Structural Health Monitoring of Composite Overwrapped Pressure Vessels

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STRUCTURAL HEALTH MONITORING OF COMPOSITE OVERWRAPPED PRESSURE VESSELS

by

LUCA LETIZIA

A thesis submitted in partial fulfillment of the requirements for the Honors in the Major Program in Civil Engineering in the College of Engineering and Computer Sciences and in The Burnett Honors College at the University of Central Florida Orlando, Florida

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Thesis Chair: Dr. Necati Catbas
ABSTRACT

This work is focusing to study the structural behavior of Composite Overwrapped Pressure Vessels (COPVs). These COPVs are found in many engineering applications. In the aerospace field, they are installed onto spaceships and aid the reorientation of the spacecraft in very far and airless, therefore frictionless, orbits to save energy and fuel. The intent of this research is to analyze the difference in performance of both perfectly intact and purposely damaged tanks. Understanding both the source and location of a structural fault will help NASA engineers predict the performance of COPVs subject to similar conditions, which could prevent failures of important missions. The structural behavior of six tanks is investigated by means of experimental modal analysis. Knowledge of statistical signal processing methods allows to sort out and extract meaningful features from the data as to gain understanding of the performance of the structures. Structural identification is carried out using Narrow Band and Broad Band algorithms. A comparison through correlation tables and figures presents the differences in natural frequencies, mode shapes and damping ratios of all structures. A careful analysis displays the deviation of these modal parameters in the damaged tanks, highlighting the evident structural defects.
ACKNOWLEDGEMENTS

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CHAPTER 1: INTRODUCTION

1.1 Structural Health Monitoring (SHM)

Structural health monitoring (SHM) is the process of implementing a damage identification strategy for aerospace, civil or mechanical infrastructures. It is in everybody’s interest to locate damage introduced in infrastructures we interact with and then assess the severity of this damage in order to have a sound decision-making process on how to address this damage. On these terms, a parallel between structural engineers and doctors can be established. Both employ sensing devices such as accelerometers and strain gages or thermometers and sphygmomanometer to better understand the condition of their patients, stadiums and bridges for the former, and human beings for the latter. Through SHM, non-biased decisions concerning operation, serviceability, safety and reliability of infrastructure is made possible.

Modal analysis in SHM comes in two categories: operational modal analysis (OMA) and experimental modal analysis (EMA). OMA uses response measurements only of structures in operational conditions under ambient or natural excitation to determine modal characteristics. EMA is the process of acquiring data and identifying modal parameters through curve fitting techniques. This is performed by making use of not only input, as excitation, but also output, as response, to identify the structural parameters of the infrastructure under investigation. The study of this thesis uses the EMA approach.
1.2 SHM Applications

The first applications of SHM are traced back to the oil industry around the 1970s. The development of vibration-based damage identification methods for offshore platforms was of appealing interest at the time. Common methodologies adopted by this industry focused on simulating damage scenarios with numerical models, to then examine the changes in resonant frequencies produced by these simulated changes. Numerous practical problems were introduced in the systems under investigation, and SHM’s focus shifted to the aerospace industry in the 1980s with forefront projects of the National Aeronautics and Space Administration (NASA). Around the same time, SHM was introduced in the civil engineering community for the study of vibration-based damage assessment of bridge structures and buildings (Farrar and Worden 2007). Currently, SHM branches out to all areas of engineering, being the most interdisciplinary it has ever been.

1.3 Objective and Scope

The overall objectives of this study are to:

1. Understand the dynamic behavior of composite overwrapped pressure vessels (COPVs)

2. Compare the differences in various types of damage induced tanks

3. Explore the effects of different induced damages on COPVs

The overall scopes of this study are to:

1. Conduct laboratory testing of COPVs using the modal impact hammer test
2. Perform structural identification using Narrow-band and Broad-band algorithms

3. Present the results using correlation tables, figures, and plots

1.4 Organization of the Thesis

The organization of the thesis is structured as follows:

- **Chapter 2: Composite Overwrapped Pressure Vessels (COPVs) and Related SHM Applications** – This chapter is introductory to the different types of pressurized vessels. A greater focus is provided for COPVs, their structural properties, their failure modes, and NASA’s employment in spacecrafts.

- **Chapter 3: Data Analysis Techniques** – This chapter serves as a review of the theory involved in the analysis of the data post data collection. Explanation of multiple and single degree of freedom systems, frequency response functions, complex mode indicator functions, and quality checks for the assessment of good results such as animation of mode shapes and modal assurance criterion are covered in depth.

- **Chapter 4: Laboratory Testing of COPVs** – This chapter describes the experimental setup organized to collect data on NASA’s COPVs in the Structures Laboratory at the University of Central Florida. Detailed information regarding tanks’ arrangement, multiple-input and multiple-output test technique, and the monitoring system’s specifications are discussed.
• Chapter 5: Results and Interpretation – This chapter offers an organized look at the obtained results. Structural dynamic parameters of every tank are identified, and mode shapes are modeled. A meaningful comparison of the structural differences from tank to tank is carried out and discussed.

• Chapter 6: Summary, Conclusions, and Recommendations for Future Work – This chapter wraps up the thesis with a concise summary of its findings and the conclusions that are carried out from the results. Lastly, recommendations for future studies are provided to aid future researchers through the obstacles and the decision making process undergone in this study.
CHAPTER 2: COMPOSITE OVERWRAPPED PRESSURE VESSELS (COPVS) AND RELATED SHM APPLICATIONS

The use of pressurized fluids in today’s world extends to all branches of engineering, and to many other areas as well. Applications range from the most trivial ones such as heating systems in today’s homes, to more technical NASA projects on board of the Space Shuttle Orbiters. In the design and selection of the most adequate system to contain a fluid under pressure, there are three main factors to consider (McLaughlan et al. 2011):

- The amount of energy the system needs to store,
- The total volume of storage required,
- The weight of the storage system, which plays a, if not the, fundamental role in the selection of the vessel used for containment. In fact, the largest cost to address in the selection of the most adequate pressure vessel system for a project is the cost tied to its storage capabilities.

When faced with the selection of a pressurized vessel system, there are two main categories to choose from. The fundamental difference in the deployment of pressurized vessels lays in the selection of either composite or metal vessels. There are three main differences between these two systems:

1. Composites of carbon, Kevlar®, and glass experience a reduction in burst strength due to surface impact, where composites experience it more than the other two.
Metallic and Kevlar® overwrapped vessels have greater structural strength due to minor surface damage.

2. Differently from all-metal vessels, composites are subject to stress rupture or static fatigue, where the composite, under operating pressure, may fail as a function of time.

3. Some quantitative nondestructive (ND) testing methods adopted for metallic structures are not applicable to COPVs.

Both types of vessels offer unique advantages. Although it is possible to find both kinds of tanks with a large burst pressure safety factor range, as well as over high efficiency ranges, from a general standpoint, COPVs are significantly lighter than all-metal tanks, by approximately a factor of two (McLaughlan et al. 2011). This spikes COPVs’ efficiency, defined as the ratio of product capacity to weight of tanks, to double the metallics’ one. The increase in weight, however, provides for a simpler, more reliable design at a lower manufacturing cost. With the advancement of knowledge in the materials’ science field, projects in the last decade have introduced the use of more structurally complex pressure vessels, which differ one from another based on the technical demand of each projects’ needs. The inherent structural complexity of COPVs over metal tanks introduces a more exotic variety of failure modes that must be accounted for in a COPV design. Hence, factors of safety are analyzed differently in both vessel categories. A more in depth description of the main failure modes of COPVs is discussed in the next section. Figure 2 below displays the two types of pressure vessels:
As this research focuses on the structural behavior of COPVs specifically, a more in depth analysis on these kinds of vessels is carried out in the following section.

2.1 Composite Overwrapped Pressure Vessel (COPV)

In composite overwrapped pressure vessels, the word composite stands to identify the combination of a matrix of continuous fibers and a resin that come together to make the overwrapped structure for a COPV. The metallic liner made up of rubber, plastic, or ductile materials such as soft aluminum or higher-strength steel is found in COPVs as a fluid permeation barrier. Its function is to conserve as much as possible leak rates and fluid purity, adding little to no structural integrity to the whole system.

The four failure modes of COPVs are:

1. Burst from over-pressurization

2. Fatigue failure of the metallic liner
3. Burst resulting from metallic liner or composite damage

4. Stress rupture of the composite overwrapped

As the first three failure modes are easier to grasp than the fourth one, the following description regarding COPV stress rupture is provided by Dr. Leigh Phoenix of Cornell University (McLaughlan et al. 2011):

“Stress rupture is a sudden failure mode for [COPVs] that can occur at normal operating pressures and temperatures. This failure mode can occur while at stress levels below ultimate strength for [an] extended time. The failure mechanism is complex, not well understood, [and] difficult to accurately predict or detect prior to failure. The location and mechanism of triggering damage causing sudden failure is highly localized, but at a random location. This location and extent of local damage has not been able to be [reliably] detected by current [NDE] techniques prior to catastrophic failure. Pressure, duration of time at pressure, and temperature experienced contribute to the degradation of the fiber and/or the fiber-matrix interface, particularly around accumulations of fiber breaks, and these increase the probability of COPV stress rupture.”

Due to the higher cost to balance the significant reduction in weight and efficiency of these vessels, most of the applications where COPVs are found are where the need for a lighter system sets the control criteria. For instance, on board of its Space Shuttle Orbiters, NASA mounts a total of twenty-four COPVs. Their shape and size vary depending on the use, fluid contained and location on the aircraft. Differently sized vessels can be seen in both spherical and cylindrical shapes in Figure 2.1 below:
2.2 Related Work

Due to the new technology and the latest scientific advancement carried out only over the last decades, there is a very selected volume of work conducted on COPVs. Research projects affiliated with NASA are the most numerous over the web. These mainly focus on identifying the advantages composite vessels have over metal tanks, from both an economic and reliability point of view. The NASA White Sands Test Facility – Jet Propulsion Laboratory evaluated the safe-life of COPVs by carrying out over one hundred test articles of which ten were burst tested to establish the delivered fiber stress (Greene et al. 2007).
Use of fiber sensing techniques has also been employed on COPVs to provide strain profiles over the operating pressure range of the vessels, allowing for a built-in assessment of their structural integrity. Strain along the tank was monitored, revealing induced damage to the structure. This study provides designers with a tool for stress reliability model verification, as well as providing rapid in-situ assessment of the structural integrity of COPVs (Klute et al. 2016).

Lastly, and more relevantly, different SHM techniques have been employed on the same tanks analyzed in this research project for a Master’s thesis in the research group directed by Dr. Catbas a year prior to this study. The objectives of Arturo Modesto’s Master’s study were to investigate the indices related to the performance and/or condition of pressure vessels and explore data analysis methodologies to detect damage, cross-correlation and Auto Regressive model with eXogeneous input (ARX) models, to finally compare the differences in various types of pressure vessels (Modesto 2015).

Nevertheless, structural identification of COPV tanks complete of natural frequencies, damping ratios, and mode shapes is unique for these aspects so far. The steps for the execution of data collection, processing and interpretation of these structural parameters through figures, graphs and animated simulations are therefore covered in the following chapter.
CHAPTER 3: DATA ANALYSIS TECHNIQUES

Data analysis employed in SHM branches out to two main methods: parametric and non-parametric. If a model is fitted to data, the technique is referred to as parametric. On the other hand, if the data is not required to fit a normal distribution, the technique is referred to as non-parametric. Although it is still highly discussed the exact definition of both methods, particularly non-parametric, it is easy to look at the difference being that parametric methods are strictly tied to the system’s parameters, while a non-parametric method is purely statistical and does not care about physical parameters. Nevertheless, parameters may be present in both methods: parametric parameters are directly related to the structure under investigation, like resonant frequencies and damping, while non-parametric parameters are determined by the training data, not the model.

3.1 Structural Dynamics of Single Degree of Freedom (SDOF) System

Practical systems, as thoroughly described in (Packard 1997), are multiple degree of freedom (MDOF) and have some degree on non-linearity, however, they can be simplified by superpositioning several single degree of freedom (SDOF) linear models. Therefore, by understanding each SDOF that combined create the MDOF system under investigation, it is possible to identify its structural dynamic parameters. A SDOF is shown in Figure 3.1 below:
SDOF are comprised of a physical system made up of a mass of mass $m$, a spring of stiffness $k$, and a damper of damping $c$. Energy is stored by the system in the mass and in the spring under kinetic and/or potential form. Energy enters this system through excitation of a force $f$, and exits by dissipation through the damper. All elements play a fundamental role in the following equation of motion:

$$[m] \dddot{x} + [c] \dot{x} + [k] x = f$$  \hspace{1cm} (1)

Where all matrices are 1x1 (scalars). Assuming all initial conditions equal zero, the Laplace transform in $s$ domain is:

$$[s^2[m] + s[c] + [k]]X(s) = F(s)$$  \hspace{1cm} (2)

A new matrix defined as the system impedance matrix or just the system matrix is introduced, and its inverse is defined as the transfer function:

$$[B(s)] = [s^2[m] + s[c] + [k]]^{-1}$$  \hspace{1cm} (3)
\[ [B(s)]^{-1} = [H(s)] \]  
(4)

By doing so, we are able to carry out the following operations:

\[ [B(s)][X(s)] = \{F(s)\} \]  
(5)

\[ [H(s)][F(s)] = \{X(s)\} \]  
(6)

### 3.2 Frequency Response Function (FRF), Transfer Function, and Their Relationship

The transfer function, as seen in the previous equation, defines the relationship between input and output of the system. System response (output) is caused by system excitation (input). The mathematical definition of transfer function is the Laplace transform of the output divided by the Laplace transform of the input. Very similarly, the frequency response function (FRF) is defined mathematically as the Fourier transform of the output divided by the Fourier transform of the input. The frequency response is simply the transfer function measured along the \( j\omega \) axis:

\[ [H(s)]_{s=j\omega} = [H(\omega)] \]  
(7)

FRFs come in various forms, based on the type of response. Each variable such as displacement, velocity and acceleration, when divided by the external force, define admittance (or compliance, or receptance), mobility, and accelerance (or inertance) respectively. Reciprocally, the transfer functions that describe the ratio of force to displacement, to velocity and to acceleration are dynamic stiffness, mechanical impedance, and apparent mass (or dynamic mass) respectively (Irvine 2000). Acceleration is the currently accepted method of measuring modal response.
Accelerance is the transfer function adopted for this case study. An example of collected data is shown in Figure 3.2-1 below:

![Figure 3.2-1: Sample Output Signal (Top) and Input Signal (Bottom)](image)

Dividing the output signal by the input signal and converting the domain from time to frequency, FRFs like the following are constructed:
An enhanced frequency response function (EFRF) is a virtual measurement used to identify the modal frequencies and scaling of a SDOF characteristic that is associated with each peak in the CMIF. The EFRF is developed based upon the concept of physical to modal coordinate transformation and is used to enhance a particular mode of vibration. For a detailed explanation of the formulation behind this function please refer to (Allemang 1998).

### 3.4 Complex Mode Indicator Function (CMIF)

In the process of estimating a system’s parameters, identifying its poles plays a fundamental role in determining the best model order assumption. To achieve this, mode indicator functions (MIFs) are adopted. MIFs are a collection of all FRFs. Through this, it is possible to explore the structural behavior of a system from a global point of view. Depending on how MIFs are constructed, some can be more complicated than others. The type of MIF employed in this
study is the complex mode indicator function (CMIF). It’s a collection of all FRFs collected, obtained by summing the not only the magnitude of all FRFs, but also the absolute value of the imaginary part of the FRFs. With this process, CMIF graphs show peaks at frequencies where global modes are identified, while less important modes are suppressed. A sample CMIF can be seen in Figure 3.4 below:

![Sample CMIF](image)

**Figure 3.4: Sample MIF**

As thoroughly described in (Catbas et al. 2004) and (Phillips et al., 1998), each differently colored line in CMIF plots corresponds to a different singular value decomposition (SVD) line. The number of SVD lines in a CMIF plot is proportional to the number of input points, $N_i$. The SVD of the FRF matrix at a spectral line $\omega_i$ can be computed from the following equation:

$$[H(\omega_i)]_{(N_0 \times N_i)} = [U]_{(N_0 \times N_i)} [S]_{(N_i \times N_i)} [V]^H_{(N_i \times N_i)}$$

(8)

Or in terms of modal expansion, through the use of individual real or complex modes:

$$[H(\omega_i)]_{(N_0 \times N_i)} = [\Psi]_{(N_0 \times 2N)} \left[ \frac{1}{j\omega_i - \lambda_r} \right]_{(2N \times 2N)} [L]^T_{(2N \times N_i)}$$

(9)
The outer left and right singular vector matrices \([U]\) and \([V]\) are unitary matrices, called parametric and participation matrices respectively, while matrix \([S]\) is the singular value matrix, a diagonal matrix with real, non-negative values stored in descending order. For a particular mode, \([\Psi]\) and \([L]\) are constant, allowing the middle matrix to locate peaks at resonant frequencies, as the fraction’s denominator approaches zero in these regions. This occurs when the system pole \(\lambda_r\) and the input frequency \(\omega_i\) are the closest.

The primary mode indicator function curve exhibits a local minimum or maximum at each of the natural frequencies of the system investigated. The secondary mode indicator function curve exhibits a local minimum or maximum at repeated or pseudo-repeated roots of order two or more. Following mode indicator function curves experience local minimum or maximum for successively higher orders of these repeated or pseudo-repeated roots. Repeated modes in a system may appear as uncorrelated to all others, however, these are a repetition of an already identified mode, excited in a perpendicular direction. On the other hand, pseudo-repeated modes seem to display similar repeated behavior, yet are completely different modes. For a correct identification of repeated and pseudo-repeated mode shapes, an accurate analysis of the mode shapes must be performed.

3.5 Modal Model Quality Assessment

After constructing the previously described equations, graphs and plots, some checks are carried out to ensure satisfactory quality of the results. The two checks employed for confirmation of good results are described here.
3.5.1 Visual Animation of the Modes

Modes’ phase should not deviate much from 0° or 180°, being usually nearly real. In fact, if the animated modes show large deviations from real-valued modes, it may be due to a bad fit. As FRF exhibit rapid phase shifts near resonance, a small error in frequency relates directly to a large error in phase. Therefore, animating the modes aids in catching these discrepancies, if the modes were fit for complex shapes. Lastly, singular points displaying an odd movement should be investigated to evaluate if such behavior is due to bad fit as well.

3.5.2 Modal Assurance Criterion (MAC) Matrix

The use of the modal assurance criterion (MAC) matrix provides this powerful tool to measure the correlation coefficient between each mode shape in a set of modes with those of another set. For instance, the MAC value between two modes, labeled “m” and “n” is:

\[
MAC_{mn} = \frac{[\{\psi\}_m^H \{\psi\}_n]^2}{\{\psi\}_m^H \{\psi\}_m \{\psi\}_n^H \{\psi\}_n}
\]

(10)

Where \(H\), once again, stands for the Hermitian transpose, inclusive of complex conjugation. MAC values range from zero to unity, where zero corresponds to no correlation of modes, and unity corresponds to exact modes. Figure XX below shows the correlation of mode shapes identified at different frequencies to one another.
Differing modes, of very low correlation, have a MAC value of zero, while a MAC value of one is obtained by comparing any mode to itself, constructing the typical high unity value on the diagonal and low value elements for uncorrelated modes in the off-diagonal region. Two modes are correlated if their correlation is greater than 0.9 (Farrar and Worden 2007), yet more subjective cases from one research study to another may have different limit boundaries.
CHAPTER 4: LABORATORY TESTING OF COPVS

4.1 Objective and Scope

In order to prevent catastrophic failures associated with any of the four major COPV failure modes, as well as additional ones, a complete understanding of the dynamic behavior of vessels subject to different structural conditions is carried out. Additionally, to perform comparisons regarding the safety factors associated with tanks subject to inadequate structural parts, either local or global, is necessary acquire data from multiple vessels with different structural conditions.

Therefore, the main objectives of this laboratory testing are to:

- Identify the natural frequencies of all six systems
- Identify damping for the natural frequencies
- Create a visual model of the mode shapes in every tank
- Compare the differences in resonant frequencies, damping ratios and mode shapes

Experimental modal analysis is performed on all tanks via impact hammer. Different testing options are investigated to come up with the design of testing most efficient at identifying the dynamic properties of every tank. Use of multiple-input and multiple output (MIMO) method is adopted.
4.2 Test Specimens

All six tanks have the same geometric properties. They are cylindrical with a six-and-a-half-inch diameter and fourteen inches in length. The hemisphere-like caps at both ends of the tanks span two more inches in length and end with a one-inch-tall metal tube as small opening. A drawing of the tanks’ geometry with respective dimensions is shown in Figure 4.2-1 below:

![Figure 4.2-1: Geometry of Tanks](image)

As all six tanks used in this research have been subject to previously published studies, the identifying number marked on every tank is maintained, to prevent confusion in case the reader comes across the other studies. Therefore, as tanks number two, three and eight are not included in this project, the description and the respective associated condition simulated of tanks number one, four, five, six, seven and nine are described in Table 1 below:
Table 1: Description of Tanks

<table>
<thead>
<tr>
<th>Tank Number</th>
<th>Description</th>
<th>Condition Simulated</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No Defects TRH-5005 hoop, helical over-wraps</td>
<td>Comparison- normal manufacturing variances</td>
</tr>
<tr>
<td>4</td>
<td>Zylon Ring midpoint after 2nd hoop wrap</td>
<td>Thermally similar hidden delamination or void</td>
</tr>
<tr>
<td>5</td>
<td>Teflon Tape X after 3rd hoop wrap</td>
<td>Thermally different hidden delamination or void</td>
</tr>
<tr>
<td>6</td>
<td>1 inch cut through hoop fibers at midpoint then covered with helical wrap</td>
<td>Hidden hoop fiber structural break</td>
</tr>
<tr>
<td>7</td>
<td>Zebra pattern 50/50 TRH-50 and zylon</td>
<td>Two materials integrated in helical pattern</td>
</tr>
<tr>
<td>9</td>
<td>5 Hoop wraps zylon covered with TRH-50 carbon helical over-wrap</td>
<td>Hidden zylon hoop with carbon over-wrap</td>
</tr>
</tbody>
</table>

Tanks four and five differ from undamaged tank one by thermally similar or different properties. Tanks six, seven and nine, on the other hand, have completely different structural components. Where in tank six an induced cut simulates a hoop fiber structural break, in tanks seven and nine different overwrapping patterns simulate completely different COPV structures. A picture of all six tanks can additionally be seen below:
4.3 Dynamic Testing

Dynamic testing for collection of a large number of frequency response functions (FRFs) from these mechanical structures is performed in the Structures Laboratory at the University of Central Florida. The choice of dynamic testing is the impact hammer due to several advantages over the shaker. The measurements are fast, without the need of suspending and attaching the shaker to the structure, which is of low mass. This brings up the second advantage the hammer has over the shaker for this particular application being the hammer does not impose extra loading onto the structure. Lastly, the choice of hammer makes it very easy to change the excitation point at every hit, very time-consuming task to constantly set up from scratch with a shaker.
4.3.1 Health Monitoring System

The health monitoring system is comprised of a single PCB Piezotronics triaxial ICP accelerometer, Model 356A32, which is roved at three different locations over the tanks. This can be seen mounted at the bottom of a tank with the special gluing paste provided by the manufacturer in Figure 4.3.1-1 below:

![Triaxial Accelerometer](image)

Figure 4.3.1-1: Triaxial Accelerometer

The accelerometer is repositioned at third points along the circumference of the cylinder at different locations along the length of the vessels, as described in the following Figure 4.3.1-2:
The triaxial accelerometer is connected to a PCB signal conditioner and this to a computer, which through software allows the system to operate at desired conditions, as well as to store the raw data ready for data analysis.

Lastly, the modally tuned impulse hammer from PCB Piezotronics utilized is the model 086C02. The hammer tip selected for this application is (084B03) hard. The stiffness of the hammer tip gives different time length of the impact. The selection of this component is preferred, as by using this hard tip, the energy transfer spans over the largest frequency band allowable, exciting modes at higher frequencies.
4.3.2 Test Procedure

Experimental modal analysis can be performed on a structure in either a suspended under free-free conditions, or simulating the connection that would be found in its operating conditions. The free-free condition has additional benefits over the replicable boundary conditions of the structure under observation. By selecting the free-free condition, it is selecting not only the easiest boundary condition to achieve in a repeatable way, yet it would be possible to study the modes of the structure under observation only, rather than inputting energy from the impact hammer into a system that is not of interest. Additionally, free-free conditions allow the identified structure to be placed in any boundary condition desired, where the difference in stiffness and other parameters can be accounted for.

Inside all tanks runs a metal wire that is connected at the bottom end to a metal bolt, whose scope is to maintain the vessels from falling, and at the upper end to an elastic cord. The metal wire prevents the structure from touching the rubbery bands that would introduce high magnitudes of damping into the system, compromising the true results. The elastic cord is hung from a metal tube that runs perpendicular to the laboratory side wall. A picture of the free-free condition of the system can be seen in Figure 4.3.2-1 below:
The selection of the placement of both sensor and hit locations follows a careful analysis. Multiple options have been tested, and it is concluded that for this study all six tanks are subject to nine hit locations, divided into three equally spaced locations over three equally spaced hoops, as seen in Figure 4.3.2-2. The triaxial sensor is placed at three spots, once per hoop.
After the tank is suspended, the hit locations marked, the sensor installed, and the data acquisition system calibrated, collection of data is initiated.
Three hits are recorded per hit location. By averaging the structure’s response over a greater number of hits, it is possible to reduce the noise introduced in the system. This signal processing technique of signal averaging is applied in the time domain as to increase the strength of a signal relative to noise obscuring it. By direct result, the signal to noise ratio performs better with an always-increasing number of trials.

4.3.3 Collection and Pre-Processing of Data

As data collection completes for all tanks, the data is transferred to another computer, where data processing follows. As just previously mentioned, the three trials per hit location are
merged into a single hit per location. The time domain graphs are converted into frequency domain graphs, creating FRFs for each hit location.

Data processing is continued through the software Modal V5.2 by OROS. Thanks to this software it is possible to further extrapolate meaningful information with the aid of the Narrow-band and Broad-band functions, MAC, and the structure’s mode shapes’ modeling.
CHAPTER 5: RESULTS AND INTERPRETATION

Results for the structural identification part are provided in two portions: initial and final. Initial results display the use of the NarBand and BroBand algorithms through CMIFs and MACs. As NarBand is consistently more efficient than BroBand at identifying the natural frequencies for each tank, the final results section displays the refined results using the NarBand algorithm only. Mode shapes for the revised results are provided with their respective resonant frequencies and damping ratios.
5.1 Initial Identification

5.1.1 Tank 1

Figure 5.1.1: NarBand (Top) and BroBand (Bottom) CMIFs of Tank 1

Figure 5.1.1-2: NarBand (Left) and BroBand (Right) MAC Comparison for Tank 1
5.1.2 Tank 4

Figure 5.1.2-1: NarBand (Top) and BroBand (Bottom) CMIFs of Tank 4

Figure 5.1.2-2: NarBand (Left) and BroBand (Right) MAC Comparison for Tank 4
5.1.3 Tank 5

Figure 5.1.3-1: NarBand (Top) and BroBand (Bottom) CMIFs of Tank 5

Figure 5.1.3-2: NarBand (Left) and BroBand (Right) MAC Comparison for Tank 5
5.1.4 Tank 6

Figure 5.1.4-1: NarBand (Top) and BroBand (Bottom) CMIFs of Tank 6

Figure 5.1.4-2: NarBand (Left) and BroBand (Right) MAC Comparison for Tank 6
5.1.5 Tank 7

Figure 5.1.5-1: NarBand (Top) and BroBand (Bottom) CMIFs of Tank 7

Figure 5.1.5-2: NarBand (Left) and BroBand (Right) MAC Comparison for Tank 7
5.1.6 Tank 9

Figure 5.1.6-1: NarBand (Top) and BroBand (Bottom) CMIFs of Tank 9

Figure 5.1.6-2: NarBand (Left) and BroBand (Right) MAC Comparison for Tank 9
5.2 Final Identification

5.2.1 Tank 1

Figure 5.2.1-1: Tank 1 CMIF

Figure 5.2.1-2: Tank 1 MAC
Mode 1
\( \omega = 886.72 \text{ Hz} \)
\( \zeta = 0.17\% \)

Mode 2
\( \omega = 918.03 \text{ Hz} \)
\( \zeta = 0.26\% \)

Mode 3
\( \omega = 924.71 \text{ Hz} \)
\( \zeta = 0.21\% \)

Mode 4
\( \omega = 975.13 \text{ Hz} \)
\( \zeta = 0.25\% \)

Mode 5
\( \omega = 977.06 \text{ Hz} \)
\( \zeta = 0.25\% \)

Mode 6
\( \omega = 1468.84 \text{ Hz} \)
\( \zeta = 0.30\% \)

Mode 7
\( \omega = 1530.48 \text{ Hz} \)
\( \zeta = 0.32\% \)

Mode 8
\( \omega = 1531.07 \text{ Hz} \)
\( \zeta = 0.40\% \)

Mode 9
\( \omega = 1845.89 \text{ Hz} \)
\( \zeta = 0.73\% \)

Mode 10
\( \omega = 1918.56 \text{ Hz} \)
\( \zeta = 0.59\% \)

Mode 11
\( \omega = 1945.24 \text{ Hz} \)
\( \zeta = 0.49\% \)

Mode 12
\( \omega = 2301.38 \text{ Hz} \)
\( \zeta = 0.52\% \)

Mode 13
\( \omega = 2347.44 \text{ Hz} \)
\( \zeta = 0.52\% \)

Figure 5.2.1-3: Tank 1 Mode Shapes
5.2.2 Tank 4

Figure 5.2.2-1: Tank 4 CMIF

Figure 5.2.2-2: Tank 4 MAC
Mode 1
ω = 971.56 Hz
ζ = 0.09%

Mode 2
ω = 975.45 Hz
ζ = 0.22%

Mode 3
ω = 977.37 Hz
ζ = 0.14%

Mode 4
ω = 1202.95 Hz
ζ = 0.07%

Mode 5
ω = 1206.81 Hz
ζ = 0.10%

Mode 6
ω = 1211.56 Hz
ζ = 0.07%

Mode 7
ω = 1434.82 Hz
ζ = 0.12%

Mode 8
ω = 1633.84 Hz
ζ = 0.24%

Mode 9
ω = 1667.79 Hz
ζ = 0.24%

Mode 10
ω = 1865.67 Hz
ζ = 0.20%

Mode 11
ω = 2148.20 Hz
ζ = 0.40%

Figure 5.2.2-3: Tank 4 Mode Shapes
5.2.3 Tank 5

Figure 5.2.3-1: Tank 5 CMIF

Figure 5.2.3-2: Tank 5 MAC
Mode 1
ω = 968.98 Hz
ζ = 0.23%

Mode 2
ω = 975.75 Hz
ζ = 0.21%

Mode 3
ω = 1189.39 Hz
ζ = 0.12%

Mode 4
ω = 2077.90 Hz
ζ = 0.21%

Mode 5
ω = 2142.33 Hz
ζ = 0.31%

Figure 5.2.3-3: Tank 5 Mode Shapes
5.2.4 Tank 6

Figure 5.2.4-1: Tank 6 CMIF

Figure 5.2.4-2: Tank 6 MAC
Mode 1
\[ \omega = 963.95 \text{ Hz} \]
\[ \zeta = 0.22\% \]

Mode 2
\[ \omega = 966.32 \text{ Hz} \]
\[ \zeta = 0.30\% \]

Mode 3
\[ \omega = 968.06 \text{ Hz} \]
\[ \zeta = 0.17\% \]

Mode 4
\[ \omega = 1117.10 \text{ Hz} \]
\[ \zeta = 0.10\% \]

Mode 5
\[ \omega = 1117.99 \text{ Hz} \]
\[ \zeta = 0.28\% \]

Mode 6
\[ \omega = 1119.00 \text{ Hz} \]
\[ \zeta = 0.16\% \]

Mode 7
\[ \omega = 1836.99 \text{ Hz} \]
\[ \zeta = 0.28\% \]

Mode 8
\[ \omega = 1859.34 \text{ Hz} \]
\[ \zeta = 0.25\% \]

Mode 9
\[ \omega = 2118.20 \text{ Hz} \]
\[ \zeta = 0.33\% \]

Mode 10
\[ \omega = 2456.75 \text{ Hz} \]
\[ \zeta = 0.26\% \]

Figure 5.2.4-3: Tank 6 Mode Shapes
5.2.5 Tank 7

Figure 5.2.5-1: Tank 7 CMIF

Figure 5.2.5-2: Tank 7 MAC
Mode 1
$\omega = 963.36 \text{ Hz}$
$\zeta = 0.25\%$

Mode 2
$\omega = 970.70 \text{ Hz}$
$\zeta = 0.17\%$

Mode 3
$\omega = 1178.78 \text{ Hz}$
$\zeta = 0.18\%$

Mode 4
$\omega = 1183.32 \text{ Hz}$
$\zeta = 0.12\%$

Mode 5
$\omega = 1185.09 \text{ Hz}$
$\zeta = 0.01\%$

Mode 6
$\omega = 2040.08 \text{ Hz}$
$\zeta = 0.36\%$

Mode 7
$\omega = 2055.08 \text{ Hz}$
$\zeta = 0.30\%$

Mode 8
$\omega = 2057.93 \text{ Hz}$
$\zeta = 0.27\%$

Mode 9
$\omega = 2125.54 \text{ Hz}$
$\zeta = 0.40\%$

Mode 10
$\omega = 2125.63 \text{ Hz}$
$\zeta = 0.40\%$

Figure 5.2.5-3: Tank 7 Mode Shapes
5.2.6 Tank 9

Figure 5.2.6-1: Tank 9 CMIF

Figure 5.2.6-2: Tank 9 MAC
Mode 1
$\omega = 968.20$ Hz
$\zeta = 0.21\%$

Mode 2
$\omega = 971.35$ Hz
$\zeta = 0.31\%$

Mode 3
$\omega = 973.03$ Hz
$\zeta = 0.25\%$

Mode 4
$\omega = 1178.27$ Hz
$\zeta = 0.21\%$

Mode 5
$\omega = 1180.41$ Hz
$\zeta = 0.00\%$

Mode 6
$\omega = 1186.55$ Hz
$\zeta = 0.14\%$

Mode 7
$\omega = 2027.40$ Hz
$\zeta = 0.38\%$

Mode 8
$\omega = 2040.31$ Hz
$\zeta = 0.42\%$

Mode 9
$\omega = 2046.63$ Hz
$\zeta = 0.23\%$

Mode 10
$\omega = 2131.56$ Hz
$\zeta = 0.34\%$

Mode 11
$\omega = 2132.18$ Hz
$\zeta = 0.39\%$

Figure 5.2.6-3: Tank 9 Mode Shapes
5.3 Comparison of Tanks

After the successful completion of the structural identification on all six tanks, the following 5.3 section focuses on discussing and displaying the results that address the differences in structural behavior of each and every damaged tank to the undamaged state, as well as among themselves. The overall CMIFs are initially compared at a first glance. Then, once again with the aid of the MAC matrix, a mode shape comparison per damaged tank to undamaged is carried out.

5.3.1 CMIF Comparison

From the CMIF plots it can be noticed that the first three tanks experience much rougher SVD lines than tanks six, seven and nine do. Tanks one, four and five also have weak amplitude peaks in the 500 Hz region that the remaining three tanks do not produce. The mode shapes just prior the 1000 Hz mark are present in all tanks. On the other hand, undamaged tank one displays mode shapes around the 1500 Hz mark that do not repeat in any other damaged tank. The last region of mode shapes around 2000 Hz can be seen scattered in all tanks with no apparent trend. The majority of repeated and pseudo-repeated modes occur in the first two peaks around 1000 Hz.
Figure 5.3: CMIFs of All Tanks
5.3.2 MAC of Damage per Tank

In this section, the mode shapes identified in the undamaged tank one are compared to the mode shapes identified in each and every damage induced tank. Through the MAC technique, it is once again possible to visually detect highly correlated modes within two tanks. The objective of this analysis is to understand how a specific mode shape in the undamaged system is found at a different mode shape number and different frequency value in the damaged system.

5.3.2.1 MAC of Damage in Tank 4

<table>
<thead>
<tr>
<th>Mode</th>
<th>Tank 1 (Hz)</th>
<th>Tank 4 (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 1</td>
<td>886.72</td>
<td>971.56</td>
</tr>
<tr>
<td>Mode 2</td>
<td>918.03</td>
<td>975.45</td>
</tr>
<tr>
<td>Mode 3</td>
<td>924.71</td>
<td>977.37</td>
</tr>
<tr>
<td>Mode 4</td>
<td>975.13</td>
<td>1202.95</td>
</tr>
<tr>
<td>Mode 5</td>
<td>977.06</td>
<td>1206.81</td>
</tr>
<tr>
<td>Mode 6</td>
<td>1468.84</td>
<td>1211.56</td>
</tr>
<tr>
<td>Mode 7</td>
<td>1530.48</td>
<td>1434.82</td>
</tr>
<tr>
<td>Mode 8</td>
<td>1531.07</td>
<td>1633.84</td>
</tr>
<tr>
<td>Mode 9</td>
<td>1845.89</td>
<td>1667.79</td>
</tr>
<tr>
<td>Mode 10</td>
<td>1918.56</td>
<td>1865.67</td>
</tr>
<tr>
<td>Mode 11</td>
<td>1945.24</td>
<td>2148.25</td>
</tr>
<tr>
<td>Mode 12</td>
<td>2301.38</td>
<td></td>
</tr>
<tr>
<td>Mode 13</td>
<td>2347.44</td>
<td></td>
</tr>
</tbody>
</table>

*Colors in table indicate correlated modes. They are not associated with a numerical MAC coefficient.

Figure 5.3.2.1: MAC of Damage in Tank 4

As seen in Figure 5.3.2.1 above, tank’s one ninth mode becomes tank’s four eleventh mode, moving up the frequency range by ~300 Hz. Mode eight conserves its order in the damaged condition, however to be found with an increase of ~100 Hz. Tank’s one fourth mode can be seen become tank’s four tenth mode with a significant increase in frequency of ~900 Hz. Mode seven in tank four can be seen to correlate fairly high with four modes of tank one: three, five, seven,
and thirteen. This is because all four of these ‘tank one modes’ have a very high correlation within themselves, as seen in Figure 5.2.1-2. However, mode seven in tank four can be seen having the highest correlation of this MAC plot with tank’s one fifth mode, at about ~460 Hz difference.

5.3.2.2 MAC of Damage in Tank 5

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Tank 1</th>
<th>Tank 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 1</td>
<td>886.72</td>
<td>968.98</td>
</tr>
<tr>
<td>Mode 2</td>
<td>918.03</td>
<td>975.75</td>
</tr>
<tr>
<td>Mode 3</td>
<td>924.71</td>
<td>1189.39</td>
</tr>
<tr>
<td>Mode 4</td>
<td>975.13</td>
<td>2077.9</td>
</tr>
<tr>
<td>Mode 5</td>
<td>977.06</td>
<td>2142.33</td>
</tr>
<tr>
<td>Mode 6</td>
<td>1468.84</td>
<td></td>
</tr>
<tr>
<td>Mode 7</td>
<td>1530.48</td>
<td></td>
</tr>
<tr>
<td>Mode 8</td>
<td>1531.07</td>
<td></td>
</tr>
<tr>
<td>Mode 9</td>
<td>1845.89</td>
<td></td>
</tr>
<tr>
<td>Mode 10</td>
<td>1918.56</td>
<td></td>
</tr>
<tr>
<td>Mode 11</td>
<td>1945.24</td>
<td></td>
</tr>
<tr>
<td>Mode 12</td>
<td>2301.38</td>
<td></td>
</tr>
<tr>
<td>Mode 13</td>
<td>2347.44</td>
<td></td>
</tr>
</tbody>
</table>

*Colors in table indicate correlated modes. They are not associated with a numerical MAC coefficient.

As in the previous comparison, tank’s one ninth mode moves up the frequency range by ~300 Hz to fulfill tank’s five fifth mode shape. Mode four in tank five can be seen correlate with four of tank one’s modes. This holds true for the same reason of the previous MAC plot: modes three, five, seven, and thirteen in tank one are very high correlated to themselves. Therefore, it is hard to establish at what exact frequency mode four of tank five is located in the damaged tank. The same event occurs for the double correlation of mode three in tank five with the first and fourth mode in tank one. Inversely, mode three in tank one correlates very well with the first and the fourth mode in tank five.
5.3.2.3 MAC of Damage in Tank 6

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>886.72</td>
</tr>
<tr>
<td>2</td>
<td>918.03</td>
</tr>
<tr>
<td>3</td>
<td>924.71</td>
</tr>
<tr>
<td>4</td>
<td><strong>975.13</strong></td>
</tr>
<tr>
<td>5</td>
<td>977.06</td>
</tr>
<tr>
<td>6</td>
<td><strong>1468.84</strong></td>
</tr>
<tr>
<td>7</td>
<td>1530.48</td>
</tr>
<tr>
<td>8</td>
<td>1531.07</td>
</tr>
<tr>
<td>9</td>
<td><strong>1845.89</strong></td>
</tr>
<tr>
<td>10</td>
<td>1918.56</td>
</tr>
<tr>
<td>11</td>
<td>1945.24</td>
</tr>
<tr>
<td>12</td>
<td>2301.38</td>
</tr>
<tr>
<td>13</td>
<td>2347.44</td>
</tr>
</tbody>
</table>

*Colors in table indicate correlated modes. They are not associated with a numerical MAC coefficient.

In this comparison, both modes nine are highly correlated in both tank one and six, although found at less than 300 Hz apart. Tank one’s mode six is found as tank six’s first mode, ~500 Hz earlier on the frequency band. The fifth mode of tank six can be seen correlate greatly with tank one’s first mode and very well, although slightly less, with the fourth mode. This occurs for the same reason described in the tank five’s MAC.
5.3.2.4 MAC of Damage in Tank 7

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency (Hz)</th>
<th>Tank 1</th>
<th>Tank 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 1</td>
<td>886.72</td>
<td>963.36</td>
<td></td>
</tr>
<tr>
<td>Mode 2</td>
<td>918.03</td>
<td>970.7</td>
<td></td>
</tr>
<tr>
<td>Mode 3</td>
<td>924.71</td>
<td>1178.78</td>
<td></td>
</tr>
<tr>
<td>Mode 4</td>
<td>975.13</td>
<td>1183.32</td>
<td></td>
</tr>
<tr>
<td>Mode 5</td>
<td>977.06</td>
<td>1185.09</td>
<td></td>
</tr>
<tr>
<td>Mode 6</td>
<td>1468.84</td>
<td>2040.08</td>
<td></td>
</tr>
<tr>
<td>Mode 7</td>
<td>1530.48</td>
<td>2055.08</td>
<td></td>
</tr>
<tr>
<td>Mode 8</td>
<td>1531.07</td>
<td>2057.93</td>
<td></td>
</tr>
<tr>
<td>Mode 9</td>
<td>1845.89</td>
<td>2125.54</td>
<td></td>
</tr>
<tr>
<td>Mode 10</td>
<td>1918.56</td>
<td>2125.63</td>
<td></td>
</tr>
<tr>
<td>Mode 11</td>
<td>1945.24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mode 12</td>
<td>2301.38</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mode 13</td>
<td>2347.44</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Colors in table indicate correlated modes. They are not associated with a numerical MAC coefficient.

Figure 5.3.2.4: MAC of Damage in Tank 7

Just like before, mode nine conserves its order in tank one and tank seven, for this case, with the same ~280 Hz gap. Similarly to the previous MAC, mode six in tank one is correlated to the first mode in tank seven, with the same ~500 Hz interval. However, a stronger correlation of this mode can be seen arise with tank seven’s seventh mode. As described in tank five’s MAC, the correlation of tank seven’s sixth mode to three well separated modes of tank one is explained, although a larger degree of correlation is obtained with tank one’s fifth mode, this time. For the same reasons, mode seven in tank seven can be seen correlate with three of tank one’s mode shapes. It can however be concluded that tank one’s mode six and tank seven’s seventh mode seven are the same and just present high similarities with other, separated modes. Using the same logic, mode five of tank one is mode six of tank seven, preserving similarities to other modes in both tanks. Lastly, the highest correlations of the third mode in tank seven to the first and fourth mode of tank one it discussed in the previous MAC.
5.3.2.5 MAC of Damage in Tank 9

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency (Hz) Tank 1</th>
<th>Frequency (Hz) Tank 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>886.72</td>
<td>968.2</td>
</tr>
<tr>
<td>2</td>
<td>918.03</td>
<td>971.35</td>
</tr>
<tr>
<td>3</td>
<td>924.71</td>
<td>973.03</td>
</tr>
<tr>
<td>4</td>
<td>975.13</td>
<td>1178.27</td>
</tr>
<tr>
<td>5</td>
<td>977.06</td>
<td>1180.41</td>
</tr>
<tr>
<td>6</td>
<td>1468.84</td>
<td>1186.55</td>
</tr>
<tr>
<td>7</td>
<td>1530.48</td>
<td>2027.4</td>
</tr>
<tr>
<td>8</td>
<td>1531.07</td>
<td>2040.31</td>
</tr>
<tr>
<td>9</td>
<td>1845.89</td>
<td>2046.63</td>
</tr>
<tr>
<td>10</td>
<td>1918.56</td>
<td>2131.56</td>
</tr>
<tr>
<td>11</td>
<td>1945.24</td>
<td>2132.18</td>
</tr>
<tr>
<td>12</td>
<td>2301.38</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>2347.44</td>
<td></td>
</tr>
</tbody>
</table>

*Colors in table indicate correlated modes. They are not associated with a numerical MAC coefficient.

Figure 5.3.2.5: MAC of Damage in Tank 9

As in all previous tanks, tank one’s ninth mode correlates to a mode, being the tenth one for tank nine, at an increase in frequency of ~290 Hz. Mode four maintains its order and correlates remarkably in both of these tanks, with a ~200 Hz offset. Similarly, the second mode in tank one corresponds to the fifth mode in tank nine. For reasons explained in the majority of the other MACs, mode three in tank nine correlates very well with both mode three and five of tank one. Lastly, although mode seven in tank seven is associated with four different modes of tank one, a direct correlation can be seen with tank one’s mode seven, maintaining its order, with a ~500 Hz difference.
5.3.3 MAC of Damage for All Tanks

Figure 5.3.3: MACs of Damage for All Tanks

Figure 5.3.3 concisely combines all of the previous section’s figures into one. Tanks four and five (top row) have thermally similar and different properties to tank one as described in Table 1, while tanks six, seven and nine (bottom row) have more inherently different structural properties compared to undamaged tank one. By doing this type of grouped comparison, it is easier to identify the trends in mode shifts that develop across differently damaged tanks.

Tank one’s ninth mode consistently correlates to the same and/or other modes in all damaged tanks. The same occurs with tank one’s mode number four. The first mode in tank one
can be found in three out of the five comparing scenarios (tanks five, six, seven). Mode shape five finds correlation within tanks four, five and nine.

To aid this final analysis, Table 2 on the following page lists the thirteen modes identified in undamaged tank one, and matches them to the respectively correlated modes found in all other damaged tanks by mode order number, frequency and correlation coefficient. Thanks to this table, it is possible to read the numerical degree of correlation of similar modes in differently damaged tanks from tank one.

As already mentioned, mode nine can be seen correlate across all damaged tanks. Remarkably enough, when mode nine travels across tanks from one damage scenario to another, it maintains the same gap in frequency range. Mode nine is in fact found around ~2135 Hz in every damaged tank at a ~300 Hz jump from the undamaged case. Tank one’s fourth mode experiences the same. Although four out of the five damaged tanks experience the high correlation of mode four in tank one at ~1170 Hz, only tank four’s tenth mode can be seen outlying the trend with a resonant frequency of 1865.67 Hz. Tank one’s first mode strongly correlates with other modes in tanks five, six, and seven with MAC coefficients greater or equal to 0.90.
Table 2: Mode Shapes Comparison In-Between All Tanks

<table>
<thead>
<tr>
<th>Tank 1</th>
<th>Tank 4</th>
<th>Tank 5</th>
<th>Tank 6</th>
<th>Tank 7</th>
<th>Tank 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 1 886.72 Hz</td>
<td>-</td>
<td>Mode 3 1189.39 Hz 0.90 MAC</td>
<td>Mode 5 1117.1 Hz 0.91 MAC</td>
<td>Mode 3 1178.78 Hz 0.91 MAC</td>
<td>-</td>
</tr>
<tr>
<td>Mode 2 918.03 Hz</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Mode 5 1180.41 Hz 0.71 MAC</td>
</tr>
<tr>
<td>Mode 3 924.71 Hz</td>
<td>Mode 4 968.98 Hz 0.75 MAC</td>
<td>Mode 4 2077.9 Hz 0.79 MAC</td>
<td>-</td>
<td>-</td>
<td>Mode 3 973.03 Hz 0.80 MAC 0.72 MAC</td>
</tr>
<tr>
<td>Mode 4 975.13 Hz</td>
<td>Mode 10 1865.67 Hz 0.79 MAC</td>
<td>Mode 3 1189.39 Hz 0.87 MAC</td>
<td>Mode 5 1117.1 Hz 0.85 MAC</td>
<td>Mode 3 1178.78 Hz 0.90 MAC</td>
<td>Mode 4 1178.27 Hz 0.79 MAC</td>
</tr>
<tr>
<td>Mode 5 977.06 Hz</td>
<td>Mode 7 1434.82 Hz 0.93 MAC</td>
<td>Mode 4 2077.9 Hz 0.86 MAC</td>
<td>-</td>
<td>-</td>
<td>Mode 3 973.03 Hz 0.72 MAC 0.75 MAC</td>
</tr>
<tr>
<td>Mode 6 1468.84 Hz</td>
<td>-</td>
<td>-</td>
<td>Mode 1 963.95 Hz 0.84 MAC</td>
<td>Mode 1 963.36 Hz 0.78 MAC</td>
<td>Mode 7 2055.08 Hz 0.84 MAC</td>
</tr>
<tr>
<td>Mode 7 1530.48 Hz</td>
<td>-</td>
<td>Mode 4 2077.9 Hz 0.86 MAC</td>
<td>-</td>
<td>-</td>
<td>Mode 7 2027.4 Hz 0.86 MAC</td>
</tr>
<tr>
<td>Mode 8 1531.07 Hz</td>
<td>Mode 8 1633.84 Hz 0.75 MAC</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Mode 9 1845.89 Hz</td>
<td>Mode 11 2148.2 Hz 0.85 MAC</td>
<td>Mode 5 2142.33 Hz 0.88 MAC</td>
<td>Mode 9 2118.2 Hz 0.82 MAC</td>
<td>Mode 9 2125.54 Hz 0.77 MAC</td>
<td>Mode 10 2131.56 Hz 0.72 MAC</td>
</tr>
<tr>
<td>Mode 10 1918.56 Hz</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Mode 11 1945.24 Hz</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Mode 12 2301.38 Hz</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Mode 13 2347.44 Hz</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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</tr>
</tbody>
</table>
CHAPTER 6: SUMMARY, CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

The main objective of this study is to understand the dynamic behavior of COPVs. The structural identification performed on both perfectly intact and purposely damaged tanks supports the understanding of the parameters that factor in their structural behavior. Natural frequencies are located with their respective damping ratios, and a successful model of every mode shape associated with each resonant frequency is carefully carried out and displayed. Thanks to these visuals, it is possible to easily grasp the inherently complex structural vibrations of COPV tanks.

The second objective of this study consists of comparing the differences in various types of damage induced tanks. With the provided results, a change in structural behavior among differently performing vessels is confirmed and becomes more noticeable through visuals, MAC comparisons, and tabulated results. This study should be pursued as a representation of general change in behavior. Based on the findings, although some differences can be seen, it is not meaningful to make a sound interpretation of the severity of the damages. Every tank has one specific condition of damage simulated.

As a suggestion, in order to perform a good comparison, a gradually increased damage scenario would need to be tested so that both the effects of certain single damage within a series of tanks and the effects of different damage characteristics can be known.

By increasing the spatial resolution with the addition of hit locations and/or sensors, it would be possible to obtain information about the response of COPV systems to external sources
of energy. Additionally, with more data points over the whole structure, it could be possible to differentiate more significantly those mode shapes that are somewhat correlated to others.
REFERENCES


