphasis is on conducting a thorough review of the literature related to the research area addressed in this thesis.

#### **1.3.1 Structural Health Monitoring (SHM)**

The most widely used technique in civil engineering these days is structural health monitoring, which makes use of various new technologies in various fields, including data management, IT, signal processing, system identification, and monitoring. The goal of structural health monitoring is to maintain constant awareness of structures, such as highways and bridges, in order to manage the health of structures. This technique is used to improve the health of the structures under observation. This way, in the event that a structure experiences a catastrophic event or ages rapidly, potential failures can be identified and an action can be taken to repair them before they cause the structure to collapse or malfunction [5].

#### **1.3.2 Damage detection of the structures**

The majority of civil engineering structures, including skyscrapers, towers, bridges, and offshore platforms, either suffering rapid damage from natural disasters or progressively experience damage during their lives. The identification of structural deterioration is important from the perspective of a structure's serviceability and safety. Therefore, the structure has to be continuously inspected in order to identify any damage and make repairs before it is too late and requires expensive fixtures or collapses [6].

Two main identification techniques can be used to determine the likelihood of damage to a structure [6]:

- Conventional damage detection
- Global damage detection

#### **1.3.3 Damage detection using conventional methods**

The two main approaches for detecting damage in a conventional manner are visual examination and focused experimental techniques like ultrasonic and acoustic emission. For any of these experimental methods to work, the area where the damage is located must already be known, and the area of the structure that is being examined must be easily accessible. Since the experiences of the responsible parties vary significantly, maintaining a consistent level of quality among inspectors tasked with identifying damage to a bridge is challenging [6].

#### **1.3.4 Global damage detection**

The terms "model-based method" and "response-based method" can be used to describe the global damage detection approach. The response-based approach

relies on experimental response data from structures, whereas the model-based approach depends on the availability of a comprehensive numerical model of the structure for damage detection [7].

### 1.3.5 Vibration analysis

Vibration analysis is one of the key instruments in every engineering discipline. To understand the significance of vibration analysis, it needs to be known that excessive vibrations have the potential to result in disastrous failures. The Tacoma Bridge collapse in 1940, when severe vibrations brought on by resonance caused the structure to completely collapse, is a prime example. Such failures can be prevented if one is aware of a structure's dynamic properties, which may be determined using modal analysis [8]. In this regard, there are three major way to do Vibration analysis [9]:

- The excitation of the structure is accomplished by means of a hammer; for example, a cylinder can be excited by use of an electromagnetic shaker.
- The reaction is sensed: the acceleration response is measured with an accelerometer.
- Acquiring and processing data involves filtering, amplifying, and converting analog to digital format (using an A/D converter) before storing the results in the computer.

Additionally, the excitation of the structure can also be achieved by depending on ambient-related factors (for example, the load of passersby on a bridge, change in temperature and etc...). In this thesis, we are relying on the ambient-related factors.

### 1.3.6 Modal analysis

Understanding a system's dynamic behavior through the identifying of its modal parameters such as natural frequency, damping factors, and mode shapes is known as modal analysis. The modal model is a mathematical model that is developed with the use of this data [10]. The dynamics of the system is broken down into frequency and position components by the analysis. It depends on the ability to represent a system's vibration response as a collection of basic harmonic motions known as natural modes of vibration. The spatial distributions of these modes and the system's physical characteristics define them. Modal testing, which has made significant improvements in recent years, is an experimental method that can be used to undertake the analysis, or it can be done theoretically using mathematical models [10]. The two main concept of each system's Dynamic, which in thesis is going to be concentrated on, are mode shape and natural frequency which their importance for this thesis cause the significance of their introduction.

The predicted curvature of a plane vibrating at a particular mode that corresponds to a natural frequency is shown by a mode shape. The surface's characteristics and boundary conditions determine the mode shape [9]. In 1982, damage on a Space Shuttle Orbiter body flap was located using the modal assurance criterion (MAC) [11]. The Modal Assurance Criterion (MAC) is a mathematical equation which is used in modal analysis to assess how similar two mode shapes are together. The MAC value ultimately yields a digit ranging from 0 to 1. The mode shapes exhibit less consistency when the MAC Value approaches zero, and vice versa [12].

$$MAC(\phi_i, \phi_j) = \frac{|\phi_i^T \phi_j|^2}{(\phi_i^T \phi_i)(\phi_j^T \phi_j)} \quad (1)$$

The symbol  $\phi_i$  is mode shape vector of the  $i$ th mode and  $\phi_j$  is The mode shape vector of the  $j$ th mode. Furthermore, natural frequency is one of the basic element which characterize a system and can be acquired using Vibration analysis. changes in the value of frequency can be used to identify structural damage. In the case, Cawley and Adams (1979) [13] used shifting to natural frequencies to detect deterioration in composite materials

### 1.3.7 Experimental Modal Analysis (EMA)

Experimental modal analysis is a field of engineering in which the main focus is to implement a testing procedure to identify the modal parameters of a Structure by using recognized input excitation and measured dynamic responses. In this procedure, the excitation is produced by shaker or Impact hammer. by utilizing this method, it would be possible to produce a variety of input frequency in terms of range of them that leads producing different modes. However, this method has disadvantages as well. The use of these known forces can apply additional loads on structure with low weight and ending up finding error in result. Also, The results acquired in the lab or by artificial excitation may not always match the results obtained under real operational settings since this kind of excitation is not able to fully reflect the real situations. The final drawback of EMA arises in large-scale structures since it is unlikely that suitable modes will be produced by activating these structures with the previously mentioned known forces [14, 15].

### 1.3.8 Operational Modal Analysis (OMA)

Operational modal analysis (OMA), also known as output-only, ambient, or natural-excitation modal analysis [16], is the technique of identifying modal parameters of a structure based on vibration data collected while the structure is operating. When a system cannot completely shut down or the structure is too big to respond to artificial excitation, OMA is used. The stimulation in OMA is provided by external forces or the forces resulting from the structure's cyclic loads. OMA only needs measurable response data because these excitation are unknown, and several techniques are utilized to extract the modal parameters

[17, 18, 19, 20]. OMA examines how naturally occurring vibrations in structures occur in everyday situations, like wind or traffic. OMA is appropriate for real-world situations since it doesn't require artificial forces. OMA and EMA both employ comparable arithmetic, but OMA is primarily concerned with practical uses, such as updating models or keeping an eye on structural health of a structural system [21].

In the past, the computing efficiency and power required for modal testing was a significant problem because many outputs must have been handled simultaneously. OMA research accelerated in the late 1980s as a result of developments in computers [22]. Since the early 1990s, OMA has advanced significantly [16].

The following are some benefits of OMA that may help it be a more effective method of determining a structure's modal parameters [23]:

- OMA is less costly than EMA and does not require stimulation instruments.
- OMA makes it possible to determine the dynamic properties of the entire system in its actual operational state and environment.
- OMA is appropriate for permanent vibration-based health monitoring and structural damage identification since it doesn't affect the structure's ability to function.

There are two categories of OMA techniques: time domain and frequency domain methods. While frequency domain approaches are focused on the relationship between input and output power spectrum density (PSD), time domain methods are based on correlation functions or the examination of response time patterns [24].

As mentioned in OMA, the excitation of the bridge comes from natural or environmental forces like wind or traffic. This type of excitation is often disrupted by noise, and the accuracy of the analysis depends on how much the excitation looks similar to white noise. One of the main issues with using ambient excitation is that it can be weak and only cover a narrow range of frequencies, limiting the number of modes that can be identified [25].

In order to perform modal identification using OMA techniques, several methods can be used to extract modal parameters such as frequency domain decomposition (FDD) and stochastic subspace identification (SSI) which are among the most important techniques which can be used.

Rune Brinker was the first person to propose frequency domain decomposition (FDD) in 2000, as a SVD-based method for spectral decomposition. SVD was used previously for decomposition (shih et al [26]), but this was the first time that the singular values of a spectral matrix were understood to be an approximation of the system's modal coordinates. The application of FDD is to obtain modal parameters (natural frequency, mode shapes and damping ratio) from ambient response. This method is an expansion of the traditional frequency domain strategy, also known as the Peak Picking(PP) or basic frequency domain

methods. The Discrete Fourier Transform is used in the classical approach's basic signal processing, which relies on the ability to estimate well-separated modes directly from the peak power spectral density matrix [17].

The natural frequency and mode shapes can be approximated, but the damping ratio cannot, according to the initial formulation for FDD. But a year later, a non-parametric method known as enhanced frequency domain decomposition was developed to accomplish that, creating the second generation of FDD [27].

Overschee and Moor proposed stochastic subspace identification (SSI) for the first time in 1991. Similar to FDD, this technique is used to determine the modal parameters of a system based on input-and-output or output-only records, derived from the so-called state space matrix. It incorporates a few strong numerical techniques, like least-square fitting, SVD, and QR decomposition, which are used to reduce computational load and eliminate noise from system models and datasets of high quality. Also, SSI makes up for the weaknesses of other methods, such as frequency domain techniques, which are inadequate for identifying closely spaced modes and have insufficient resolution in the frequency domain. This technique is quite efficient because it can simultaneously determine the modal frequencies, mode shapes, and damping ratios of several system modes [1].

There are two primary steps that define the fundamental concept of the Stochastic Subspace Identification (SSI) method [1]:

1. Using SVD to get the system matrix from the output vector's covariance matrix.
2. Using the system matrix to determine the studied system's modal parameters.

As it can be seen in the figure 1.2, The first step in using this technique is to create a Hankel matrix from the output data. Following projection procedures, the Hankel matrix can be utilized to produce the Toeplitz matrix, which has enough data to create the system matrix, which is made up of the two matrices  $A$  (State matrix) and  $C$  (Output matrix). The Toeplitz matrix plays a key role in greatly lowering the quantity of analytical data while preserving the signal's original content. Subsequently, system matrix can be obtained using SVD manipulation. Ultimately, by using eigenvalue decomposition, the structure's modal parameters can be determined [1].

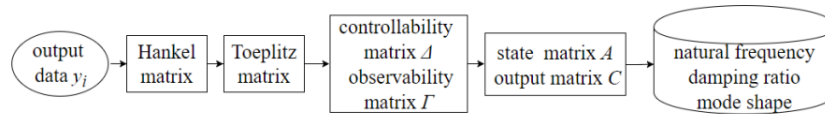


Figure 1.2: Detailed flowchart of the SSI technique[1]

The challenges in figuring out the system's computational order for modal

analysis with SSI approach led Reynders et al. to create the stabilization diagram, since the standard technique was found to be less successful for some structures because of the extreme noise contamination in their output records. The standard technique counts the number of non-zero singular values of the Toeplitz matrix and looks for a noticeable jump in the amplitude of descending singular values to account for noise. Finding the true modes, which relate to more stable values of the modal parameters than the false modes, which are typically generated by noise, is the goal of the stabilization diagram.[1]

As it can be seen in Figure 1.3, a stabilization diagram is depicted which is a plot containing different model orders versus the identified frequencies in each model order. in the x-axis of this plot, frequency is shown, which the y-axis is dedicated to the model order.

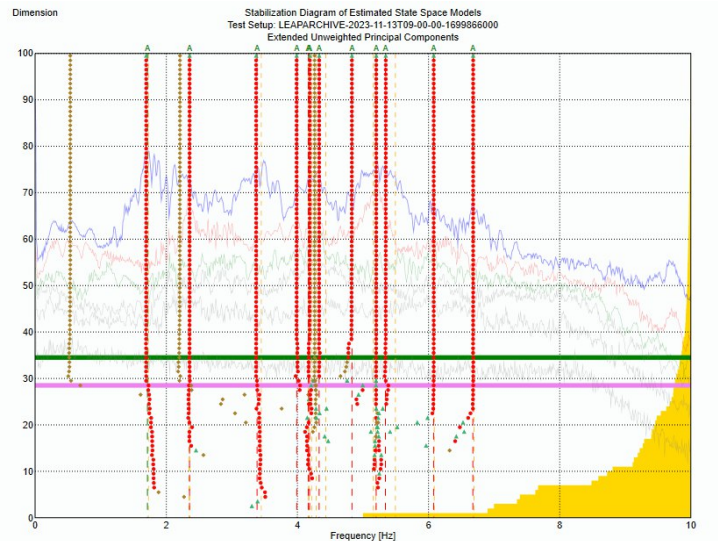


Figure 1.3: Stabilization diagram associated with the SSI method

### 1.3.9 Case studies of Operational Modal Analysis in practice

In recent years operational modal analysis has been widely used in many project as it has a lot of importance in the area of construction engineering for structural health monitoring and extraction of modal parameters. this section is focused on presenting an overview on how OMA was used in some projects.

Chen et al. [28] examined the modal parameters of an eleven-span concrete bridge exposed to mild ambient excitation by recording the acceleration responses. The research was aimed to measure the extend of possibility of modal identification under weak ambient excitation. In this research, modal analysis was carried out employing Peak Picking (PP) , FDD and SSI techniques. 12 modal frequencies below 10 HZ including nine laterals and three verticals were identified, although the excitation power was low. beside, The identified

modal parameters were compared with those from a numerical modal analysis, revealing that several higher-order vertical modes were absent in all experimental outcomes. Also, FDD and SSI methods could not identify some important lateral modes. Finally, they came to the conclusion that both SSI and FDD can be utilized for deep and complete studies, but that the PP and FDD approaches can be helpful for obtaining handy and basic results and quick analysis.

Silva and Neves [29] applied operational modal analysis technique on a three-span concrete railway bridge under excitation made by jumping of some people over the bridge. 2 sensors, were installed in each span and one accelerometer at each end of the bridge, 8 sensors were installed on the bridge totally. The result of modal analysis in their research signified the importance of need of powerful excitation force, because after comparison between modal parameters extracted from the SSI method with numerical modeling developed in CSiBridge software and Due to the lack of simultaneous excitation in all three spans, identification of the high order modes was not possible. Their study found that even minor vibrations from human activity yielded dependable results in modal identification using the SSI method.

Pedrosa et al. [30] studied on evaluating the Portela bridge's safety status in order to identify a dependable renovation option and after carrying out modal parameters identification, the FE model of the bridge was refined based on the modal which extracted during modal analysis. Modal analysis of the bridge was done using Artemis software and utilizing Enhanced Frequency Domain Decomposition (EFDD) and SSI. In this study, less than two percent difference was identified between the result of modal identification by the two used techniques.

Magalhaes et al. [31] used the PP, FDD and SSI modal identification approaches in the frequency and time domain to determine the modal characteristics of the international Guadiana cable-stayed bridge that connects Spain and Portugal. The modal parameters that were found were compared to equivalent modal parameters that were derived from a numerical model. They discovered a wide spread of damping ratios but a small range of variance for frequency and mode shapes.



### 1.3.10 Finite Element Model Updating (FEMU)

The term "finite element method" describes a procedure where a physical structure is transformed into a mathematical model. A numerical solution is then used to communicate the dynamic features of that structure through that mathematical model. Features such as damping ratio, mode shapes, and natural frequency. Finite element methods were initially used in civil and Aerospace engineering to solve difficult elasticity and structural analysis problems [9]. The pioneers of finite-element modeling were Courant and Robbins (1941) and Hrennikoff (1941) [9]. The following problems can be modeled using finite-element analysis [32]:

1. Vibration analysis is a method used to check for random vibrations, shock and impact in a structure. Natural frequencies and mode shapes are two topics covered in this examination.
2. Fatigue analysis to estimate cyclical loads, engineers may forecast the life cycle of a material or a structure. The most vulnerable structural portions to the propagation of fractures can be identified thanks to this analysis.
3. Heat-transfer analysis, which simulates the material's or structure's thermal fluid dynamics or conductivity.

While after using Finite element method in making a mathematical model of a structure, it was found that results from the finite element model (FE model) often differ from those obtained from experiments. The following are the causes of the difference between measured and FE model data [9]:

1. The error in the model of a structure due to hardness of modelling some parameter such as Damping, joint, welds and edges.
2. Model order mistakes, which could be made by the challenge of modeling nonlinearity.
3. Model parameter errors, which in fact allow us to determine the appropriate material properties.
4. Errors in measurements.

In order to minimize the difference between measured and finite-element model, FE model updating technique is performed. These are two ways to carry out finite element modal updating which are direct and iterative. In direct model the main focus is to update the model without altering the various physical parameters of the case we are supposed to do model updating of (such elastic modulus and etc.). Without taking the structure under study, direct approaches typically produce models that represent the measured parameters. This leads to mass and stiffness matrices that are unrelated to physical changes in the finite parts of the original model and have minimal physical relevance. Moreover, there is no guarantee of node connectivity, thus matrices are typically fully

occupied rather than sparse [9]. However, the iterative approach often updates the physical features and restructures the finite element method to roughly produce the same measured data [9]. In this thesis the main concentration is to carry out finite element method updating through iterative approach.

It is notable that before carrying out FE Model updating, performing a process called parameter sensitivity analysis on Initial FE model which the updating is going to be performed on is important. The parameter sensitivity analysis refers to a process used in the field of structural engineering where the primary goal is to evaluate how modifications to a system's or model's input parameters impact the outputs or outcome. The objective is to determine which factors have the most effects on the results and to comprehend how sensitive the model is to changes in particular parameters. Making intelligent decisions, upgrading designs, and enhancing system robustness all depend on this study [33].

The main goal of updating the finite element model (FEM) is to optimize the values of certain parameters that are known to have uncertainties; these are found through the procedure parameter sensitivity analysis. The finite element model may be altered to better represent the system's actual performance under real-world circumstances by changing these parameters. As such, the first step is to pinpoint the precise characteristics that need to be updated. Next, modify an objective function also known as fitness function based on the initial FE model and the experimental modal parameter [9]. Among a wide range of available algorithms for updating process, it is possible to choose from options such as Particle Swarm Optimization, Genetic Algorithm, Simulated Annealing, and others. Each of these algorithms is rooted in optimization techniques that seeks to find the optimal solution through an iterative process.

In the recent, various algorithms were employed for FE model updating. Neural networks were used by Park et al. [34] to assess the bridge boundary condition. With an emphasis on the rotational stiffness of the boundary conditions, they used ANN to identify the correlations between the bridge responses and the constraining impact of the boundary condition.

Liu et al. [35] used Fuzzy theory to optimize FE models. The model parameters and design variables were considered as fuzzy variables in their study, and this technique was successfully applied to a real concrete bridge.

Chang et al. [36] designed a technique for measuring the structural health of a steel bridge using an adaptable neural network. They used an iterative technique, updating the model repeatedly until they saw a reasonable level of convergence between the bridge's calculated and measured modal responses.

Jung and Kim [37] for updating finite element models developed a hybrid genetic method, which they tested on a numerical bridge model. Combining a genetic algorithm with the Nelder-Mead simplex approach created a hybrid genetic algorithm. It was discovered that the suggested method worked well for upgrading bridge constructions using finite elements.

## 1.4 Problem

Bridges are among the most Widely-used infrastructures in modern societies, experiencing various loads throughout their life-cycle, including wind, traffic, and earthquakes. Over time, bridges experience aging, making it essential to address the degradation. One effective solution is to assess their condition using Finite Element Modeling (FEM). FEM models of these structures are typically constructed using technical data, as-built drawings, and engineering rationale. However, they often fail to accurately replicate the real-world responses of the structures due to inherent uncertainties. Therefore, FEM updating is employed as a technique to minimize the discrepancies between actual structures and their corresponding FE models.

Finite Element Model (FEM) updating first appeared outstandingly in the last decade of the 20th century and quickly became a useful tool in the fields of structural design, construction, and maintenance. This technique can be implemented through two primary methods: direct and iterative. Direct methods involve a single-step procedure to update the system's stiffness and mass matrices without altering the physical parameters. In addition, the iterative method focuses on updating the physical parameters of the model. This process is repeated until the model accurately reflects the real-world behavior of the actual structure. It requires an objective function to manage the minimization of discrepancies between the theoretical model and actual behavior. Additionally, the parameters selected for updating should play a role in the structure's performance, to ensure that the modifications significantly improve the model.

The primary goal of this thesis is to create a digital twin of the Herøysund bridge, aiming to refine the finite element model (shell-based model) of the bridge that was originally developed by Zeeshan Azad [2]. This enhancement will be achieved through the use of technologies such as Ansys software, Artemis software, and various programming techniques.

## 1.5 Research questions

This section is dedicated to outlining the key questions that this thesis seeks to answer. In relation to this thesis, the following questions are essential to address:

1. What effects do Environmental variables (temperature, wind speed and humidity) have on the consecutive MAC values and natural frequencies of mode shapes in structural dynamics?
  - This question aims to understand the correlation between environmental variations and their effects on the structural responses extracted doing modal analysis.
2. What is the impact of parameters chosen for updating on The initial FE model of the bridge?
  - This question focuses on evaluating how changes in chosen parameters for updating affect the model's response and whether the process of updating bring the FE model closer to represent real-world behaviors.
3. How effective is the genetic algorithm in optimizing the parameters of an FE model to improve its correlation with actual structure's behavior?
  - This examines the efficiency and effectiveness of using a genetic algorithm for parameter optimization in FE models, assessing its ability to converge on optimal solutions that improve model accuracy.
4. To what extent can the iterative updating of the FE model, using a Ansys software connected to the optimization algorithm, minimize the gap between theoretical and experimental Modes?
  - This question assesses if using Ansys software in connection with optimization algorithm could assist in making the process of updating easier or possible.

## 2 Methods and Tools

In this section, the focus is on introducing the methodologies and tools utilized in the thesis. Initially, a summary of the primary instruments utilized in this thesis is presented.

1. Artemis modal(version 7) : A platform that is used for modal analysing, modal testing, and modal problem solving using vibration data.
2. Ansys workbench 2023: To evaluate parameter analysis on the Herøysund bridge Finite element model(Shell-based model) and use it as a tool for iterative FE model updating.
3. Python programming language : Implementing python Scripts for Data visualization, cleaning data before processing and post processing data of modal analysis of Vibration data on Artemis modal.
4. Matlab 2023: Using Matlab to implement optimization algorithm used to optimize parameter's values and updates the initial FE model to make it better resemble the bridge in real life.

Although the tools were mentioned briefly, it is important to delve deeper into their specifics and how they are applied within the methodology of this thesis.

### 2.1 Preparation of data

Data preparation is a fundamental process in this thesis toward having a qualified modal identification by the software which was used for this purpose.

#### 2.1.1 Data description

For the modal identification in this thesis, multiple data chunks captured by sensors installed on the bridge have utilized, which their locations previously mentioned in Figure 1.1. Each chunk of data consists of roughly 1,800,000 rows across 12 columns, corresponding to the number of sensors employed. Notably, 48 chunks of data collectively represents a full day's worth of data. Table 2.1 gives an insight into what kind of data this thesis is used for modal analysis.

Num.Rows	Num.columns	Time coverage	Num.Dataset
Approximately 1800000	12	30 Minutes	144

Table 2.1: Dataset specification in the Thesis from 12-14/11/2023

### 2.1.2 Data preparation process

To prepare the raw vibration data for importing into the software for modal identification, it was necessary to remove certain data columns that were unnecessary, as they originated from sensors installed on the deck that were not required for the process. Hence, python scripting was utilized for data cleaning and processes such as removing specific column, rows and necessary information in dataset such as comma between each element in a row of data.

## 2.2 Modal Analysis

In this thesis, the goal of the modal analysis is to determine the modal parameters (natural frequency, mode shape, damping ratio) of the bridge from various segments of data using Artemis modal software.

The Artemis software, was created 25 years ago, facilitates modal analysis of systems through ambient vibration analysis [38]. It provides various services in modal analysis, including modal parameter identification using FDD (Frequency Domain Decomposition), EFDD (Enhanced Frequency Domain Decomposition), and SSI (Stochastic Subspace Identification). This thesis employs the SSI technique as a method to obtain the modal parameters of the Herøysund bridge considering ambient factors. Artemis modal offers advantages for this purpose such as[39]:

1. Selection of mode shapes by SSI technique is done automatically by this application with high accuracy.
2. SSI techniques, including the UPCX method, can be used effectively. This method provides several benefits, such as more precise estimation of modal parameters and better handling of unstable noises.

Using the SSI-UPCX technique within the Artemis application requires a series of preparatory steps. It includes either creating or importing a geometry that is appropriate and compatible with the model intended for modal analysis. In this thesis, the geometry which was used, was designed to approximate the structure of the Herøysund bridge which can be seen in the Figure 2.1, while the location of sensors in the geometry of the bridge is mentioned in Table 2.2. Beside, making sure that the determined interval recognized correctly by Artemis and it should be 30 minutes(or 1800 seconds) for each chunk(in the case that Artemis can not set it correctly, it can be changed manually by entering a value between 497 to 502 for Nyquist Frequency for each dataset). A crucial part of this procedure is estimating the range of natural frequency which is important for the modal analysis of the bridge, which significantly depends on the structure's type and size. Research into modal updating for bridges and discussions with advisors revealed that due to the structure's weight and size, its natural frequencies typically fall within the low frequency range of 0-25 Hz. Further evaluation and testing determined that the most significant modes are found between 0-10 Hz. Once these settings were applied, a stabilization

diagram was generated with respect to the mentioned setup for each chunk of data, allowing for the identification and extraction of modal parameters from the application. To monitor the frequency over a 72-hour period(12-14/11/2023), involving 144 data segments, the process of identifying and extracting mode shapes was carried out.

The modal parameters identified by the software were then exported in text format for further examination through Python analysis to determine the pattern of frequency changes across different mode orders.

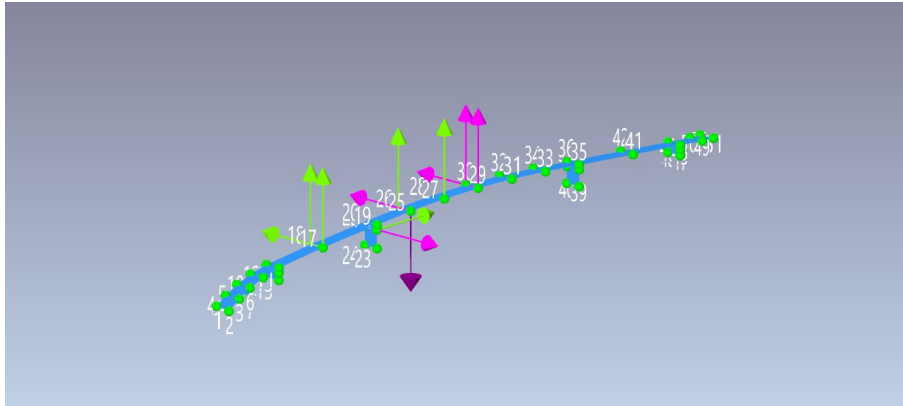


Figure 2.1: Bridge geometry for Modal Analysis

Number of sensor	Direction	Number of node
8	+Y	17
9	+Z	17
10	+Z	19
11	+X	21
12	-Y	21
13	+Y	25
14	-Z	25
15	+Z	26
16	+Z	27
17	+Y	29
18	+Z	29
19	+Z	30

Table 2.2: Sensor placement for Modal Analysis in Artemis

### 2.3 Data analysing of the modal parameters

One of the aim of the thesis is to analysis the modal parameters to find out if it is possible to discover any correlation between the modal parameters and ambient factors such as Humidity, wind speed and Temperature.

The environmental data which is used in this analysis is sourced from the Norwegian Meteorological Institute and NRK[40], which stores weather data as one of its services. The bridge under analysis is situated in Herøy municipality in Norway, which lacks its own weather recording station. Consequently, weather data was obtained from the nearest available station from mentioned organization’s website. This station is located in Sandnessjøen municipality (approximately 16 kilometers when measured as a straight line in Google map), from where the relevant weather data for the analysis was captured.

The primary modal parameter which was interesting for analysis from the three days dataset was natural frequency. This key parameter, obtained from conducted modal analysis, is crucial for detecting anomalies. For instance, unusual frequency values during one segment or a few segments among all of these three days could indicate a bridge malfunction. Furthermore, by applying regression analysis, it is possible to assess how much environmental factors(temperature, wind speed and humidity) affect the natural frequency values. Another parameter examined was the degree of similarity between each mode shape and the previous one, to investigate how the similarities between consecutive mode shapes vary with changes in environmental factors. It is important to note that only the first three modes extracted were chosen for analysis.

After the files of modal analysis of all chunks were exported in the form of text file from Artemis, which included extracted modal parameters, The important content of them were then extracted and listed. Among all the content of these files, natural frequency of the first three orders from each segment were selected and saved in an excel file to create a database, which also included the date-time of each segment and corresponding environmental data, accompanied with calculated MAC value of each consecutive modes of the first three orders(to evaluate the similarities of the two consecutive mode shapes using equation 1 ). After completion of this comprehensive dataset, data analysis performed. Section B includes the list of first three order modal frequencies extracted.

To explore the connection between changes in natural frequency of the first three order, MAC value of each consecutive modes of the first three orders and environmental factors, a regression analysis was performed along with calculating correlation with the method of Pearson in python. For this purpose, statsmodels and pandas in python were used. Environmental variables were designated as the independent variables (predictors), while the elements of interest specifically the first, second, and third natural frequency columns that we aimed to understand in terms of their response to environmental changes were considered as dependent variables (responses). The regression procedure was executed to obtain essential values, including the correlation coefficient, which measures the extent of the influence of the independent variable on the dependent variable, and the coefficient, or slope, which determines the degree



of change in the response for each unit change in the predictor.

Ultimately, as previously mentioned, a new dataset was created using extracted modal parameters which were then visualized through a python script that employed Matplotlib for plotting purposes.

## 2.4 Mode selection and parametric sensitivity analysis

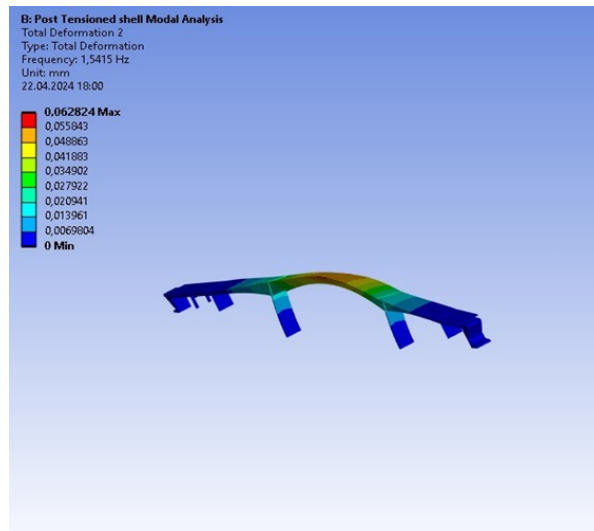
To perform FE model updating, it is essential to identify the impact of various parameters on the initial FE model since identifying the most influential parameters enables us to decide which values to modify. After selecting and adjusting these key parameters, It would be possible to modify the initial FE model(Shell-based model), so that its behavior more closely aligns with how the bridge functions in reality. Simultaneously, another crucial aspect to consider before updating the FE model is selecting specific mode shapes from both the measured model and the initial FE model. The choice of which mode shapes to focus on can depend on several factors, one of which includes estimation of similarity of each pair of mode shape from each other, by calculating the MAC value (Modal Assurance Criterion). This ensures that each chosen mode shape from initial FE model has nearly similar behavior with the one selected from modal analysis. Another criterion utilized in this thesis for selecting pairs is based on the proximity of the selected mode’s natural frequency values. Pairs of modes from both measured modal analysis and initial FE model with closely matched frequencies were selected. It is important to note that selection of specific modes was significantly influenced by their structural behavior, as categorized from both measured modes and the initial mode. As mentioned in Table 2.3, the two modes chosen demonstrate first and second order vertical bending behavior with difference in their value of natural frequency. Hence, after selecting pair of mode from both initial FE model and measured model, either based on natural frequency value or MAC value of mode shapes or using both methods, the optimization techniques is used to minimize the current discrepancy between each pair of mode as much as possible.

Modal Frequency [HZ]		
Mode	Initial FE model	Identified From Measurements
First Bending Mode	1.54150 (HZ)	1.64217 (HZ)
Second Bending Mode	2.5613 (HZ)	2.66703 (HZ)

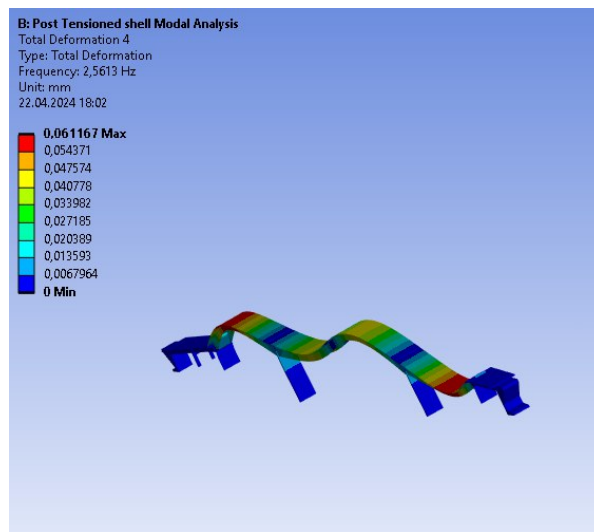
Table 2.3: Frequency ratio of initial FE model and measured modes

The first and second bending modes were selected from initial shell model [2] and selected from modal analysis of the bridge can be observed in the Figures 2.2(Initial model) and 2.3(selected modes from modal analysis). The stabilization diagram in Figure 2.4 belongs to the chunk from 21:00 to 21:30 of 13.11.2023 which is the segment that the modes for updating selected from. As shown in Figure 2.4, this Stabilization Diagram produced by SSI-UPCX contains mass of noises and uncertainties. In order to find a period of time which has less noises

and uncertainties to choose modes for updating from, it was advised by an expert (Palle Andersen creator of Artemis modal ) to merge some of the chunks together to check this possibility of having less noises in the stabilization diagram of a chunk which covers longer monitoring time. This new chunk was from 09:00 to 11:00 of 13.11.2023, but the result for this new chunk was the same as before and the modes identified had almost the same qualities, so it was decided to use the 30 minutes files of vibration data to select the modes for updating from. The stabilization diagram of that longer chunk can be found out in the section D.

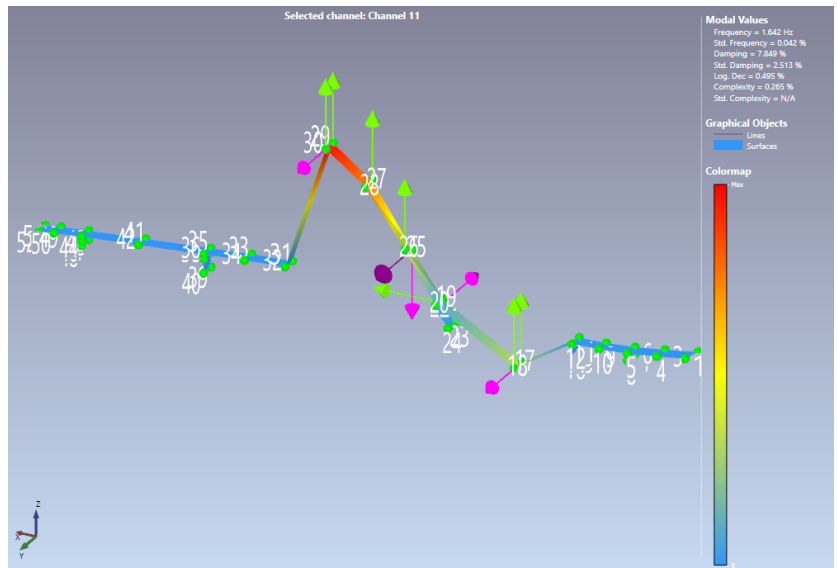


(a) First vertical bending mode

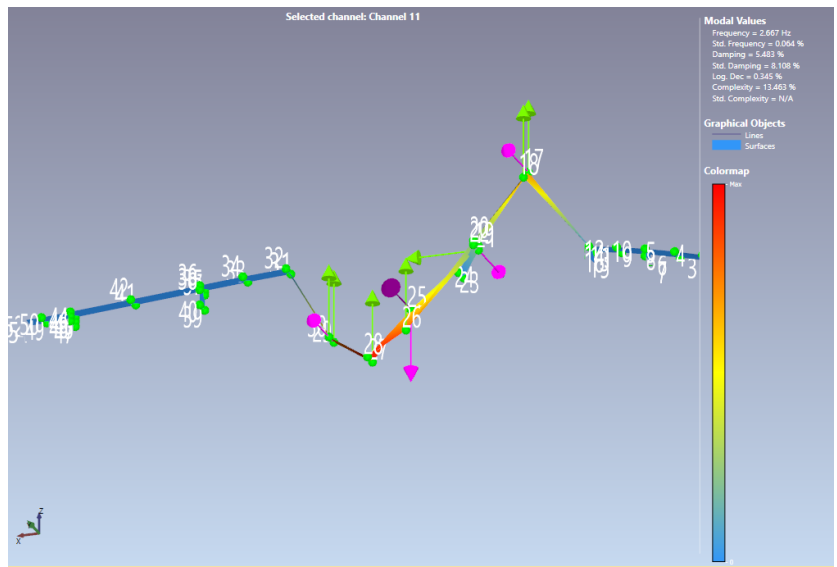


(b) Second vertical bending mode

Figure 2.2: Selected modes for updating initial FE Model[2]



(a) The first order mode shape of vertical bending mode



(b) The second order mode shape of vertical bending mode

Figure 2.3: Selected modes for updating from measured data

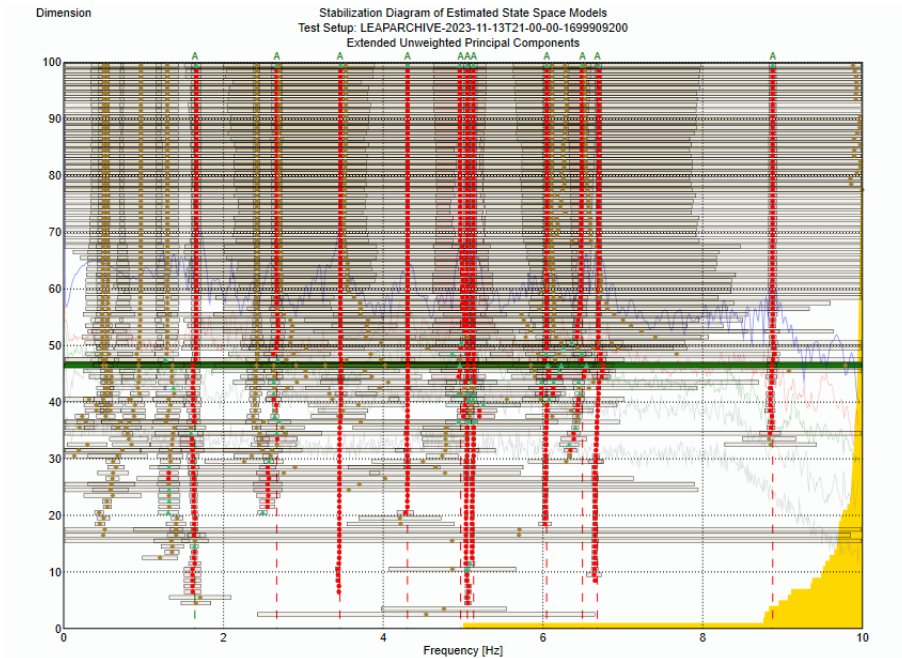


Figure 2.4: Stabilization diagram for selected mode dataset

The process of identifying which bridge's parameters are to be updated, generally requires a deep parameter sensitivity analysis of the bridge. However, in this thesis, in the lack of prior comprehensive study about sensitive parameters of the bridge, three parameters of the bridge were selected for studying their affect on the bridge and to be updated. Consequently, the precision in selecting the exact parameters for updating may not be optimal, possibly due to a deficiency in specialized knowledge. The selected parameters for updating are based on the engineering properties of the bridge's concrete elements as shown in Table 2.4.

Parameter's Name	Initial Value
Young's modulus [Pa]	19360000000
Poisson's Ratio	0.1414
Density [ $\text{kg m}^3$ ]	0.2392

Table 2.4: The sensitive parameters for updating

As shown in Table 2.4, three parameters were chosen for updating from initial FE model. The impact of change in mentioned parameters on the initial FE model was analyzed. This analysis was pivotal to determine if updating these parameters would improve the initial FE model, with the goal of better matching the real-world model. For the sensitivity analysis, the Response Sur-

face tool in the Ansys software, where the initial FE model was developed, was used. To utilize the Response Surface for parameter analysis, it was necessary to select the chosen parameters as input variables in Ansys by checking the set as parameter button in front of the value of these properties in Ansys software, while the frequencies of the selected mode shapes (Table 2.3-initial FE model) were set as outputs. An experiment using the Response Surface was then conducted to assess the impact of the inputs on the outputs. The settings for this experiment are detailed in Table 2.5, and the total pathway toward designing this experiment is provided in Section A .

Experiment Setting Name	Chosen Option
Type of Experiment	Central Composite Design
Design type	Auto Defined
Number of Possibility points	15

Table 2.5: The settings of Response surface Experiment

After the experiment was carried out in Ansys Response Surface Tool, diagrams were produced indicating the affect of each parameter selected for updating on each mode from initial FE model selected for updating. The experiment by Response Surface tries to set different values as inputs and investigate on the pattern of how input would affect output by the selected inputs and their respective outputs.

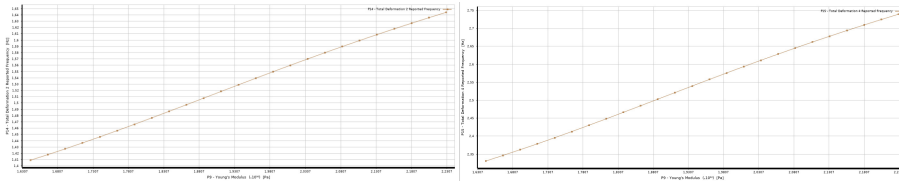


Figure 2.5: Young's modulus influence on updated modes

The value of Young's modulus positively affects the frequencies of both the first and second order vertical bending. On the other hand, the experiments indicated that Density and Poisson's ratio negatively impact both bending orders, as illustrated in Figures 2.5, 2.6, and 2.7. Meanwhile, the local sensitivity diagram displayed in Figure 2.8 reveals that Young's Modulus has the most significant effect on the natural frequencies of both bending modes, while Poisson's Ratio has the least impact.

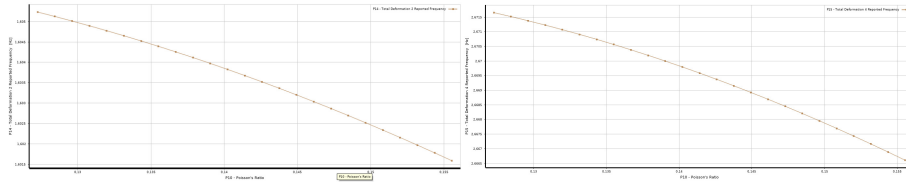


Figure 2.6: Poisson's Ratio influence on updated modes

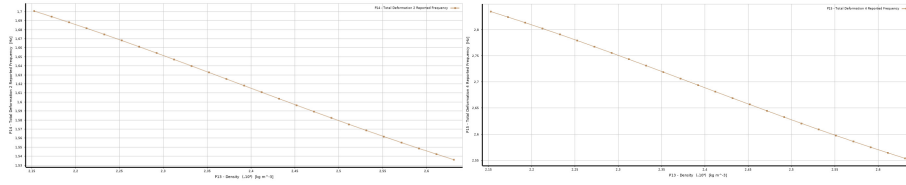


Figure 2.7: Density's influence on updated modes

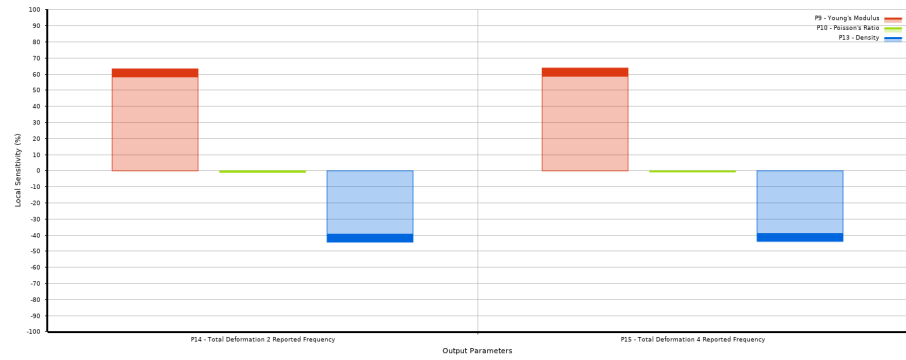


Figure 2.8: Local sensitivity diagram

Ultimately, the experiment performed with the Response Surface tool in Ansys established the upper and lower limits for the parameter chosen for updating, as documented in Table 2.6. These limits, as specified in the table, were then utilized as the upper and lower boundaries in the optimization algorithm.

Name of parameter	Lower Bound	Upper Bound
Young's Modulus [Pa]	16724000000	22296000000
Poisson's Ratio	0.12726	0.15554
Density [kg m <sup>3</sup> ]	2152.8	2631.2

Table 2.6: Bounds of parameters selected for updating

## 2.5 Optimization using genetic algorithm

In this thesis, the Genetic algorithm was chosen and set up as an optimization algorithm, which is explored in detail in this section.

### 2.5.1 Genetic algorithm

The genetic algorithm was originally developed by John Holland and his team in the late 20th century. This algorithm is fundamentally based on Charles Darwin's theory of natural selection [41]. There are numerous optimization algorithms available, each with its own set of strengths and weaknesses. The genetic algorithm was chosen for its well-established reputation, having been successfully implemented in various projects previously. Levin and Lieven introduced this method in 1998. However, a significant limitation of the genetic algorithm is known to be its slow convergence speed, which brings challenges when applied to large-scale structures due to the extensive selection of parameters and choices involved. Moreover, the design of the fitness function, the determination of population size, the selection of critical parameters like mutation and crossover rates, and the criteria for selecting new population members all require conservative consideration. Any missteps in these decisions can prevent the algorithm from converging or might lead to irrelevant outcomes. Nonetheless, the genetic algorithm offers notable advantages such as the capacity to handle complex issues and its intrinsic parallelism. It is versatile enough to manage different types of optimization problems, regardless of whether the objective function is static or dynamic, linear or nonlinear, continuous or discrete, and even in the presence of stochastic disturbances. The distributed nature of multiple offspring in a population allows for simultaneous exploration of multiple directions within the search space [41].

### 2.5.2 Functions

The genetic algorithm which was implemented for updating consists of several functions which is explained here.

The initial function is the main function that begins by setting general parameters such as population size, number of generations, mutation rate, crossover rate, etc. It then proceeds to create the first generation population and the main loop of the algorithm appears where it iterates as many times as there are generations.

During the iteration stage, the genetic algorithm attempts to identify the best solution through a structured process. First, the last generation's population is subjected to a technique called tournament selection. This approach randomly selects several population members (in the case of this thesis, tournament members are 5) and from them, chooses the one with the best fitness (objective) value. This selection is carried out repeatedly, equal to the size of the population to make sure of the having elite individuals (Those with best fitness values) in the next generation from current generation.



After conducting the tournament, a population is created of the tournament winners, who represent the best individuals from the previous population. In the subsequent stage, the crossover and mutation methods are employed to thoroughly explore the solution space and enhance the search to cover more possibilities. Following the application of mutation and crossover, an offspring is generated from the last generation, which must then repeatedly cycle through the loop for each offspring until we reach the loop's end, which corresponds to the predetermined number of generations at the algorithm's start.

A crucial aspect of developing an optimization algorithm is establishing a suitable fitness function for the problem, as the fitness function (or objective function) characterizes the problem and directs the process towards the optimal solution. In this thesis, implementing the fitness function is divided into two parts. Firstly, the method for calculating the fitness value is detailed. Secondly, the process of integrating the algorithm with the application is described to obtain feedback from parameter changes, which are essential for calculating fitness. When evaluating fitness, each individual must be tested in the initial FE model to find the response to the value that the fitness function would be calculated based on. This section only addresses setting up the fitness function; the automation of this process will be explained in the following sections.

The fitness function which was used in this thesis is based on the Equation 2.

$$E = \frac{1}{m} \sum_{j=1}^m \left| \frac{f_j - \hat{f}_j}{\hat{f}_j} \right| \quad (2)$$

The equation is formulated by comparing the measured frequencies with those predicted by the initial FE model. The symbol 'm' represents the total number of modes considered for the updating process, given both from the measured data and the initial FE model; in this thesis, 'm' is set to 2, indicating that the update is based on two modal frequencies. Furthermore,  $f_j$  indicates the natural frequency for the j-th mode, while  $\hat{f}_j$  refers to the experimental natural frequency for the same mode acquired from modal analysis (implemented Matlab algorithm of fitness function is found in section E).

The process of updating initial FE model using the genetic optimization algorithm is clearly shown in Figure 2.9, which includes a flowchart that outlines the steps involved.

## FEM Updating Using Genetic Algorithm

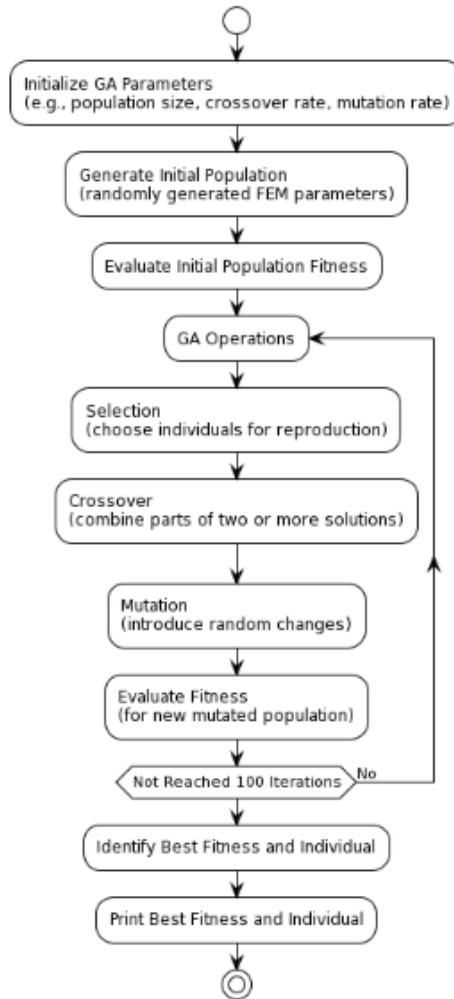


Figure 2.9: Genetic algorithm flowchart for FE model updating

### 2.5.3 General settings

When using the Genetic algorithm for optimization, it is important to carefully configure the general settings to guide the algorithm effectively toward a correct pathway to converge the problem. The initial considerations included the population size, set to ten times the number of elements selected for updating (3), resulting in a population size of 30. Additionally, the number of generations was fixed at 100. The crossover rate was established at 0.7, and the mutation rate at 0.05. These rates were chosen to hold a balance: encouraging the production of offspring from ancestors with superior fitness while also allowing for a 5 percent chance to explore broader areas of the solution space. Notably, the first population of this algorithm is 30 individuals of the initial values of the parameters (Table 2.4) that would be optimized.

## 2.6 Automation: Connecting algorithm to Ansys software

Young's modulus, Poisson's ratio, and Density are the main input variables that require updating, as previously mentioned. The frequencies of the first and second order in the original FE model are the corresponding output parameters, and their values depend on mentioned inputs. These frequencies will be used to compute the fitness value. In order to automate the procedure, the population values (Young's modulus, Poisson's ratio and density are the individual values of each population) for each iteration are sent to Ansys software, which uses the input values to calculate the output parameters (frequency values of the first and second order vertical bending of initial FE model). The procedure of updating these variables is time-consuming and computationally demanding since it necessitates a thorough redesign of the entire FE model. Reduced Order Models (ROMs) was the technique used to quickly determine the output values in relation to the input values in the initial FE model in Ansys software. This method greatly simplifies the procedure.

Reduced order models (ROMs) simplify complex models into more manageable forms. These ROMs keeps the essential behavior of the original models, allowing engineers to efficiently examine the system's primary effects with fewer computational demands [42].

Reduced order models has a lot of application in the area of engineering such as [42]:

1. Optimize product designs
2. Create larger systems simulations
3. Test control software
4. Create digital twins
5. Create Internet of Things (IoT) devices
6. Enable non-experts to use simulations

To automate the process of updating in Ansys software, two specific tools within Ansys software were utilized. The first is the Response Surface tool (A tool which represents Reduced order models in Ansys software), which had already been used for sensitivity analysis. The utility of the Response Surface tool depends on its ability to perform an experiment to determine the impact of selected input parameters on desired outputs. A significant advantage of using the Response Surface is that once the initial time-consuming experiment is conducted, predicting outputs with new inputs becomes straightforward and requires minimal computational effort, which is crucial for automating processes.

Additionally, Ansys software contains another tool known as the journal file, which was also integrated into this process. The journal file automates the execution of a series of commands that would otherwise have to be manually inputted each time. In fact, the tasks that need to be automated in Ansys are captured and saved in a journal file (Sample journal file in section F). During each iteration, instead of manually repeating the process, the corresponding journal file is loaded, allowing the code to execute automatically from start to finish. This facilitates a smooth and efficient operation, improving the automation of the update process in Ansys. The content of the used journal file is depicted in the Figure 2.10.

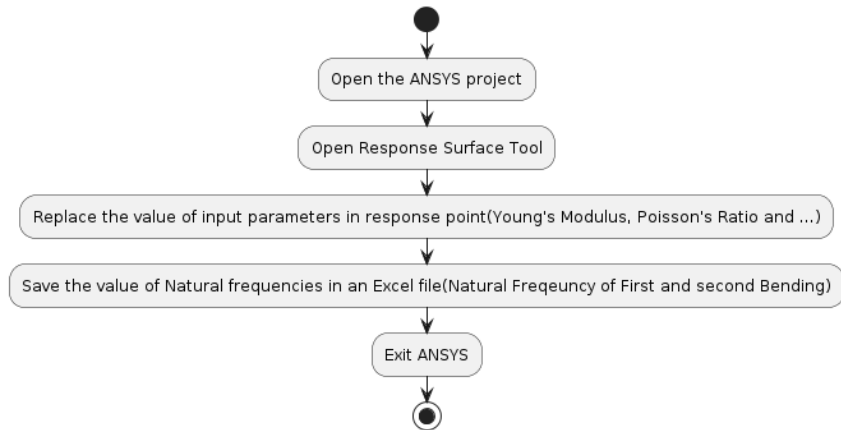


Figure 2.10: Journal file execution flowchart per iteration

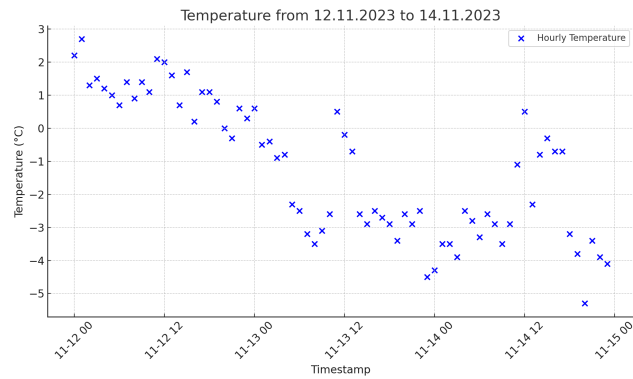
Once the experiment was set up with a response surface to examine the relationship between chosen inputs and outputs, Ansys Software was used to produce a journal file. The code-based instructions in this file explain how to manipulate the inputs and save the expected output results to an excel file. Every generation of a genetic algorithm changes the journal file, causing Ansys Software to update the inputs with every individual's values. Next, using the inputs, the software determines the new frequencies of the first and second vertical bending modes; the outputs are then saved to an excel file. The fitness

function, which calculates the fitness value, acquires these values after reading the excel file to obtain the updated natural frequencies (outputs).

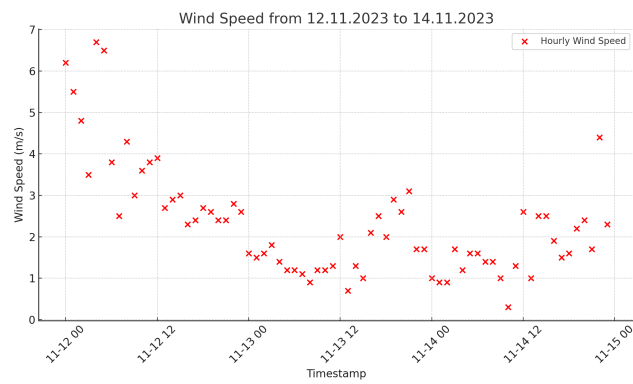
### **3 Result**

This section is designed to demonstrate the outcomes of this thesis. Initially, the results of the modal analysis and the ambient factor plots are presented. Following this, the focus shifts to illustrating the outcomes of the finite element (FE) model updating.

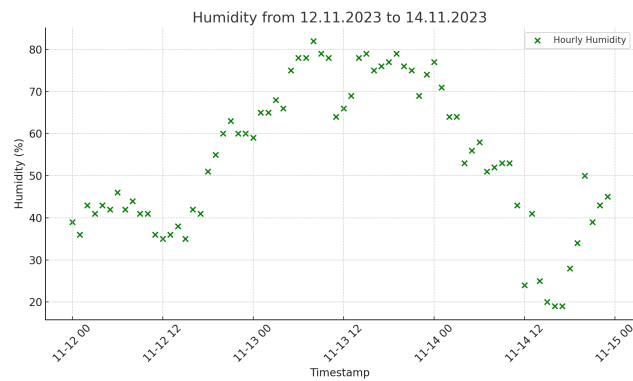
### 3.1 Modal Analysis



(a) Temperature

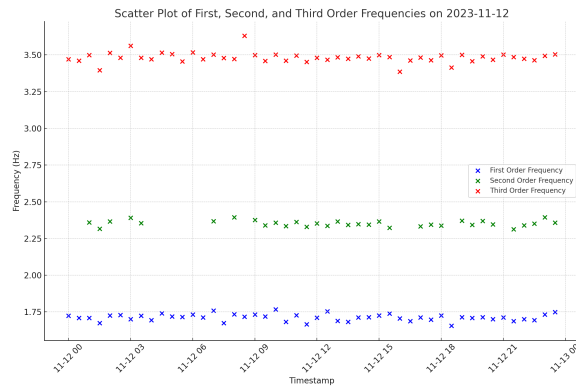


(b) Wind Speed

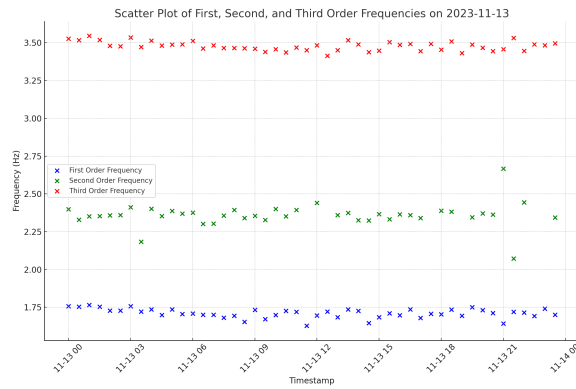


(c) Humidity

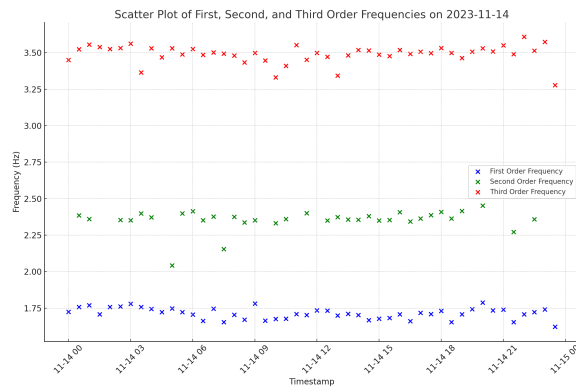
Figure 3.1: Scatter plot of temperature, wind speed and humidity



(a) Tracking of first three modal frequencies on 12.11.2023



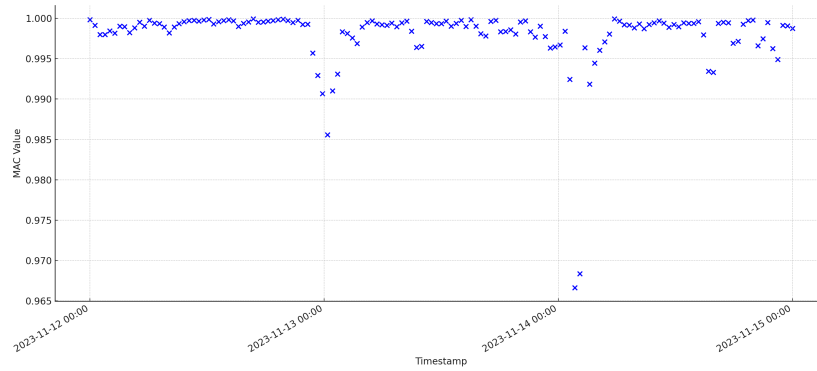
(b) Tracking of first three modal frequencies on 13.11.2023



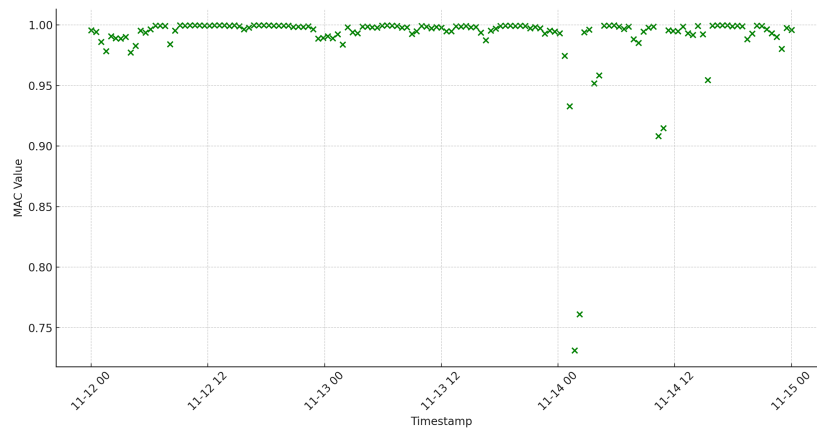
(c) Tracking of first three modal frequencies on 14.11.2023

Figure 3.2: Scatter plot of modal Frequencies on 12-14/11/2023





(a) First Mode Order



(b) Third Mode Order

Figure 3.3: MAC value tracking across consecutive mode shape pairs

Note : The tracking of similarities among each mode shape compared to previous ones is illustrated in Figures 3.3-a and 3.3-b. Figure 3.3-a displays the tracking for the first order mode shapes, while Figure 3.3-b depicts the tracking for third order mode shapes. The tracking for the second order mode shape is missing, due to the fact that many second order modes were not identified during modal analysis, leading to numerous gaps in the tracking diagram of that modal order. As a result, tracking was deemed futile and subsequently disregarded.

The correlation calculated in Tables 3.1 and 3.5 is based on the method of Pearson correlation coefficient which calculate linear relationship between two datasets.

<b>Factor</b>	<b>First Frequency</b>	<b>Second Frequency</b>	<b>Third Frequency</b>
Wind Speed	0.0384	0.0051	0.0778
Temperature	-0.0197	-0.0221	-0.0119
Humidity	0.0610	-0.0094	-0.0902

Table 3.1: Correlation of environmental factors on first three modal frequencies

<b>Variable</b>	<b>Coefficient</b>	<b>p-Value</b>	<b>95% CI Lower</b>	<b>95% CI Upper</b>
Constant	1.6983	<0.001	1.6735	1.7232
Wind Speed	0.0022	0.374	-0.0027	0.0072
Temperature	-0.0005	0.751	-0.0039	0.0028
Humidity	0.0002	0.393	-0.0002	0.0005

Table 3.2: Regression coefficients for the first order natural frequency

<b>Variable</b>	<b>Coefficient</b>	<b>p-Value</b>	<b>95% CI Lower</b>	<b>95% CI Upper</b>
Constant	2.3551	<0.001	2.2934	2.4167
Wind Speed	0.0017	0.826	-0.0139	0.0174
Temperature	-0.0017	0.696	-0.0103	0.0069
Humidity	-0.0001	0.835	-0.0009	0.0007

Table 3.3: Regression coefficients for the second order natural frequency

<b>Variable</b>	<b>Coefficient</b>	<b>p-Value</b>	<b>95% CI Lower</b>	<b>95% CI Upper</b>
Constant	3.4870	<0.001	3.4515	3.5225
Wind Speed	0.0037	0.302	-0.0034	0.0108
Temperature	-0.0029	0.239	-0.0076	0.0019
Humidity	-0.0003	0.273	-0.0008	0.0002

Table 3.4: Regression coefficients for the third order natural frequency

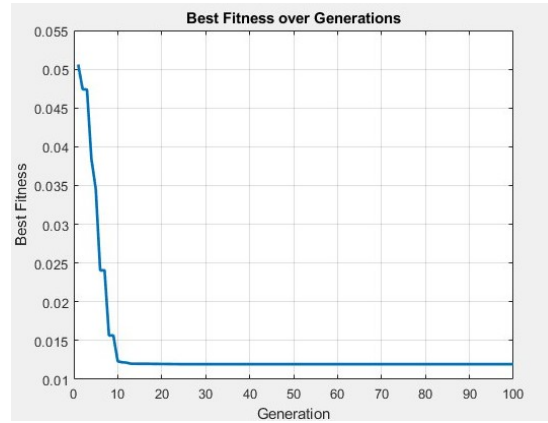
<b>Environmental factors</b>	<b>Mode order 1</b>	<b>Mode order 3</b>
Temperature	0.177	0.180
Humidity[%]	-0.126	-0.077
Wind Speed [m/s]	0.172	0.154

Table 3.5: Correlation coefficients of MAC values by environmental factors

The p-values in Tables 3.2, 3.3 and 3.4 indicates that if the environmental variables are likely to influence the natural frequencies. And as much as this value is lower, this effect is more. Also, 95% CI (Confidence Interval-lower and upper) indicates a range that, for the most part, we are 95 percent sure of representing the actual effect.

### 3.2 FE model updating result

The result of FE model updating is shown in this section with the focus on how much the value of updated parameter changed since before updating and also the result to the performance of fitness function during iterative process of model updating.



(a) Trend of convergence of problem over iterations

```

Generation 100: Best Fitness = 0.01195
Best Individual Parameters: 20170204904.4955    0.133368524062082    2316.78461283177
Best Fitness: 0.01195
f >>

```

(b) Final result in Matlab

Figure 3.4: Optimization process outcome figures

Parameter's name	Initial Value	Updated Value
Young's Modulus[Pa]	19360000000	20170209404
Poisson's Ration	0.1414	0.1333
Density [kg m <sup>3</sup> ]	0.2392	2316

Table 3.6: Updated value of sensitive parameters after optimization

## 4 Discussion

The practical work on this master thesis started with the use of Artemis software that includes various OMA. SSI-UPCX technique was used to obtain the modal parameters. The process worked well and identified almost most of the key modes between 0 to 10 Hz from the ambient data, which was the main goal of this study. While the procedure was not able to catch every significant mode in every chunk of data, it was mostly effective in capturing the majority of the essential and basic modes. Most notably, out of the first three modes, the first and the third were fully recorded. However, throughout the course of this three days vibration dataset, the second mode was not recorded in around 23 percent of the cases. This might have been caused by a number of factors, including an insufficient level of excitation energy, among many others. It is notable that by looking at the frequency list of three listed orders (observable in section B), it can be seen that the value of all three modal frequencies remains close without witnessing surprising change in any of them which can be an indication of identifying correct modes.

After performing regression and correlation analyses on the first three modes derived from modal analysis and evaluating how they relate to variations in environmental factors, it was found that there is no meaningful relation between these environmental factors and the first three modal frequencies. For instance, by looking into Table 3.1 in this thesis, it can be seen that the effect of ambient factors (temperature, wind speed, humidity) on the first three modes based on the correlation values, is less than 0.1 in (whether positive or negative effect) which is in fact a weak correlation rate. In addition, according to the regression study, the high p-values and coefficients near zero across all three frequencies demonstrate that environmental elements like temperature, humidity, and wind speed have no statistical impact on a structure's modal frequencies on the chosen dataset (12-14/11/2023). For instance, the effect of wind speed on third order natural frequency has a coefficient of 0.0037 and a p-value of 0.302, indicates a very little and statistically unimportant effect. Another example is that temperature variations are linked to almost zero changes in frequencies (coefficients of -0.0005 for First order natural frequency and -0.0029 for third order natural frequency). This tendency remains true for other parameters as well. These results suggest that other factors could be more important in determining these frequencies, potentially even fundamental structural features like material stiffness or damping qualities. The modal frequencies are probably more sensitive to the fundamental properties and physical layout of the structure than they are to the external environmental factors under investigation, as indicated by the absence of significant connection in this research. However, it is crucial to recognize that, there was not a weather monitoring station on-site, therefore, the weather station data from nearest weather station located in Sandnessjøen (approximately 16 km distance) was used. This geographical variance could be responsible for variations between the recorded data and the actual circumstances at the bridge site, which might be another explanation

of the apparent lack of relationship between the environmental factors and the modal frequencies.

On the other hand, Table 3.5 shows that environmental influences seem to have a greater impact on the MAC values for mode order 1 and mode order 3 than on the modal frequencies. However, this effect is still insufficient to make it safe to draw firm judgments. The patterns in MAC values are typically similar to the observations obtained regarding the modal frequencies and their link with environmental variables.

The FE model updating process is the main emphasis of this thesis, which showed encouraging outcomes. The fitness function trend showed a consistent decrease in the fitness value (from above 0.0505 to 0.012 in 100 iterations) during the update process, indicating the differences between the modal sequences chosen for the initial and experimental models. This trend is shown in Figure 3.4-a. The optimization method reached the best solution at about iteration 10, indicating a high degree of convergence accuracy for this technique. The model's dependence on Young's modulus, as previously examined, is responsible for the notable increase of 810,209,404 Pa in Young's modulus, which occurred within the parameter values' ranges. Other parameters also showed some change throughout the optimization process, although these were less severe than those in Young's Modulus and they happened in a negative direction(They saw a decline in the gap between the original model and the behavior of the real world, which is why the direction was negative).

## 5 Conclusion and Future work

The first section of the chapter tries to pinpoint which of the thesis's objectives were met. It also includes the summary of the important results. The second section of this chapter focuses on how the results of this thesis can be further developed and introduce additional opportunities within the scope of this study.

### 5.1 Concluding remarks

**Remark 5.1** The operational modal analysis was conducted on the vibration dataset (12-14/11/2023) from Herøysund Bridge. Among all the techniques of OMA, SSI-UPCX was used in this thesis. Using this method, it was possible to identify first three modal parameters that closely validate shell-based FE model developed in the master thesis of Zeeshan [2].

**Remark 5.2** Linear regression and Pearson correlation techniques which were used to find a potential relation between environmental factors(temperature, wind speed and humidity) and extracted modal parameters. As already mentioned in remark 5.1, the dataset used was only for three days, so using the method mentioned, no meaningful correlation was identified as there was not significant variation in the environmental factors.

**Remark 5.3** Shell-based FE model was developed in Ansys software. Response Surface tool was employed to assess the sensitivity of this FE model to the parameters selected for updating(Young's modulus, Poisson's ratio and Density).

**Remark 5.4** Genetic algorithm developed in Matlab was used for FE model updating. The Matlab script was linked to Response Surface tool of Ansys software. Linking of the algorithm with the tool was carried out using journal file. This link was used for updating the values of selected modal frequencies with respect to the value of sensitive parameters in initial FE model. Modal frequencies acquired is used to calculate fitness values. The convergence happened after a few iterations and optimal solution was found for the sensitive parameters.

## 5.2 Future work

- As previously described in this thesis, vibration data used in this thesis was only from a subset of sensors, which only were monitoring part of the bridge. As a future work, data from the complete grid of sensors installed over entire bridge can be used to develop a global FE model updating of Herøysund Bridge.
- In this master thesis, FE model updating was carried out without an in-depth parameter sensitivity analysis. This parameter sensitivity analysis can be carried out as separate master thesis.
- The process of updating the FE model is an interesting task that may be used as a fundamental problem to enable the use of different optimization techniques such as neural networks and particle swarm optimization. It would then be possible to assess each algorithm's performance and make comparisons in order to identify the best algorithm for this use.
- In this master thesis, with the used dataset it was not possible to find correlation between environmental factors and modal parameters obtained from operational modal analysis. A possible reason behind not finding correlation might be the fact that the dataset used was covering short monitoring time and there was not much variation in the environmental factors. Working with a dataset from the entire campaign will form a basis of a new master thesis with the aim of finding correlation.
- The process of FE model updating can be also extended to update other models of the bridge in the future such as beam model or solid model.



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## A Experiment for selecting sensitive parameters

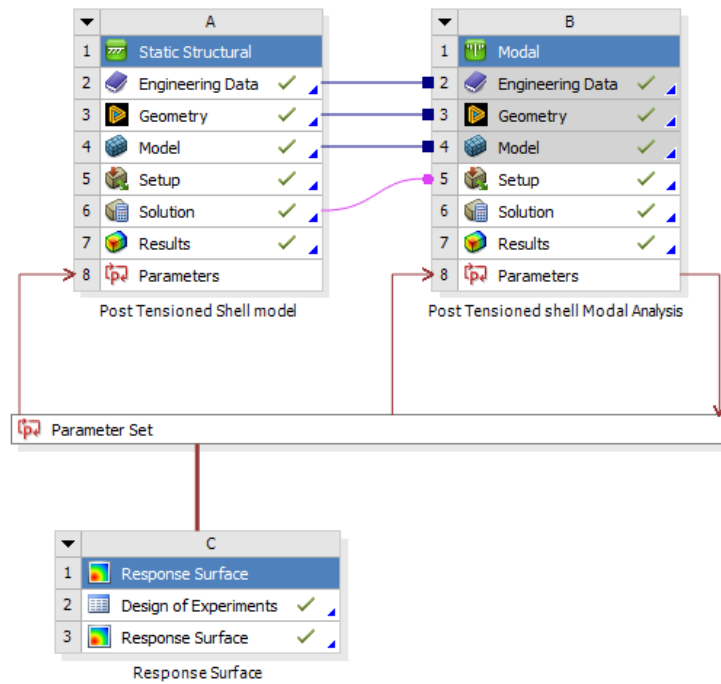


Figure A.1: Schematic of the ANSYS project for setting up sensitivity analysis

It is depicted in the Figure A.1 that Response surface tool is added to the Ansys project containing Shell-based finite element model of the bridge made by Zeeshan Azad [2]. The inputs(Young's Modulus, Poisson's Ratio and Density) and output parameters(Selected modal frequencies from initial FE model) which were selected in this project can be seen in Figure A.2. This configuration, can lead to performing an experiment by Response surface tool to evaluate the effect of inputs on outputs by assigning values to inputs. In Figure A.3, different scenarios chosen for performing the experiment in Response surface tool are illustrated.

Outline of All Parameters				
	A	B	C	D
1	ID	Parameter Name	Value	Unit
2	[-] Input Parameters			
3	[-] Post Tensioned Shell model (A1)			
4	P9	Young's Modulus	1,936E+10	Pa
5	P10	Poisson's Ratio	0,1414	
6	P13	Density	2392	kg m <sup>-3</sup>
*	New input parameter	New name	New expression	
8	[+] Output Parameters			
9	[+] Post Tensioned shell Modal Analysis (B1)			
10	P14	Total Deformation 2 Reported Frequency	1,5415	Hz
11	P15	Total Deformation 4 Reported Frequency	2,5613	Hz
*	New output parameter		New expression	
13	Charts			

Figure A.2: Parameter settings utilized in the thesis

Table of Schematic C2: Design of Experiments (Central Composite Design - Auto Defined)						
	A	B	C	D	E	F
1	Name	P9 - Young's Modulus (Pa)	P10 - Poisson's Ratio	P13 - Density (kg m <sup>-3</sup> )	P14 - Total Deformation 2 Reported Frequency (Hz)	P15 - Total Deformation 4 Reported Frequency (Hz)
2	1 DP 15	1,936E+10	0,1414	2392	1,5415	2,5613
3	2	1,642E+10	0,1414	2392	1,4186	2,2473
4	3 DP 58	2,2296E+10	0,1414	2392	1,6553	2,7885
5	4 DP 29	1,936E+10	0,12726	2392	1,5421	2,562
6	5 DP 43	1,936E+10	0,15554	2392	1,5409	2,5607
7	6	1,936E+10	0,1414	2152,8	1,6251	2,704
8	7	1,936E+10	0,1414	2631,2	1,4696	2,4384
9	8 DP 49	1,6973E+10	0,1299	2197,5	1,5055	2,4964
10	9	2,1747E+10	0,1299	2197,5	1,7061	2,8443
11	10 DP 47	1,6973E+10	0,1529	2197,5	1,5045	2,4954
12	11	2,1747E+10	0,1529	2197,5	1,705	2,8432
13	12 DP 50	1,6973E+10	0,1299	2586,5	1,3874	2,2944
14	13	2,1747E+10	0,1299	2586,5	1,5724	2,616
15	14	1,6973E+10	0,1529	2586,5	1,3865	2,2935
16	15 DP 57	2,1747E+10	0,1529	2586,5	1,5713	2,615

Figure A.3: Design points used for experiment in Response Surface

The points which were chosen during the experiment in response surface in Figure A.3, are in fact a try to understand how the outputs are affected by different values of the inputs. Once all the outputs are measured, for all the outputs, the Response surface is able to evaluate the effect of each input on the outputs, also to predict the value of the outputs with respect to any desired input.

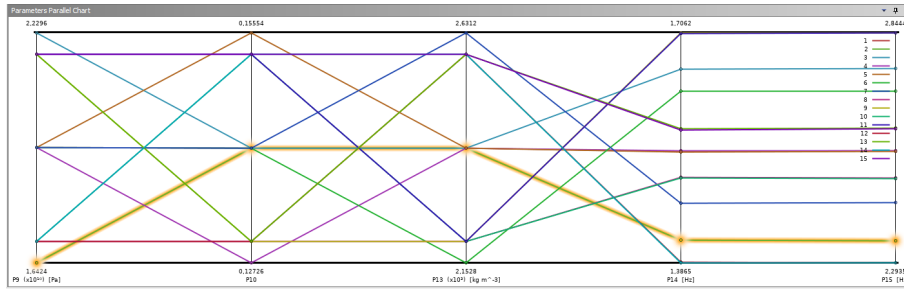


Figure A.4: Parameter parallel chart of input and output parameters

Parameter parallel chart is a valuable tool for multidimensional analysis and optimization which shows the influence of multiple parameters across different scenarios in a single view. It shows how different values of each input were chosen in the form of a trajectory and a pathway toward the values of outputs. Even, the marginal values of each input ,shown on the x-axis of the chart ,were chosen which were used as upper and lower limits in this thesis.

## B First three modal frequencies

The table in this section contains first three modal frequencies extracted by the process of modal analysis of all 144 chunk of data analysed in this thesis.

Table B.1: Natural frequency data of first three mode orders

Timestamp	1th order[HZ]	2th order[HZ]	3th order[HZ]
2023-11-12 00:00:00	1.72359	NaN	3.4716
2023-11-12 00:30:00	1.70901	NaN	3.46079
2023-11-12 01:00:00	1.70992	2.35984	3.4991
2023-11-12 01:30:00	1.67506	2.31672	3.39545
2023-11-12 02:00:00	1.72631	2.36642	3.51424
2023-11-12 02:30:00	1.72901	NaN	3.48076
2023-11-12 03:00:00	1.70134	2.39168	3.56304
2023-11-12 03:30:00	1.72445	2.35498	3.48117
2023-11-12 04:00:00	1.69339	NaN	3.47075
2023-11-12 04:30:00	1.74055	NaN	3.51537
2023-11-12 05:00:00	1.71965	NaN	3.50597
2023-11-12 05:30:00	1.71614	NaN	3.45593
2023-11-12 06:00:00	1.73244	NaN	3.51711
2023-11-12 06:30:00	1.71231	NaN	3.4701
2023-11-12 07:00:00	1.75904	2.36747	3.50281
2023-11-12 07:30:00	1.67438	NaN	3.47966
2023-11-12 08:00:00	1.73418	2.39384	3.47202
2023-11-12 08:30:00	1.71695	NaN	3.63046
2023-11-12 09:00:00	1.73252	2.37688	3.49883
2023-11-12 09:30:00	1.7197	2.33913	3.45845
2023-11-12 10:00:00	1.76796	2.35731	3.5018
2023-11-12 10:30:00	1.68257	2.33477	3.4603
2023-11-12 11:00:00	1.72679	2.36235	3.49596
2023-11-12 11:30:00	1.66674	2.32922	3.45233
2023-11-12 12:00:00	1.71119	2.3525	3.48109
2023-11-12 12:30:00	1.75375	2.33697	3.46795
2023-11-12 13:00:00	1.68843	2.3661	3.48456
2023-11-12 13:30:00	1.68219	2.34295	3.47347
2023-11-12 14:00:00	1.71173	2.34868	3.49015
2023-11-12 14:30:00	1.71373	2.34463	3.47527
2023-11-12 15:00:00	1.72549	2.36585	3.49964
2023-11-12 15:30:00	1.73967	2.32315	3.48563
2023-11-12 16:00:00	1.70535	NaN	3.38653
2023-11-12 16:30:00	1.68694	NaN	3.46214
2023-11-12 17:00:00	1.71293	2.33282	3.4817
2023-11-12 17:30:00	1.6982	2.34498	3.46418
2023-11-12 18:00:00	1.72647	2.33801	3.49778

Continued on next page

Table B.1 – continued from previous page

Timestamp	Frequency_1	Frequency_2	Frequency_3
2023-11-12 18:30:00	1.65572	NaN	3.41479
2023-11-12 19:00:00	1.71413	2.3718	3.50052
2023-11-12 19:30:00	1.71002	2.343	3.45766
2023-11-12 20:00:00	1.71488	2.37016	3.49135
2023-11-12 20:30:00	1.70079	2.34609	3.46666
2023-11-12 21:00:00	1.71281	NaN	3.5025
2023-11-12 21:30:00	1.68765	2.31315	3.4863
2023-11-12 22:00:00	1.70023	2.33999	3.47344
2023-11-12 22:30:00	1.69476	2.35137	3.46358
2023-11-12 23:00:00	1.73194	2.39409	3.49402
2023-11-12 23:30:00	1.74985	2.35834	3.50452
2023-11-13 00:00:00	1.75663	2.39923	3.52665
2023-11-13 00:30:00	1.75385	2.32911	3.51753
2023-11-13 01:00:00	1.7651	2.35124	3.546
2023-11-13 01:30:00	1.75446	2.35317	3.51902
2023-11-13 02:00:00	1.72795	2.35835	3.48008
2023-11-13 02:30:00	1.72743	2.35977	3.47689
2023-11-13 03:00:00	1.75621	2.41123	3.53439
2023-11-13 03:30:00	1.72169	2.18391	3.47118
2023-11-13 04:00:00	1.73608	2.40112	3.51335
2023-11-13 04:30:00	1.69905	2.35269	3.48067
2023-11-13 05:00:00	1.73543	2.38685	3.4884
2023-11-13 05:30:00	1.70499	2.37008	3.49
2023-11-13 06:00:00	1.70866	2.37553	3.51247
2023-11-13 06:30:00	1.70098	2.30225	3.46172
2023-11-13 07:00:00	1.69964	2.30289	3.48364
2023-11-13 07:30:00	1.68065	2.35676	3.46532
2023-11-13 08:00:00	1.69435	2.39305	3.46571
2023-11-13 08:30:00	1.6542	2.33979	3.46333
2023-11-13 09:00:00	1.73249	2.35428	3.45968
2023-11-13 09:30:00	1.67172	2.3269	3.43965
2023-11-13 10:00:00	1.69892	2.3994	3.45764
2023-11-13 10:30:00	1.72568	2.35225	3.43663
2023-11-13 11:00:00	1.71934	2.39399	3.46895
2023-11-13 11:30:00	1.62725	NaN	3.45057
2023-11-13 12:00:00	1.6949	2.44008	3.48331
2023-11-13 12:30:00	1.72125	NaN	3.41333
2023-11-13 13:00:00	1.68421	2.35925	3.45041
2023-11-13 13:30:00	1.73572	2.37431	3.5174
2023-11-13 14:00:00	1.72614	2.32658	3.48915
2023-11-13 14:30:00	1.64585	2.32349	3.4376
2023-11-13 15:00:00	1.6842	2.36579	3.44806
2023-11-13 15:30:00	1.70968	2.33251	3.50437

Continued on next page



Table B.1 – continued from previous page

Timestamp	Frequency_1	Frequency_2	Frequency_3
2023-11-13 16:00:00	1.69748	2.36453	3.48685
2023-11-13 16:30:00	1.73519	2.36055	3.49232
2023-11-13 17:00:00	1.67959	2.34082	3.44457
2023-11-13 17:30:00	1.7076	NaN	3.49335
2023-11-13 18:00:00	1.70367	2.38833	3.45369
2023-11-13 18:30:00	1.73374	2.38318	3.50906
2023-11-13 19:00:00	1.69442	NaN	3.43112
2023-11-13 19:30:00	1.75075	2.3452	3.48754
2023-11-13 20:00:00	1.73098	2.37162	3.46668
2023-11-13 20:30:00	1.71168	2.36235	3.44393
2023-11-13 21:00:00	1.64217	2.66703	3.45795
2023-11-13 21:30:00	1.72001	2.0717	3.53167
2023-11-13 22:00:00	1.71433	2.44439	3.44561
2023-11-13 22:30:00	1.69237	NaN	3.4897
2023-11-13 23:00:00	1.74097	NaN	3.48373
2023-11-13 23:30:00	1.69998	2.34295	3.49572
2023-11-14 00:00:00	1.72491	NaN	3.45012
2023-11-14 00:30:00	1.75768	2.38592	3.52374
2023-11-14 01:00:00	1.76979	2.36057	3.55514
2023-11-14 01:30:00	1.70819	NaN	3.53975
2023-11-14 02:00:00	1.75837	NaN	3.52646
2023-11-14 02:30:00	1.76136	2.35465	3.53237
2023-11-14 03:00:00	1.77996	2.35262	3.5623
2023-11-14 03:30:00	1.75751	2.39972	3.36458
2023-11-14 04:00:00	1.74512	2.37154	3.53007
2023-11-14 04:30:00	1.72252	NaN	3.46887
2023-11-14 05:00:00	1.74723	2.04247	3.53148
2023-11-14 05:30:00	1.72206	2.39904	3.48847
2023-11-14 06:00:00	1.70659	2.41444	3.52627
2023-11-14 06:30:00	1.66275	2.35196	3.48558
2023-11-14 07:00:00	1.74652	2.37744	3.5021
2023-11-14 07:30:00	1.65338	2.15469	3.49307
2023-11-14 08:00:00	1.70399	2.37546	3.48126
2023-11-14 08:30:00	1.67121	2.33773	3.43296
2023-11-14 09:00:00	1.78181	2.35214	3.49951
2023-11-14 09:30:00	1.66392	NaN	3.44625
2023-11-14 10:00:00	1.67659	2.3323	3.33164
2023-11-14 10:30:00	1.67746	2.36099	3.41045
2023-11-14 11:00:00	1.70888	NaN	3.55264
2023-11-14 11:30:00	1.70323	2.4005	3.45138
2023-11-14 12:00:00	1.73497	NaN	3.49885
2023-11-14 12:30:00	1.7322	2.35101	3.47258
2023-11-14 13:00:00	1.69943	2.37399	3.34329

Continued on next page

Table B.1 – continued from previous page

Timestamp	Frequency_1	Frequency_2	Frequency_3
2023-11-14 13:30:00	1.7104	2.35661	3.48251
2023-11-14 14:00:00	1.70196	2.35481	3.51838
2023-11-14 14:30:00	1.66695	2.38075	3.51623
2023-11-14 15:00:00	1.67796	2.35111	3.48639
2023-11-14 15:30:00	1.68189	2.35396	3.47748
2023-11-14 16:00:00	1.70839	2.40801	3.51901
2023-11-14 16:30:00	1.66052	2.34335	3.49154
2023-11-14 17:00:00	1.71787	2.36387	3.50647
2023-11-14 17:30:00	1.70917	2.38771	3.49791
2023-11-14 18:00:00	1.73147	2.40843	3.53218
2023-11-14 18:30:00	1.65421	2.36468	3.49867
2023-11-14 19:00:00	1.70789	2.41648	3.4641
2023-11-14 19:30:00	1.74326	NaN	3.50672
2023-11-14 20:00:00	1.78867	2.45251	3.53105
2023-11-14 20:30:00	1.73512	NaN	3.50875
2023-11-14 21:00:00	1.73875	NaN	3.55141
2023-11-14 21:30:00	1.65444	2.27181	3.4905
2023-11-14 22:00:00	1.70689	NaN	3.60929
2023-11-14 22:30:00	1.72252	2.35911	3.5138
2023-11-14 23:00:00	1.74174	NaN	3.57497
2023-11-14 23:30:00	1.62196	NaN	3.27746

## C Further information of modal analysis process

Figures C.1, C.2 depict two steps of process of modal analysis in Artemis software. The first one shows The geometry which has been used in this thesis without placing the sensors in their location on the bridge. The second one show the modal analysis process for one chunk of data, when it is completed, and the SVD diagram is generated. In this step, it is possible to claim for generating the respective Stabilization Diagram.

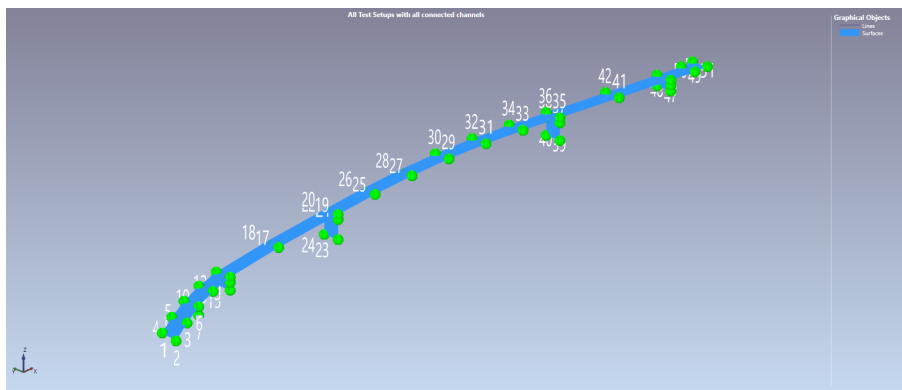


Figure C.1: The geometry used for Modal Analysis before adding sensors

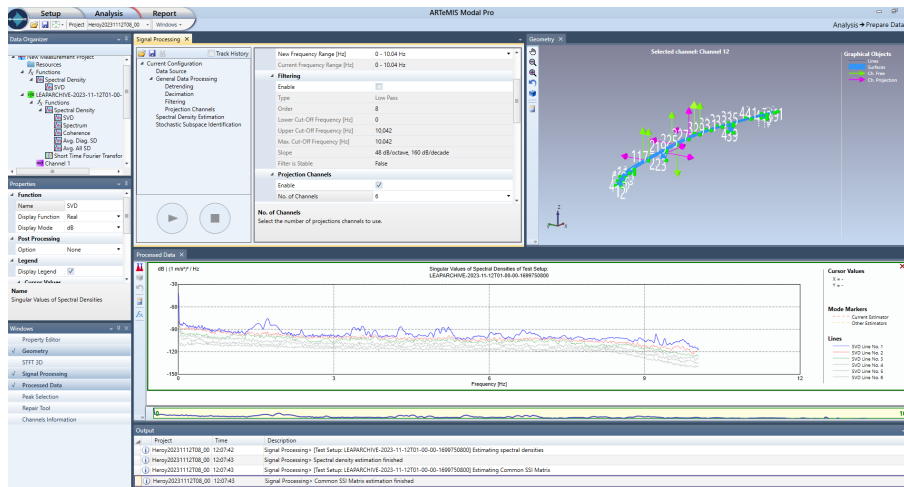


Figure C.2: Artemis modal after completion of modal analysis

## D Modal analysis on the 2-hours dataset

The Figure D.1 depicts stabilization diagram of the period 09:00 to 11:00 13.11.2023 which was acquired during modal analysis by Artemis software. This period is the result of combining 4 chunks of vibration data. The Idea behind doing the modal analysis came from the fact that 30 minutes dataset of bridge's monitoring which was used for modal analysis in this thesis, contain noises in their stabilization diagrams when using SSI-UPCX, Hence, It was decided to see the performance of modal analysis on a longer period of monitoring by combining some of 30 minutes chunks. However, the result is almost the same as the result with modal analysis using 30 minutes dataset.

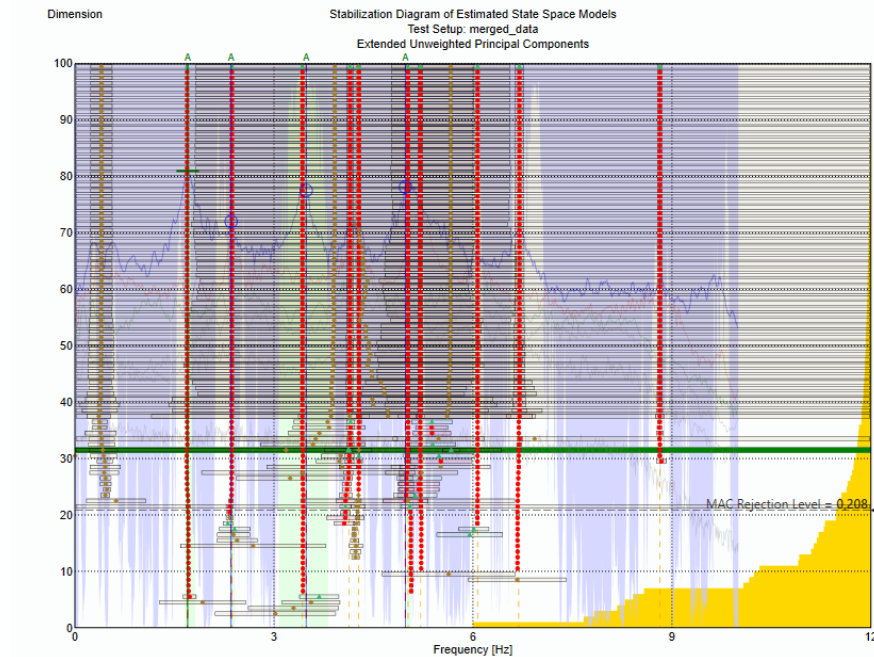


Figure D.1: Stabilization diagram of the identified modes from 9-11 AM 13.11.2023

## E Implemented fitness function in Matlab

The following fitness function receive candidate parameters which are selected to be updated in the process of optimization, and it calculates the fitness value based on the value of initial FE model first and second modal frequencies and measured model first and second modal frequencies selected after modal analysis. In this function, new candidate are sent to the another function called UpdatingFrequency to interact with Ansys software and calculate the value of selected frequencies for updating in the initial FE model based on the value of candidates sent to the software. Finally, when the value of those selected frequencies are returned, the fitness values for the whole candidates are calculated by the fitness function.

```
1 function fitnessArray = Fitness(population)
2
3     experimentalFreqs = [1.64217, 2.66703]; % Replace selected
4     mode natural frequeuncies from the initial FE Model.
5
6     originalFreqs = UpdatingFrequency(population); % linking to the
7     third file of optimization algorithm
8     originalFreqs(5,4);
9
10    m = length(originalFreqs); % Number of mode shapes
11    E = zeros(m , 1);
12
13    % Calculating fitness vaele of the population for the current
14    population
15
16    for j = 1:m
17        sumErrors = 0; % Initialize sum of errors for each row
18        for i = 1:length(experimentalFreqs)
19            errorRatio = abs((originalFreqs(j, i) -
20            experimentalFreqs(i)) / experimentalFreqs(i));
21            sumErrors = sumErrors + errorRatio;
22        end
23        E(j) = sumErrors / length(experimentalFreqs); % Normalize
24        by the number of experimental frequencies
25    end
26
27    fitnessArray = E;
28
29 end
```

Listing 1: Matlab Script of Fitness Function

## F Sample journal file used for automation of optimization process

The script below is a sample journal file which can be loaded in the project of Shell-based finite element model every time is needed to calculate fitness value of the candidate parameters for updating from a model in Ansys software. This journal file takes inputs and calculate the outputs in the Ansys project containing the initial FE model. As it can be seen in the script below, it takes P9,P10 and P13 as inputs, representing Young's modulus, Poisson's ratio and Density , and at the end, a table including outputs is saved in an excel File.

```
1 # encoding: utf-8
2 # 2023 R1
3 SetScriptVersion(Version="23.1.153")
4 Open(FilePath="D:/Reza- Do not Delete/Shell_Model_Analysis/
5 Shelllatest-final/exportlatest.wbpj")
6 Extensions.UnloadExtension(
7     Id="5e7e01a6-8601-11e8-9f8c-28f10e13ffe6",
8     Version="2022.2",
9     Format="Binary")
10 Extensions.UnloadExtension(
11     Id="5f463412-bd3e-484b-87e7-cbc0a665e474",
12     Version="2023.1",
13     Format="Binary")
14 Extensions.UnloadExtension(
15     Id="20180725-3f81-49eb-9f31-41364844c769",
16     Version="2023.1",
17     Format="Binary")
18 Extensions.UnloadExtension(
19     Id="f3e3da52-fb02-4910-8cc9-980efd047bc6",
20     Version="2023.1",
21     Format="Binary")
22 Extensions.UnloadExtension(
23     Id="6ef906f8-8529-4043-bfde-06577efdf7c8",
24     Version="2023.1",
25     Format="Binary")
26 Extensions.UnloadExtension(
27     Id="45058e82-7f3c-4daf-9e58-937467e63ee3",
28     Version="2023.1",
29     Format="Binary")
30 system1 = GetSystem(Name="RSR")
31 responseSurface1 = system1.GetContainer(ComponentName="Response
32 Surface")
33 responseSurfaceModel1 = responseSurface1.GetModel()
34 inputParameter1 = responseSurfaceModel1.GetParameter(Name="P9")
35 responsePoint1 = responseSurfaceModel1.CreateResponsePoint(
36     ParameterValues={inputParameter1: "20170204904.495529 [Pa]"}
37 inputParameter2 = responseSurfaceModel1.GetParameter(Name="P10")
38 responsePoint1.SetParameter(Parameter=inputParameter2, Expression
39     ="1.333685e-01")
40 inputParameter3 = responseSurfaceModel1.GetParameter(Name="P13")
41 responsePoint1.SetParameter(Parameter=inputParameter3, Expression
42     ="2.316785e+03")
```

```
40 inputParameter4 = responseSurfaceModel1.GetParameter(Name="P9")
41 responsePoint2 = responseSurfaceModel1.CreateResponsePoint(
    ParameterValues={inputParameter4: "20170204904.495529 [Pa]"})
42 inputParameter5 = responseSurfaceModel1.GetParameter(Name="P10")
43 responsePoint2.SetParameter(Parameter=inputParameter5, Expression
    ="1.333685e-01")
44 inputParameter6 = responseSurfaceModel1.GetParameter(Name="P13")
45 responsePoint2.SetParameter(Parameter=inputParameter6, Expression
    ="2.316785e+03")
46
47
48
49 parametricTable1 = responseSurfaceModel1.GetParametricTable(Name="
    ResponsePoints")
50 parametricTable1.ExportData(FileName="D:/Reza- Do not Delete/
    Shell_Model_Analysis/Shelllatest-final/mydata.csv")
```

Listing 2: Sample journal file for automation

