

T.R.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL

**INTERNAL POROSITY DETECTION WITH A NON
DESTRUCTIVE TESTING APPROACH IN ADDITIVELY
MANUFACTURED SAMPLES**

MUSTAFA OZAN AYVERDİ

**A THESIS OF MASTER OF SCIENCE
DEPARTMENT OF MECHANICAL ENGINEERING**

ADVISOR: DR. ÖĞR. ÜYESİ RECEP ONLER

FEBRUARY 2024

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T.C.
GEBZE TEKNİK ÜNİVERSİTESİ
LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

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NUMUNELERDE TAHRİBATSIZ MUAYENE
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ABSTRACT

The use of Additive Manufacturing (AM) for prototyping, low number production and mass-produced parts is increasing every year, owing to developments in additive manufacturing technology, enabling higher quality parts, and shorter process times. However, certain limitations still exist in AM parts, as in every other manufacturing process. Material and process related defects and flaws, such as voids and cracks can form within the part, limiting part performance. Defect detection is an important step to understand the underlying factors, to either minimize the number and size of defects, or eliminate them. However, most of the common nondestructive tests can be expensive and time consuming. In this work, defect detection in Ti6Al4V parts that are produced with SLM additive manufacturing method, using various nondestructive methods such as modal analysis and natural frequency comparison were examined. Beam models that have identical outer dimensions with different deliberately modeled defects and a defect-free sample were produced and model integrities were validated using X-ray CT testing. The samples were then fitted to a mechanical vibration testing setup in free-free boundary conditions, which employs a high-fidelity Infrared laser distance sensor to measure vibrational displacement and excited using an impact hammer. The displacement signals produced by the infrared distance sensor during the test were then processed with Fast Fourier Transform algorithms to determine the samples' frequency response functions and natural frequency values. Finite element modal analysis on models was also conducted to extract their mode values under identical boundary conditions as in the experiment. The experimental natural frequency values were compared to the finite element analysis results to validate experimental data. Natural frequency value differences between control and defective samples were observed. Also, the damping effect of the loose powder within the voids caused a reduction in vibration amplitudes.

Key Words: Additive Manufacturing (AM), Selective Laser Melting (SLM), Defect Detection, Non-Destructive Testing (NDT), Natural Frequency

ÖZET

Eklemeli İmalat teknolojilerindeki gelişmelerin parça kalitesi ve proses sürelerine olumlu katkıları sayesinde, eklemeli imalat ile prototipleme, düşük sayılı üretim ve seri üretim parça üretimi her geçen yıl artmaktadır. Ancak her üretim yönteminde olduğu gibi eklemeli imalat yöntemleriyle üretilmiş parçalarda da belirli kısıtlamalar bulunmaktadır. Malzeme veya proses kaynaklı, parça performansını kısıtlayabilen parça içi boşluklar ve çatlaklar gibi kusurlar oluşabilmektedir. Kusur tespiti, kusurların sayısını ve boyutunu en aza indirmek veya ortadan kaldırmak için, kusurlara sebep olan etkenleri anlayabilmek için önemli bir adımdır. Bununla birlikte yaygın tahribatsız muayene yöntemleri pahalı ve zaman alıcı olabilmektedir. Bu çalışmada, Seçici Lazer Ergitme eklemeli imalat yöntemi ile Ti6Al4V alaşımından üretilen parçalar, modal analiz ve doğal frekans değerlerinin karşılaştırılması gibi tahribatsız muayene yöntemleri ile incelenmiştir. Özdeş dış boyutlara ve dış görünümlere, ancak kasten modellenmiş farklı kusurlara sahip giriş numuneleri ve kusur barındırmayan bir kontrol numunesi üretilmiş olup, parçaların yapıları X-ışını BT testi yöntemiyle doğrulanmıştır. Daha sonra numuneler, titreşim genliklerinin ölçümü için yüksek hassasiyetli bir kızılötesi lazer mesafe sensörü ve titreşim kaynağı olarak bir darbe çekici içeren bir mekanik titreşim ölçüm düzeneğine, serbest-serbest sınır koşullarında yerleştirilmiştir. Mesafe sensöründen elde edilen yer değiştirme değerleri hızlı Fourier dönüşümü algoritmaları ile işlenip, frekans-cevap fonksiyonları oluşturulmuş, doğal frekans değerleri elde edilmiştir. Deneysel sonuçlar ile kıyaslamak amacıyla, sonlu elemanlar yöntemi ile giriş modelleri üzerinde, özdeş sınır şartları ile modal analizler gerçekleştirilmiş ve doğal frekans değerleri elde edilmiştir. Bu sonuçlar deneysel verileri doğrulamak amacıyla kullanılmıştır. Kusur barındıran numuneler ve kontrol numunesi arasında, doğal frekans değeri farklılıkları gözlemlenmiştir. Ayrıca, parça içerisindeki boşluklarda kalan toz malzeme sönümleyici etki göstererek titreşim genliklerinde düşüşe sebep olmuştur.

Anahtar Kelimeler: Eklemeli İmalat, Seçici Lazer Ergitme (SLE), Kusur Tespiti, Tahribatsız Muayene, Doğal Frekans

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LIST OF SYMBOLS AND ABBREVIATIONS

AM	: Additive Manufacturing
3D	: 3 Dimensional
CAD	: Computer Aided Design
NDT	: Non-Destructive Testing
CT	: Computer Tomography
LAM	: Laser Additive Manufacturing
SLM	: Selective Laser Melting
FDM	: Fused Deposition Modeling
SLA	: Stereolithography
BJ	: Binder Jetting
UV	: Ultraviolet
AE	: Acoustic Emission
XCT	: X-ray Computer Tomography
UT	: Ultrasonic Testing
FEA	: Finite Element Analysis
FFT	: Fast Fourier Transform
DFT	: Discrete Fourier Transform
FRF	: Frequency Response Function

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1. INTRODUCTION

1.1. Additive Manufacturing

Additive Manufacturing (AM, Also known as 3D printing or Layered Manufacturing) methods are collection of several manufacturing techniques that take 3D CAD models as input and form those models by dividing them into layers and fuse them from powders, filaments, or resin, rather than performing subtractive operations on raw materials[1]. Although additive manufacturing methods have their unique certain limitations, in comparison to traditional manufacturing techniques they can offer far more design flexibility and cost savings to designers. For each different stage of product design and fabrication, there are several different additive manufacturing options one can choose from. AM offers design confirmations for designers before moving to industrial scale production methods, such as casting or injection molding, which require significant capital investments upfront. For certain applications, AM methods can be more advantageous than subtractive manufacturing. Figure 1.1[2] visualizes the difference between additive manufacturing and subtractive manufacturing and emphasizes that the amount of wasted material is lower in additive manufacturing compared to subtractive manufacturing.

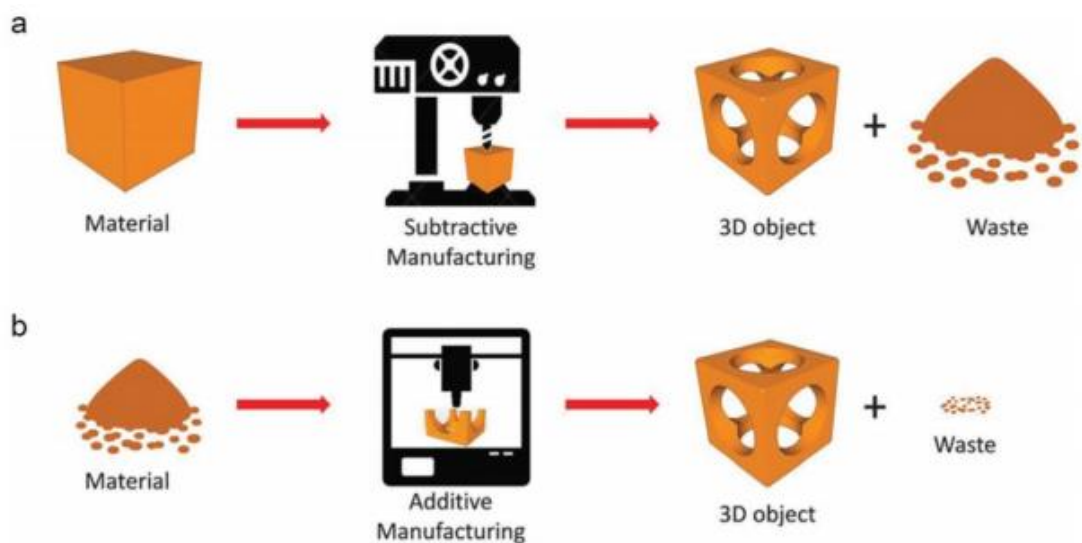


Figure 1.1: Subtractive manufacturing vs. additive manufacturing.

Since additively manufactured parts don't need to meet certain number quotas like traditionally manufactured parts, they can be customized easily and adjustments to the part geometry or manufacturing method can be much easier[3]. Additive manufacturing methods are used in various industries throughout different stages of a products development and use, most prominent ones being consumer products, medical implants, and automotive industry, as shown in Figure 1.2[4].

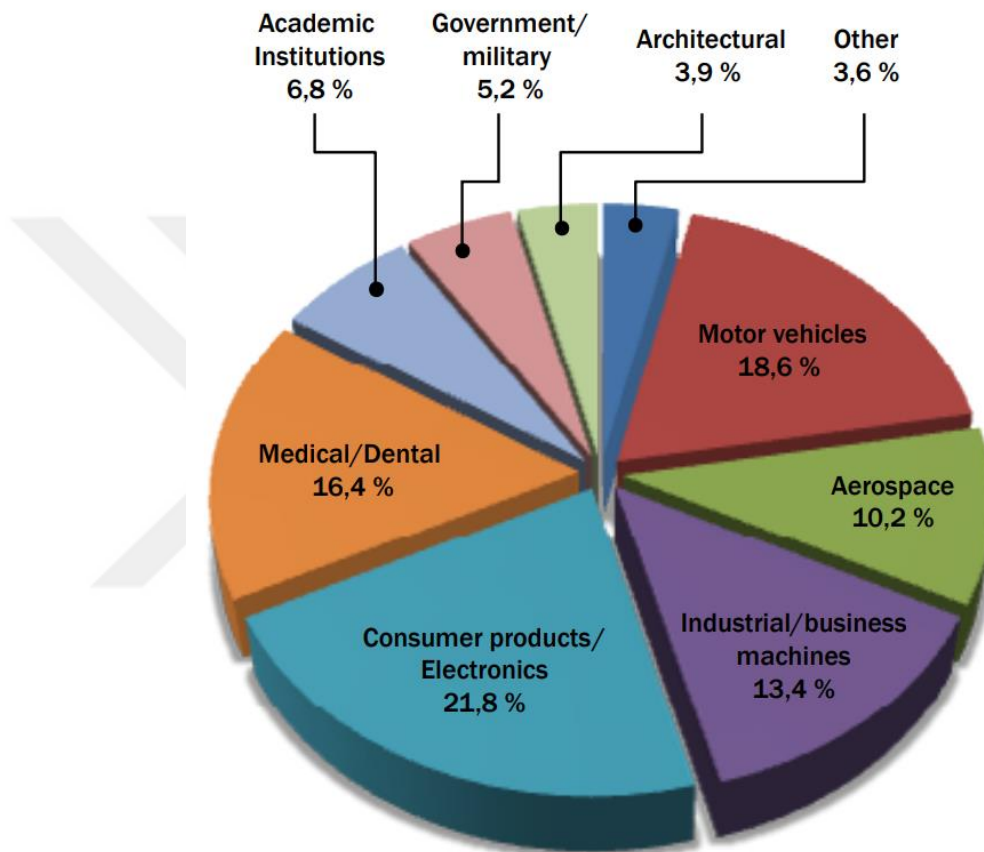


Figure 1.2: Industrial market share of additive manufacturing.

Besides their advantages, additive manufacturing methods have their unique drawbacks which can be prevented by certain post processing operations or choosing the right design parameters. For the defects that are harder to detect, certain methods have become available as the use of additive manufacturing technology spread.

1.2. Non-Destructive Testing

Non-Destructive Testing (NDT) is an essential practice across many industries, offering a non-invasive means to assess the structural integrity and quality of materials and parts without causing damage or permanent alterations[5]. Most common NDT methods can be listed as X-ray CT testing, ultrasonic testing, acoustic emissions testing, Eddy Current testing, and visual inspection. Each of them is applicable to different materials and geometries. They can also be utilized to inspect AM parts. Their working principles can be summarized to gain an understanding of how they can be applied to AM processes and parts. X-ray CT testing uses X-rays to scan a part in 2D or 3D to reveal surface level or hidden defects inside the part. Ultrasonic testing uses high frequency waves and acoustic emissions testing uses sound waves to detect cracks and voids. Eddy current testing uses magnetic fields to detect internal defects and visual inspection can be used to identify surface level defects.

NDT techniques are widely used for quality control and preventative maintenance applications in high-safety industries like aerospace, automobile, oil-gas, and medical industries[6], increasing the confidence in the performance and service life of components. Since failures in these applications can be serious, they are an important tool to prevent catastrophic failures.

It is a dynamically evolving set of tools for high quality parts and setting higher safety standards. NDT methods are used to strengthen reliability and quality across many industries at many different levels.

1.3. Defect Detection in Additive Manufacturing

Quality control, structural monitoring and preventative maintenance are important throughout a parts service life from prototyping to final use. In recent years, Additive Manufacturing has become widespread in both commercial and personal use, owing to its design flexibility and accessibility. However, since almost every AM method uses a CAD model to receive part geometry, and builds the part layer-by-layer, there are unique drawbacks that need to be overcome. Certain defects that are caused by either corrupted CAD files or AM, can yield to lower quality parts. Those defects can

be in the form of voids, invisible cracks, porous regions etc. Therefore, it is important to be able to detect and eliminate those defects to achieve a higher part quality.

Porosity and voids are common in additively manufactured parts. They can be caused by incomplete fusion between layers, printer or CAD file faults, or more complex mechanisms can be at place. As seen in Figure 1.3, Leung et.al. observed that in laser additive manufacturing (LAM), fusion of molten material can lag behind the actual laser beam, since the laser also pushes the loose powder. AS the molten material cools down, gas bubbles form causing voids and porosity[7]. These defects can pose serious threats to part integrity since they can allow crack formation and propagation under cyclic loads. There are other factors other than voids and porosity which contribute to crack formation. Poor layer adhesion and thermal stresses caused by inadequate cooling can also play a role in crack formation. Whether these cracks are at surface or inside the part, detecting them is important to prevent catastrophic failure.

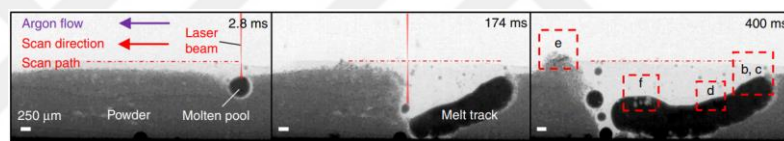


Figure 1.3: Observed melt track during LAM.

Dimensional inaccuracies can also be classified as defects in AM parts. Geometric dimensions or surface finishes of a part can affect how a part functions. This phenomenon is more common in press-fit assembly parts or sealing products which have tighter tolerances than usual.

Layer based nature of AM parts poses a challenge to detect internal defects after the part has been produced. To detect internal defects, Non-Destructive testing methods are valuable tools.

AM materials can range from elastic TPU to titanium alloys. Also, production methods to turn these materials into functional parts are very different from each other even though they are all classified as AM. This poses a challenge to determine a widely applicable NDT method that can be used in all AM parts inspection. This means that certain NDT methods can be successful to detect defects in certain materials and AM methods and other NDT methods may not even be applied at all to that part. The most common NDT methods are X-ray CT testing, Eddy Current testing, ultrasonic testing,

acoustic testing, infrared thermography, magnetic particle testing and visual inspection. The parts can also be monitored in real time, during production; or can be inspected after the part has been completed. Real time monitoring can allow the user to identify and derive a solution to the defect by adjusting production parameters in some cases. An example for this is melt pool monitoring with optical cameras[8] by Wu et.al., which also developed a model to simulate the power bed in SLM.

Detection of defects in AM parts is critical to part reliability and functionality of systems that include these parts. As the use of AM becomes more widespread, the need for NDT tools to verify AM parts will increase with that.

1.4. Objective

This work aims to introduce a novel approach to non-destructive testing for defect detection in additively manufactured parts, via a low-cost, and fast setup that employs a laser displacement sensor, which is used to measure the vibration signals of the several AM beam samples. Similar systems that use laser doppler vibrometers, need added reflective tapes to the surface of the test specimen to enhance measurement quality [9], which is not the case with the sensor that was used in this work. The samples are excited with an impact hammer, which is capable of measuring the force input to the test setup. These input and output signals, captured real time from multiple measurements, are then processed and analyzed to determine the presence of a defect in the beam sample. Motivating results from a similar system by Khoo et al., that utilize a laser vibrometer and an impact hammer was used for structural damage evaluation of a wooded structure, which has a simulated pest damage [10].

2. ADDITIVE MANUFACTURING AND INTERNAL DEFECTS

2.1. Additive Manufacturing Methods

There are numerous manufacturing methods that can be classified as additive manufacturing. These methods have several common characteristics and unique advantages and drawbacks. Almost all additive manufacturing methods need a 3D-model as CAD data to define part geometry. This model data is then divided into layers and formed by several different methods that use heat, infrared lights, UV lights, lasers etc. Materials used can be polymers, metals, ceramics, or composites. Polymeric materials and polymer-glass or carbon fiber composites can be in the form of filaments, powders and resins depending on the additive manufacturing technology. Metallic materials are usually in the form of powders, although wires and filaments are also used. Ceramic and metal-ceramic composites are mostly in the form of powders. Most techniques also require post-processing operations from sanding to sintering, to achieve a functional part. Figure 2.1. [11] visualizes the classification of AM techniques by material state and part forming method. In the following sections, the most popular AM techniques will be explained briefly.

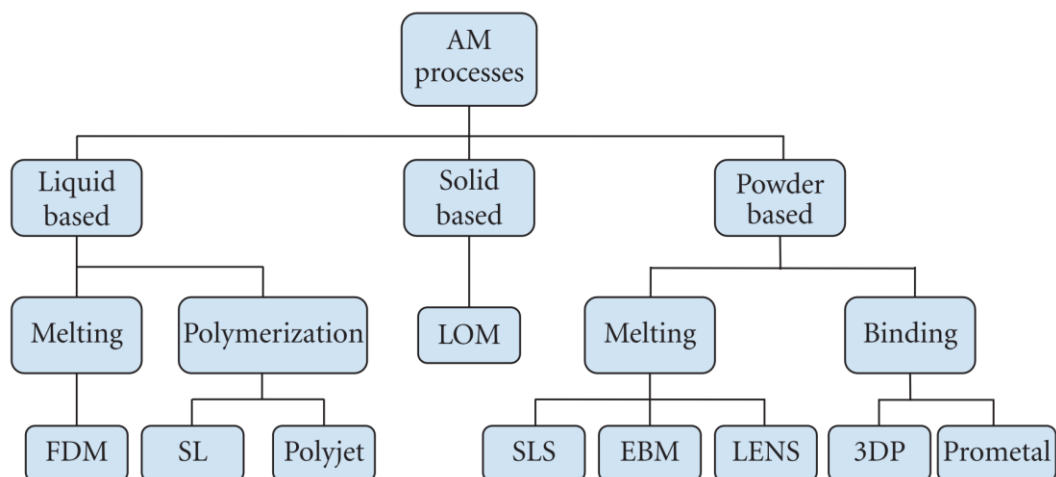


Figure 2.1: Classification of additive manufacturing processes.

2.1.1. Selective Laser Melting (SLM)

Selective Laser Melting (SLM) is one of the most widespread Additive Manufacturing methods today. Developed during the 1990's by Fraunhofer Institute, it gained popularity in the field of additive manufacturing of metal alloys by early 2000's. SLM's part formation methodology can be defined as a powder based additive manufacturing process that uses metal powders which are melted on top of each previously melted and solidified layer by a laser, according to a 3D model [12]. Manufacturing process takes place in protective atmosphere, such as N₂ or Ar, against powder oxidation. The process melts the powder material fully, meaning that desired geometry and mass density can be achieved without post processing operations, saving time and money. Similar techniques such as Selective Laser Sintering (SLS) do not melt the powders, therefore parts produced with SLS, and other sintering based additive manufacturing methods require additional post processing operations to achieve desired properties and functionality. SLM additive manufacturing can be used on several different metal alloy powders, such as aluminum alloys, stainless steel alloys, titanium alloys and nickel alloys. Alongside these advantages, there are some challenges and drawbacks also. Owing to its high-energy and high temperature nature, large temperature gradients on parts can be observed during printing process when process parameters are sub-optimal, and may cause delamination between individual layers, crack formation and residual stresses, resulting in poorer part quality. Another disadvantage of SLM is balling, which is the lack of continuous melt track. Balling can be caused by unsuitable process parameters such as high speed and low melt energy[13].

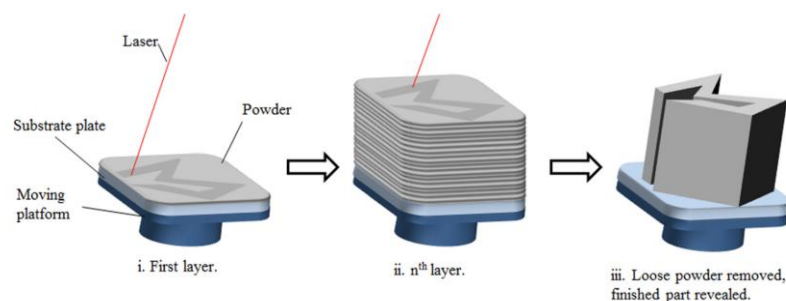


Figure 2.2: Illustration of SLM process.

2.1.2. Fused Deposition Modeling (FDM)

Fused Deposition Modeling (FDM) is an additive manufacturing technique that is mostly known for its versatility and low cost. Developed by Stratasys, FDM gained popularity during 2010's and continues to improve. Part fabrication begins with a CAD model, which is sliced to form layers. This model is then built layer upon layer by liquifying and extruding a filament through a nozzle. The ejected molten material then solidifies and fuses with the rest of the model to form the part. Depending on the model orientation, the produced part may need support structures during printing. These structures can then be removed once the print is complete. FDM parts are mostly used for prototyping and visual modeling applications. There are several limitations that FDM technology needs to improve upon, largest one being the low load carrying capacity due to void formation and poor layer adhesion[14]. Various solutions are available to limit these problematic phenomena, such as using fiber-polymer composite filaments as printing materials[15], or adjusting print parameters to suit the application better.

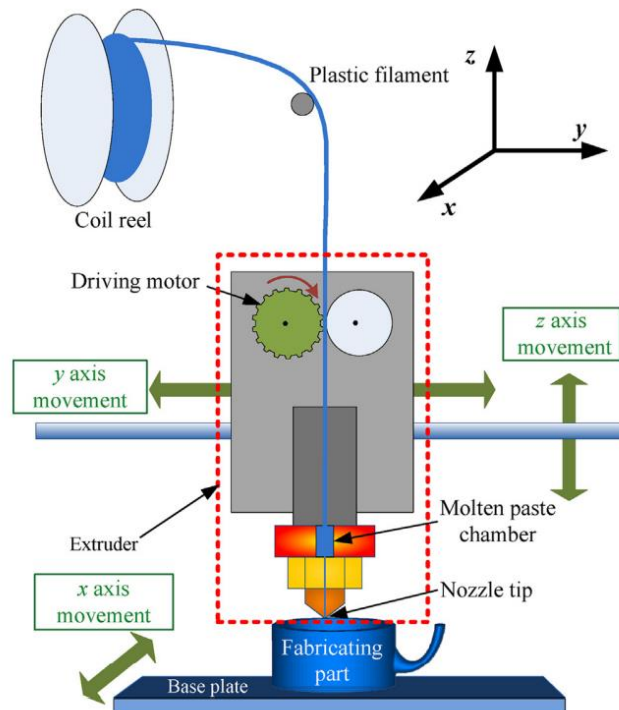


Figure 2.3: Visualization of FDM process[16].

2.1.3. Stereolithography (SLA)

Stereolithography (SLA), also known as photopolymerization, is another common method of additive manufacturing. SLA process fabricates parts by locally photopolymerizing liquid resins by UV light, building layers simultaneously. Like FDM process, parts built with SLA process also require support structures depending on the part geometry and orientation. SLA printing processes have evolved significantly today, thanks to many improvements such as dynamic masking using digital micromirrors, thus increasing part quality and efficiency compared to earlier systems [17]. It is a fast additive manufacturing process that produces dimensionally accurate parts with high speed. However, due to its UV sensitive resin-based nature, material choices are limited, and areas of application should be chosen considering the parts' UV light exposure. Parts that are not designed correctly for SLA process can also deform during print, causing warps.

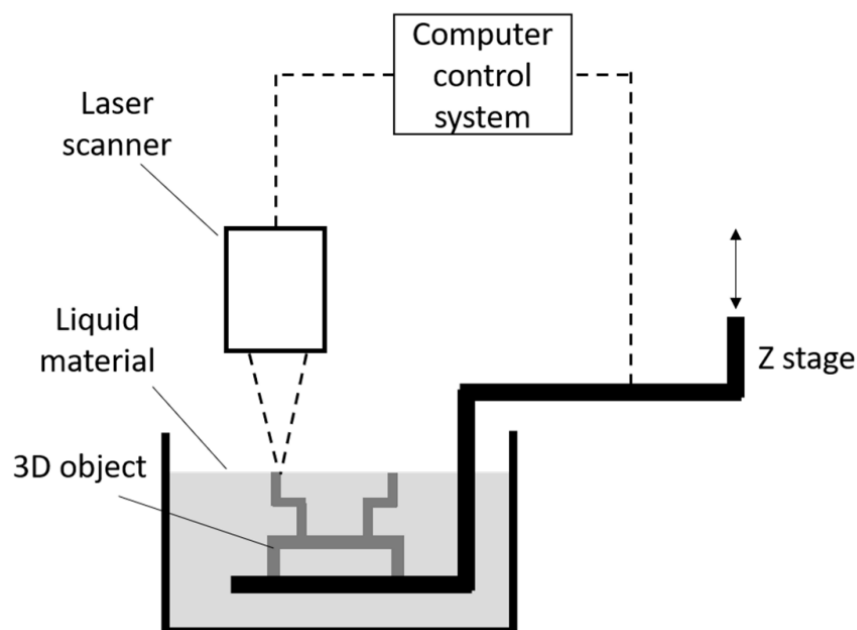


Figure 2.4: SLA Process[18].

2.1.4. Binder Jetting (BJ)

Binder Jetting is a powder based additive manufacturing process. It was developed by Sachs et al. at MIT in the 1990's. BJ process uses powder based metallic, ceramic, or composite materials; and adhesives called binders that are jetted from a print head, to build parts from a CAD model, layer upon layer[19]. Unlike most other AM methods, BJ does not use a heat source during printing process. Also, the need for support structures is eliminated by the non-bonded powder in lower layers[20]. Powder deposition from a reservoir to build plate is performed by a roller mechanism, according to the layer height. After the printing process of the part is completed, it is called a “green part”. This green part then needs to undergo several post processing operations to obtain a functional part. The first one of them is to depowder the part to remove any remaining loose powder on part surface and cavities. Then, binder adhesives are removed from the part, usually by heat, for “debinding” the part. Finally, the debinded part is subjected to a heat treatment called sintering, to achieve higher part densities and further bonding within the part[21]. Generally, printing process defects such as binder balling and jet positioning errors are rarer than post processing errors such as geometric distortion and shrinkage during sintering.

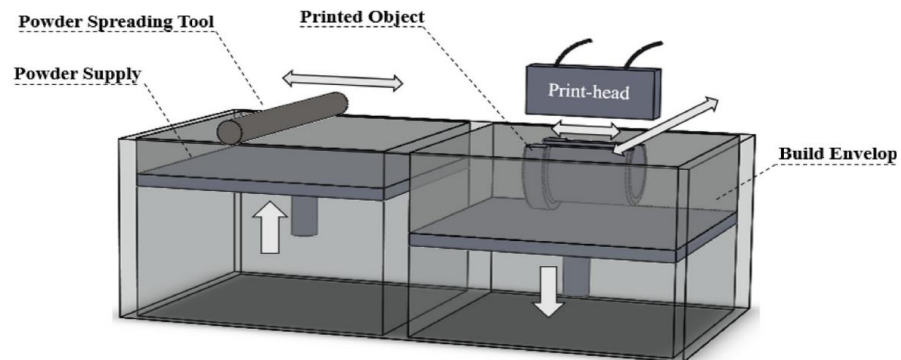


Figure 2.5: Binder Jetting printing process[20].

2.2. Additive Manufacturing and Common Defects

There are numerous types of defects that can be encountered when fabricating parts via additive manufacturing processes. Due to differences in their nature, some processes may have lower probability of having certain defect types, whereas others may be prone to those said defects. Taheri et al. [22] categorizes the defects that are encountered in AM parts as the following:

- Microstructural defects
- Porosity (Gas, Lack of Fusion)
- Anisotropy
- Inclusions
- Dimensional defects
- Balling
- Cracks
- Delamination

Meaning there is a long list of flaws that require to be checked and solutions to be addressed.

Microstructural defects are porous structures, cracks and other structurally worsening phenomena that are small in scale but impact the overall performance of the printed part. Porosity defects can be classified under 2 categories, gas porosity and porosities that are caused by lack of fusion [23]. Gas porosity is generally caused by protective inert gases in high energy powderbed-based methods such as SLM that are trapped between molten particles. Hann et al. [24] suggested that normalized enthalpy can act as an indicator of amount of porosity. Powder properties and process parameters can be adjusted to achieve optimal results. Also, in powderbed-based AM processes, lack of fusion porosity can be observed due to unmelted powders. Anisotropy of certain properties in a part that is manufactured with isotropic materials is also considered to be a defect. Anisotropy is mainly caused by variations in microstructure and poor interlayer bonding. Inclusions encompass oxides of the printing material or traces of other materials inside the printing material.

Dimensional defects, such as warpage and distortions, can be observed on parts that have been fabricated with high temperature methods. Geometric deviations and inaccuracies are present to some degree in almost every AM process. Material, process, and CAD model parameters can be adjusted to achieve optimal results. Balling defects are formed as a result of lack of liquification in high energy AM processes. As shown in Fig. 2.6., poor melting of powder material causes coalescence during solidification process. This can be mitigated by experimenting with process parameters such as print speed, laser power and layer thickness[22].

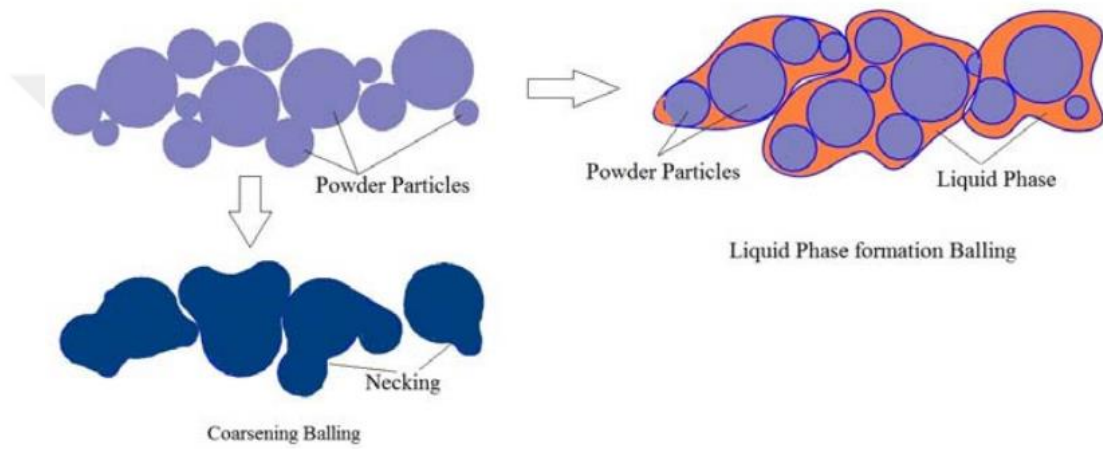


Figure 2.6: Balling in BJ AM process [22].

Surface and internal cracks are also one of the main reasons that prevent the fabrication of a functional part with AM processes. Their formation is mainly caused by temperature gradients and poor interlayer adhesion. Those cracks can cause sudden fractures or severely impact the fatigue strength of the part[25].

3. NON-DESTRUCTIVE TESTING

3.1. Visual Inspection

Visual inspection is the simplest form of non-destructive testing methods. It is performed by either cameras or personal visual inspection[26]. It can be utilized to detect surface level, macro scale flaws such as cracks, voids; and combined with the correct measurement tools, can detect geometric and dimensional inaccuracies and defects. It is particularly useful for real time monitoring of AM parts that are produced with low energy AM processes and post process inspection of AM parts in general. It is a low-cost method, depending on the sensitivity and accuracy of required flaw detection.

3.2. Acoustic Emission Testing

Acoustic Emission (AE) non-destructive testing method uses sound waves that are emitted from a test specimen, which is subjected to stress. These sound waves then can be picked by using various types of sensors to determine discontinuities and flaws within the whole part[27]. The types of defects that can be detected with AE on AM parts include surface level and internal defects. In addition, AE can be used to detect the location of those said flaws. However, it requires relatively expensive equipment for measurement and interpretation. AE can also be used for quality control and system monitoring. Moreover, some sources[26] claim that it is not entirely a non-destructive test since its measurements rely on crack propagation.

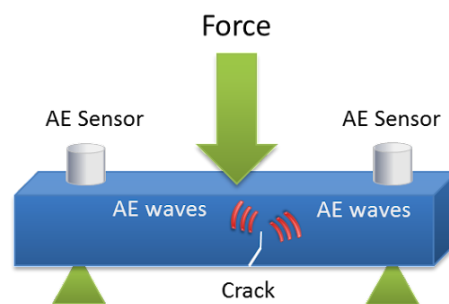


Figure 3.1: Acoustic emission testing.

3.3. X-Ray Computer Tomography Testing

X-ray Computer Tomography (X-Ray CT or XCT) Testing is a widely used process for nondestructive testing of metallic parts. It was first used for medical imaging starting around 1970's, then began to be used in industrial applications in the 2000's. X-ray CT testing uses high energy X-ray radiation to capture cross sectional 2D image of the test subject [28]. 3D models can also be constructed with multiple 2D images that are produced by rotating the test subject. X-ray CT method can be used to capture both external defects and internal defects within the part. Since X-ray CT uses high energy beams in the form of ionizing radiation, this method is suitable for metallic or ceramic parts that are produced using BJ and SLM processes, to detect cracks, porosity, voids, dimensional or process related flaws within the additively manufactured part. It provides high fidelity data to analyze the part and is not limited by geometric constraints such as surface properties and complex geometry. However, it is a high-cost method compared to most NDT techniques and has certain limitations in terms of material thickness, and measurement uncertainty. It has other industrial applications such as dimensional measurement of or combining XCT with SEM to capture microscopic XCT scans[28]. Figure 3.2 shows the XCT image of an aluminum engine cylinder head, and the right image showing porous structures detected via X-ray CT nondestructive testing.

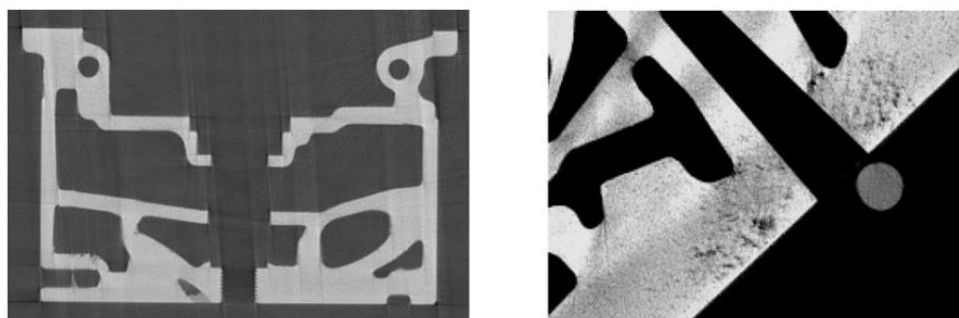


Figure 3.2: X-ray CT image of aluminum cylinder head.

3.4. Ultrasonic Testing

Ultrasonic Testing (UT) is another advanced method of nondestructive testing that is used for detection of internal defects. First developed as a testing method during the 1940's, today it is one of the most widely used methods of nondestructive testing. UT uses beams of high frequency (ultrasonic) waves, typically in the range of 1 to 6 MHz, to induce mechanical vibrations within the tested part. These vibrations then reflect either from the back surface of the specimen or the discontinuity that the beam encounters. These reflected echo signals are then captured and interpreted [26]. Since the vibrations travel at the speed of sound, locations of the defects can also be calculated. The basic method of UT is often called conventional pulse-echo ultrasonic testing, however there are other types of UT methods available such as phased array UT, immersion UT, electromagnetic acoustic transducer UT and laser UT [29]. All those methods can be used to detect subsurface defects such as cracks, lack of fusion, layer delamination, and macro scale voids-porosities in additively manufactured parts, regardless of material. However, it requires expensive equipment and good surface conditions for the test subject part. Also, most UT methods are a point-based method, meaning it needs numerous measurements to come to a verdict about part integrity. Figure 3.3. shows the difference between a structurally sound area (a) and an area that has delaminated (b). Notice that the back surface reflection is almost lost in the delaminated specimen, meaning that there is a discontinuity within the part.

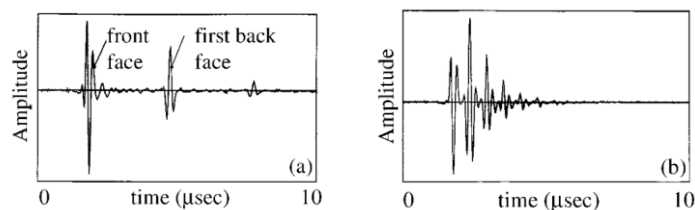


Figure 3.3: Ultrasonic testing results of a specimen from different areas.

4. METHODOLOGY & EXPERIMENT DESIGN

4.1. Sample Design and Manufacturing

To be used in both experimental and finite element analysis setups, 1 control sample and 4 beam samples with deliberately placed defects were designed, to simulate voids that can form during fabrication of parts in almost any additive manufacturing process. The design process was performed using CAD software, and the design files were then converted to STL file format for transferring into a 3D printer. All 5 beam samples are identical in outer dimensions, 12mm wide, 8mm tall and 80mm long. Sample dimensions were purposefully small, to simulate the difficulties that are faced with modal testing of small systems, due to their low mass. Technical drawings that show each beam's defect locations and sizes are provided in Appendix C.

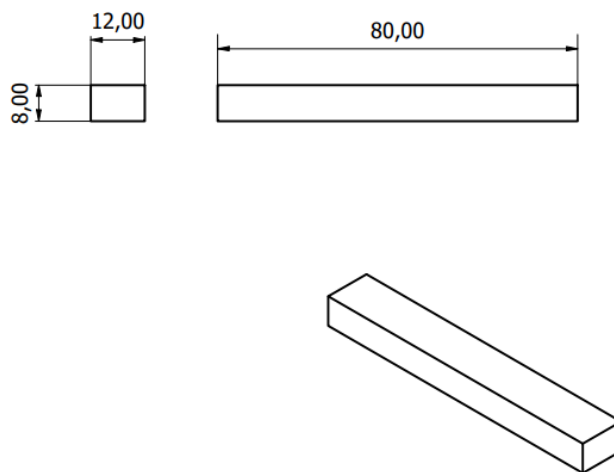


Figure 4.1: Sample's outer dimensions.

Then, the samples are printed using E-Plus 3D EP-M150 Pro Printer, which is a 3D printer that operates based on SLM additive manufacturing. Ti6Al4V titanium alloy powder was used to fabricate the beam samples, which have the following material properties, powder properties, and print parameters as seen in Table 4.1.



Figure 4.2: E-Plus EP-M150 Pro SLM 3D Printer.

Table 4.1: Print material properties[30][31].

Density (kg/m ³)	4500
Young's Modulus (GPa)	120
Poisson's Ratio	0.3
Particle size (μm)	10-45
Print Layer Thickness (μm)	100

4.1.1. Print Validation via X-ray CT Testing

To validate the location and size of the designed defects within the parts, beam samples were tested via X-ray CT testing. Figure 4.2 shows that beam samples 1,2,4, and 5 include voids that have same dimensions and locations as the designed defects. Those said geometric defects affect the beams' vibrational behavior, since the voids alter the moment of inertia of beams, therefore causing a slight shift in their natural frequency values, and corresponding frequency response function values. These voids, due to the nature of SLM additive manufacturing process, contain loose powders, which act as particle dampers, therefore affecting the modal behavior of beam samples.

Non-designed defects were not detected within the beam samples in X-ray CT testing results. Samples were renamed, disregarding the numbers in Figure 4.3. to rename the control sample as sample 1 for simplicity.



Figure 4.3: X-ray CT images of beam samples.

4.2. Finite Element Analysis

Finite element analysis (FEA) is a valuable tool for determining a systems modal behavior. This is due to the fact that it only requires CAD models and FEA software to perform modal analysis, rather than the expensive equipment that is used during modal experimental analysis. Because of these reasons, FEA was utilized in this work to be used as a comparison to experimental results. Similar approaches were found in the literature, Nahvi et al. [32] used both experimental and finite element model modal analysis data to detect cracks in a beam model, and Orhan [33] utilized a finite element model to analyze free and forced vibrations of a cantilever beam with a crack.

A finite element analysis of the control sample (beam sample 1) was performed to compare the preliminary experimental modal analysis results, such as natural frequency values and their amplitudes, to a simulated finite element model. To perform these analyses, Ansys Workbench 2023 R2 software was used. CAD model was imported into the software, and material properties of Ti6Al4V alloy were retrieved from the Ansys material library. The beam model was then meshed to divide into finite

elements. Solid 187 element was utilized in the meshing process. Meshing resulted with 63704 nodes and 35987 elements. Figure 4.4 shows the meshed model of beam sample 1 in Ansys Workbench software.

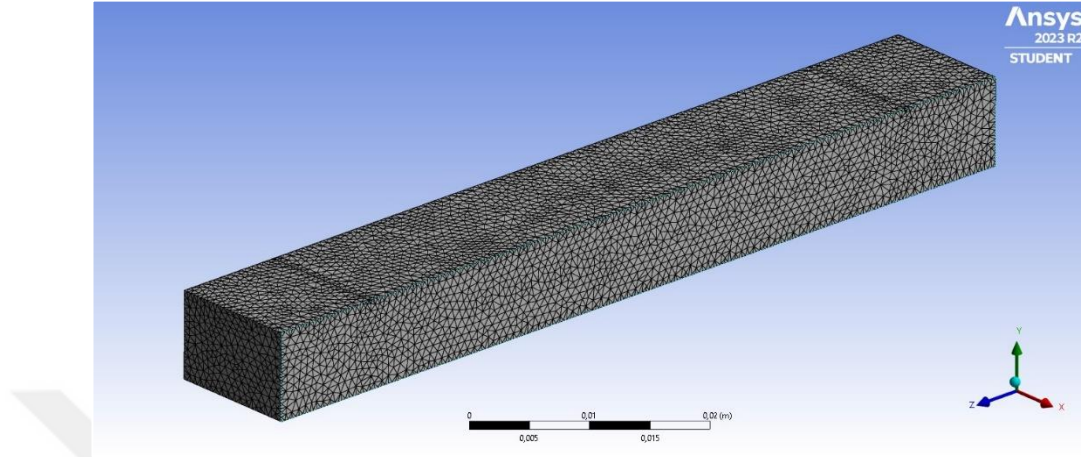


Figure 4.4: Isometric view of meshed beam sample 1.

Since the purpose of the analysis is to compare the results to the experimental results, to simulate the experimental boundary conditions, 2 elastic supports extending 10mm from both ends of the beam samples, as shown in blue, in Fig 4.5, with foundations stiffness values of $4.8 \times 10^6 \text{ N/m}^3$, which were obtained iteratively from experimental results, were added to the finite element setup.

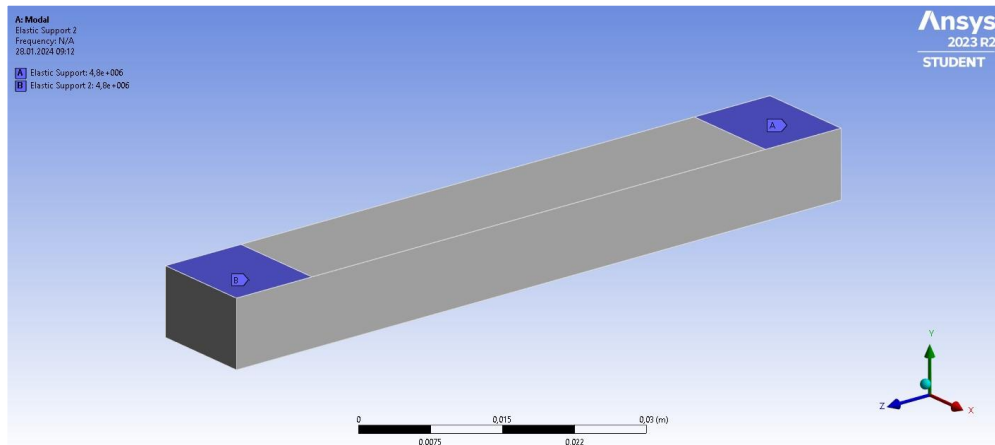


Figure 4.5: Elastic Supports.

Then, the finite element analysis was performed, and natural frequency values were obtained for the first 6 modes, between 0 Hz and 100 Hz frequency values.

In the second finite element analysis setup, all 5 beam samples were constrained in fixed-free boundary conditions, to determine whether the small geometric changes in the beams affect the modal behavior of the beam samples. The analysis was performed with Autodesk Inventor, which uses Tetra10 element type [34] to mesh the model. The meshed models had approximately 130000 elements each. The modal frequency results for the first 4 modes of the beam samples are given in Table 5.2.

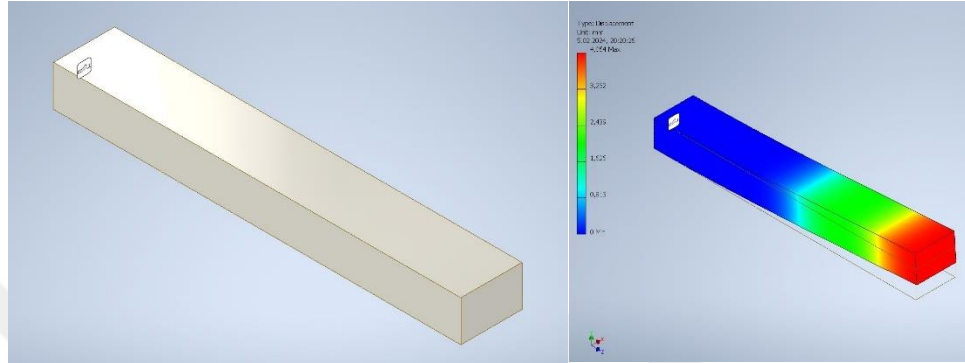


Figure 4.6: Fixed-Free finite element analysis.

4.3. Modal Testing

In order to perform modal tests, conventional approach is to fit transducers and sensors such as accelerometers to the test subject part and then to excite the system with a shaker or an impact hammer, both of which provide a form of input to the experimental setup that can be measured. This approach works for medium to large objects, from engine blocks to bridges [35]. However, this method can be difficult to implement in small scale systems, like the beam samples that are used in this work. This is a result of the fact that accelerometer or other sensors and transducers that measure the system output, are fixed to the test subject, change the test subject's modal behavior significantly due to their relatively high mass (4.1 grams, for Brüel&Kjaer 4500a accelerometer [36]) and size compared to small objects. Servagent et. al. experimented with a similar setup to the one in this work, claiming that the added mass from the accelerometer caused a measurement error of 10% [37]. Non-contact sensors that can detect vibrations, such as laser-based displacement sensors, can be utilized instead of accelerometers to measure system output.

The sensor that was used in experimental setup is Micro-Epsilon OptoNCDT 1420-100, which is a high fidelity, laser distance sensor that was developed for industrial applications. It has a measuring range between 50mm-150mm of distance and maximum sampling rate of 4kHz. The sensor measures the distance value by the principle of triangulation, where a CMOS receiver captures the reflection of the laser beam. Since the distance between the laser beam and the CMOS receiver sensor is fixed and known L , by calculating the angle between the laser beam and the reflected beam θ , the distance between the laser distance sensor and the measured surface, D , can be obtained as:

(4.1)

$$D = \tan^{-1}(\theta)L.$$

The instantaneous measurement data from the distance sensor is transferred through a interface module that converts the data from RS422 to USB format, which is then interpreted by the SensorTool software that runs on a PC. The connection is made via a USB cable. Figure 4.7 shows the schematic representation of the Micro-Epsilon OptoNCDT laser distance sensor, with start of measurement range (dead zone) and measurement range illustrations.

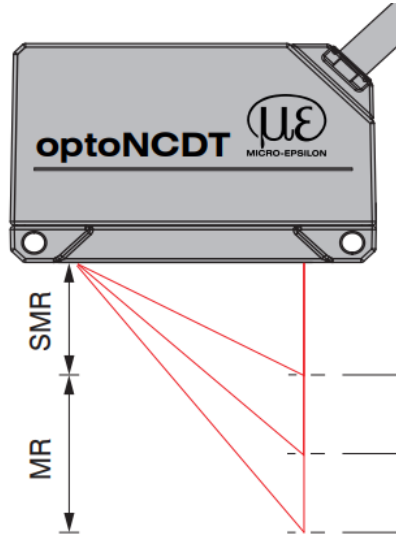


Figure 4.7: Schematic representation of the Micro-Epsilon OptoNCDT laser distance sensor.

For a measurable force input, Brüel&Kjaer 8206 Impact hammer, with its hard plastic (Delrin-POM) tip installed. This device works by measuring the impact force as a

voltage (mV/N) output with its built-in sensor and transfers this data to an I/O module, which then transfers this information to a PC that runs BK Pulse software via an ethernet cable. The impact hammer also features acceleration compensation feature, which removes the hammers effect on the output signal. Software collects the corresponding force values at 4kHz sampling rate for a time interval of 4 seconds.



Figure 4.8: Brüel&Kjaer 8206 impact hammer.

The test setup consists of two isolating polyurethane foams 350 mm x 170 mm x 10 mm, supporting the test specimen along its width, 10mm from both ends. Since the beam samples' mass and dimensions were miniscule, some sort of isolation from the rest of the test setup table was necessary for correct measurements.

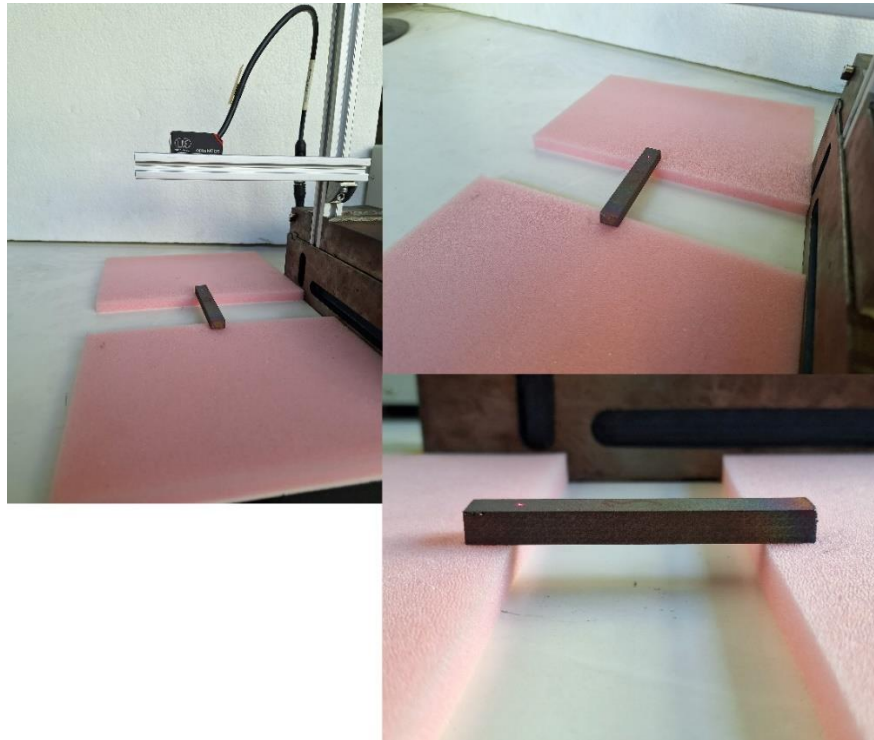


Figure 4.9: Experimental Setup.

Laser distance sensor was placed above the beam samples by using slotted aluminum extrusions, approximately 65 mm from the specimen surface. Laser light spot was placed 10mm from the end, centered with respect to the width of the beam sample. Then, the samples were hit with the impact hammer, 10mm away from the opposite end, centered with respect to the width of the beam sample. This setup was used for all 5 beam samples, with 5 measurements for each sample, for a total number of measurements of 25. Figures 4.9. and 4.10 shows the pictures and schematics of the test setup, with samples placed.

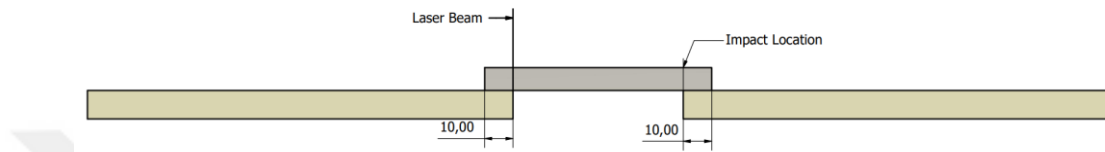


Figure 4.10: Schematic representation of experimental setup.

4.4. Experimental Data Analysis

4.4.1. Fast Fourier Transform

For the transformation of the experimental input and output data from time domain into the frequency domain for extracting the system's Frequency Response Function, Fast Fourier Transform algorithms can be utilized. This transformation is usually automated in modal analysis software, where both the input and output signals are received from their respective sensors and processed to provide the user with a FRF result.

However, the experimental setup uses 2 different programs to receive input and output signals. Brüel&Kjaer's Pulse was used to receive and save the input signal from the Impact hammer, and Micro-Epsilon's SensorTool was used to receive and save the output signal from the infrared laser displacement sensor. Then, those signals were pre-processed to be transformed into frequency domain with MATLAB's fft function.

MATLAB's fft function is based on Fast Fourier Transform algorithms, which are a modified version of Discrete Fourier Transforms (DFT). For a signal with N data points and sampling time T; DFT can be summarized by the following equations [38]:

Let $f(t)$ be the continuous signal, and $f[0], f[1] \dots f[N - 1]$ be the N discrete samples of that signal, the Fourier Transform of original signal $f(t)$, denoted as F , will be:

$$F(j\omega) = \int_{-\infty}^{\infty} f(t)e^{-j\omega t} dt \quad (4.2)$$

Assuming each discrete sample $f[k]$, is an impulse with an area $f[k]$, F becomes:

$$F(j\omega) = \int_0^{(N-1)T} f(t)e^{-j\omega t} dt \quad (4.3)$$

Which can be written as:

$$\begin{aligned} f[0]e^{-j0} + f[1]e^{-j\omega T} + \dots f[k]e^{-j\omega kT} + \dots + f(N-1)e^{-j\omega(N-1)T} \\ = F(j\omega) = \sum_{k=0}^{N-1} f[k]e^{-j\omega kT} \end{aligned} \quad (4.4)$$

Eq. 4.4 can also be written [39] in another form, to be modified into Fast Fourier Transform, with several operations, also known as Cooley-Tukey algorithm:

$$X(j) = \sum_{k=0}^{N-1} A(k) \cdot W^{jk}, \quad j = 0, 1, \dots, N-1, \quad (4.5)$$

Where $A(k)$ are complex fourier coefficients and W can be defined as the N th principal root of unity, which is:

$$W = e^{2\pi i/N} \quad (4.6)$$

With Eq. 4.5, calculation of $X(j)$ requires N^2 operations. However, assuming that $N = r_1 \cdot r_2$, modifying the indices Eq. (5) as the following reduces the count of operations to $2N \log_2 N$:

$$X(j_1, j_0) = \sum_{k_0} \sum_{k_1} A(k_1, k_0) \cdot W^{jk_1 r_2} W^{jk_0} \quad (4.7)$$

Where:

$$\begin{aligned} j &= j_1 r_1 + j_0, & j_0 &= 0, 1, \dots, r_1 - 1, & j_1 &= 0, 1, \dots, r_2 - 1, \\ k &= k_1 r_2 + k_0, & k_0 &= 0, 1, \dots, r_2 - 1, & k_1 &= 0, 1, \dots, r_1 - 1 \end{aligned} \quad (4.8)$$

And the following equation can be written as:

$$W^{jk_1 r_2} = W^{j_0 k_1 r_2} \quad (4.9)$$

A new array, A_1 , which is only dependent on j_0 and k_0 can be defined as:

$$A_1(k_0, j_0) = \sum_{k_1} A(k_1, k_0) \cdot W^{j_0 k_1 r_2} \quad (4.10)$$

Which can be rewritten in the form of:

$$X(j_1, j_0) = \sum_{k_0} A_1(j_0, k_0) \cdot W^{(j_1 r_1 + j_0) k_0} \quad (4.11)$$

Eq. 4.11 yields the array A_1 with N elements, that require r_1 number of operations, which means one needs to perform Nr_1 operations to get A_1 . To get X from A_1 , we need to perform Nr_2 operations. So, to obtain Eq. (11),

$$S = N(r_1 + r_2) \quad (4.12)$$

Number of operations are needed. An algorithm with m number of steps can be formed,

$$S = N(r_1 + r_2 + \dots + r_m), \quad N = r_1 \cdot r_2 \dots \cdot r_m \quad (4.13)$$

Assuming that all $r_j = r$, then from Eq. 4.13 we get:

$$m = \log_r N, \quad S(r) = rN \log_r N \quad (4.14)$$

Choosing $r = 2$ is the most beneficial [39] in calculations with software, which helps by reducing the use of storage. Inputting this to Eq. 4.14, yields the total number of operations, S , as:

$$S = 2N \log_2 N \quad (4.15)$$

4.4.2. Frequency Response Function

For better observation of Modal behavior of a system, Obtaining the frequency response function of that system is a vital step. During data evaluation, after processing the input and output signals with fast Fourier transform algorithm, to visualize the relationship between input and output signals, with respect to different frequency values, a graph, often called Bode diagrams [40] can be plotted.

Let input and output signals, force and displacement be F and D , respectively [41]. Then, those signals can be defined as:

$$\text{fft}(F) = F(\omega), \quad \text{fft}(D) = D(\omega). \quad (4.16)$$

Where both $F(\omega)$ and $D(\omega)$ are amplitudes of input and output signals, in complex form. The frequency response function of the system, FRF , is:

$$FRF = \frac{D(\omega)}{F(\omega)} \quad (4.17)$$

Figures 4.11 and 4.12 show samples of input and output signals in time domain, before the Fourier transforms into frequency domain.

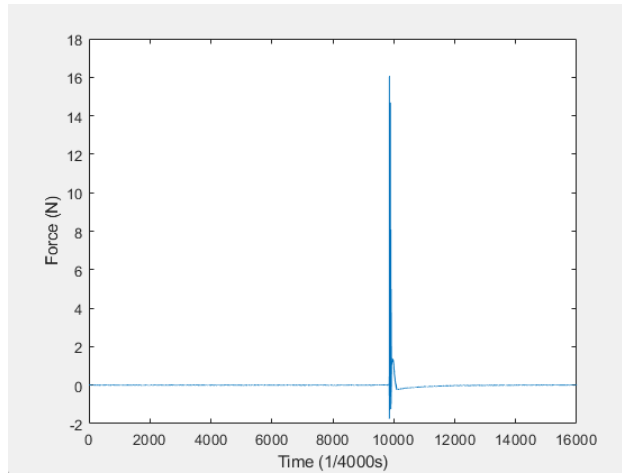


Figure 4.11: Sample plot of force signal vs. time.

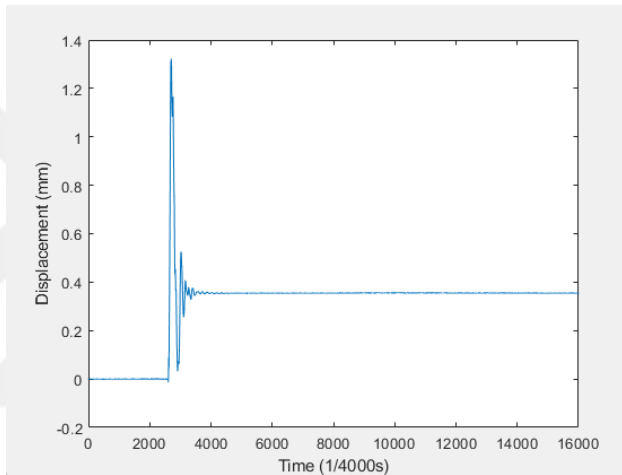


Figure 4.12: Sample plot of displacement signal vs. time.

The figures 4.13. to 4.15 visualize a sample of the input and output signals' fft vs. frequency plots.

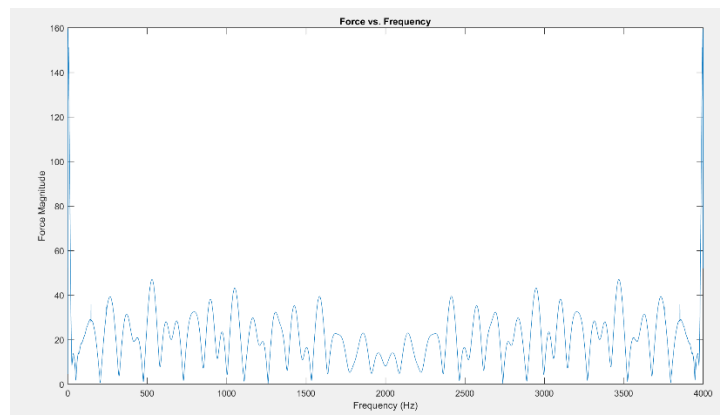


Figure 4.13: Sample plot of FFT result of force signal vs. frequency.

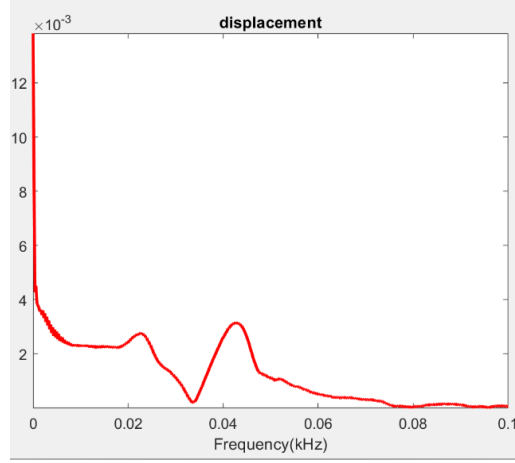


Figure 4.14: Sample plot of FFT result of displacement signal vs. frequency.

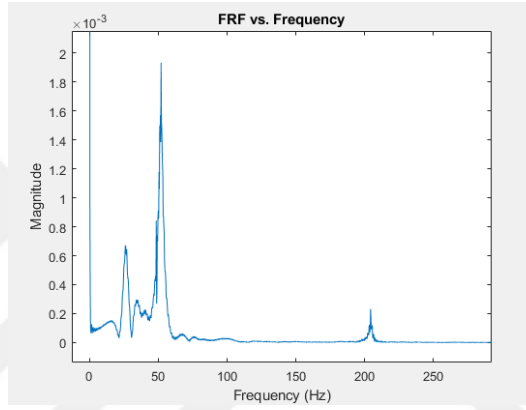


Figure 4.15: Sample Bode plot (FRF vs. frequency).

Additionally, for samples with at least 2 measurements, the relationship between these 2 datasets, called coherence, or magnitude squared coherence, can be defined as the following equation [42] :

$$C_{xy}(f) = \frac{|G_{xy}(f)|^2}{G_{xx}(f)G_{yy}(f)} \quad (4.18)$$

Assuming that x and y are the frequency responses of the different measurements for the same system. $G_{xy}(f)$ is defined as the cross spectral density between x and y and $G_{xx}(f)$ and $G_{yy}(f)$ are defined as the auto spectral densities of x and y respectively. Figure 4.16. shows a sample of visual representation of coherence values of five different signals that originate from the same system, vs. the frequency values that correspond to those coherence values.

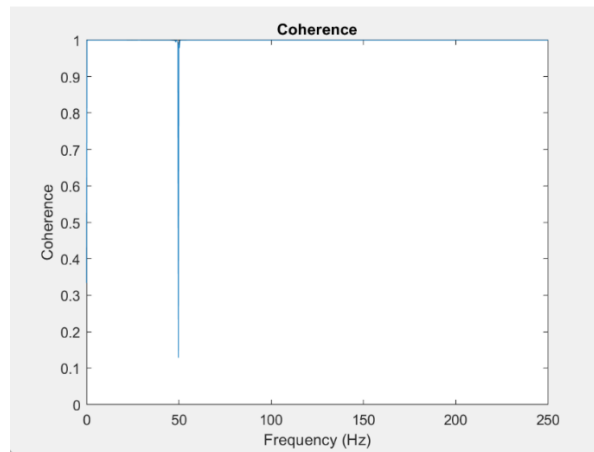


Figure 4.16. Sample plot of coherence vs. frequency.

5. RESULTS

Two different finite element analyses and experimental analyses were conducted to determine the test setup's ability to detect defective beam samples. In the first FEA, experimental boundary conditions (free-free) were replicated to compare the results to the mean modal frequency values of 5 different measurements of beam sample 1. Then, in the second FEA, models of 5 beam samples were constrained in a way to simulate fixed- free boundary conditions, and then their modal frequency values were compared to the control sample' frequency values.

In the experimental analysis, frequency response function values were obtained from the test setup. These values were then interpreted to determine whether the defect in a beam sample can be detected or not via the results obtained from input and output signals that are collected from testing.

5.1. Finite Element Analysis Results

First finite element analysis was performed in Ansys Workbench to benchmark the experimental mean modal frequency values of 5 different measurements of beam sample 1, by replicating the boundary conditions in the experiment, as explained in section 4.2. Figure 5.1. shows the modal frequency results for the first 6 modes of the beam sample 1. Note that the first 3 modes are nearly identical, at 0 Hz. The other 3 modes' frequency values are given as 24.37 Hz, 29.29 Hz and 44.32 Hz. In table 5.1., the values in FEA are compared to Experimental frequency results, and their differences are given as percentage values. Although the first mode values are similar in experimental values and finite element model values, the finite element model fails to determine the 3rd modal frequency, which is approximately 205Hz in experimental values.

Table 5.1: Free-free boundary conditions experimental and FEA results comparison of beam sample 1.

	FEA	Experimental	Difference
Mode 1	24.37 Hz	25.20 Hz	3.3%
Mode 2	44.32 Hz	49.30 Hz	10.1%
Mode 3	N/A	205.50 Hz	N/A

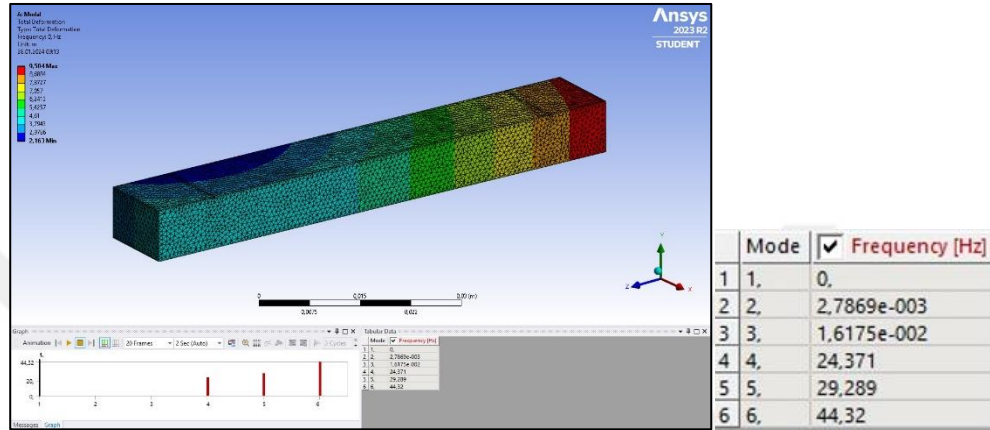


Figure 5.1: Free- Free boundary conditions finite element analysis results of beam sample 1.

For the second finite element analysis, models of beam samples were constrained in a way to simulate fixed-free boundary conditions, and then their modal frequency values for the first 4 modes of vibration were compared to the control sample' frequency values. As seen in Table 5.2., the difference between the control sample' values and defective sample's values were miniscule, meaning that the small changes in the geometry of the beam did not cause significant changes in the modal behavior of the beam samples in fixed-free boundary conditions, for the scope of finite element model.

Table 5.2: Fixed-free boundary conditions frequency differences in defective samples first 4 modes with respect to control sample.

	Mode 1	Difference	Mode 2	Difference	Mode 3	Difference	Mode 4	Difference
S1	965.31	0	1431.04	0	5778.53	0	7746.02	0
S2	963.37	0.2%	1421.64	0.7%	5804.11	0.4%	7711.5	0.4%
S3	962.44	0.3%	1420.76	0.7%	5780.35	0.0%	7717.69	0.4%
S4	956.89	0.9%	1428.2	0.2%	5780.45	0.0%	7688.82	0.7%
S5	963.52	0.2%	1424.26	0.5%	5799.43	0.4%	7690.97	0.7%

5.2. Experimental Results

To obtain experimental results, test setup and data analysis methods that are explained in section 4.3. were used. 5 different measurements were taken with each one of the 5 beam samples. The input and output signals obtained from those measurements were then processed with FFT algorithms and frequency response functions with respect to frequency values were plotted for the average values of magnitudes of frequency response. Extensive plots of those results are given in Appendix D, which are also given in tabular form in Table 5.3. Those results are visualized in Fig. 5.2., in which the control sample' results are shown with green. From these results it can be seen that, due to the dramatic decrease in the magnitude values of frequency responses in 2nd and 3rd modes, defective samples can be differentiated from the control sample. This drop in the frequency response magnitude can be affiliated to particle damping effect, which has been studied extensively as a way to integrate vibration dampers to additively manufactured structures [43] [44].

However, this outcome means that this methodology relies on another defect-free sample, which needs to be validated via another method, in order to determine whether the test specimen is defective or not. This fact indicates that measurements with only one sample or multiple samples without a control sample can be indecisive, although still can be beneficial with a sample that is known to be defect-free.

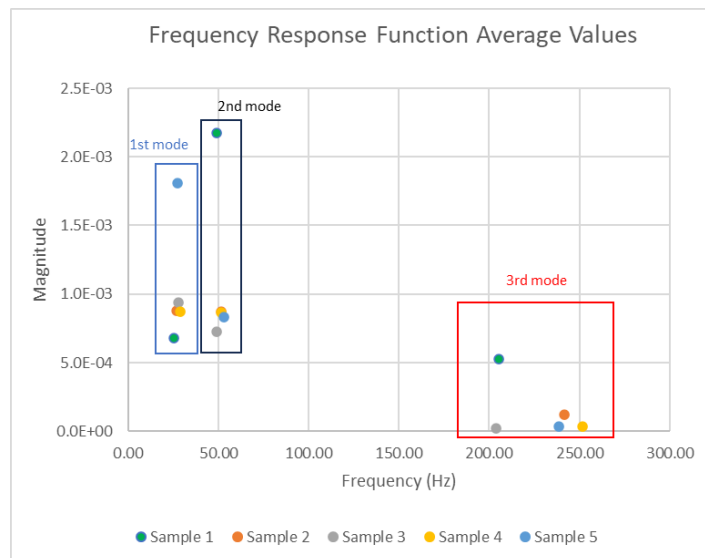


Figure 5.2: FRF average values vs. frequency.

Table 5.3: Experimental frequency response function values.

Sample 1													
Mode	Data Set 1		Data Set 2		Data Set 3		Data Set 4		Data Set 5		Mean	SD	RSD
1	Freq. (Hz)	Amp.	Freq. (Hz)	Amp.	Freq. (Hz)	Amp.	Freq. (Hz)	Amp.	Freq. (Hz)	Amp.	Freq.	Amplitude	
	0		0		0		0		0			0	
2	25.25	0.00043	26	0.00067	24.75	0.00069	24.5	0.00075	25.5	0.00085	25.20	0.53	2%
3	49.75	0.00419	52	0.00193	47.75	0.00227	47.75	0.00119	49.25	0.00128	49.30	1.57	3%
4	213.25	0.00011	204.25	0.00023	206.25	0.00123	206.25	0.00067	197.5	0.00038	205.50	5.03	2%
Sample 2													
Mode	Data Set 1		Data Set 2		Data Set 3		Data Set 4		Data Set 5		Mean	SD	RSD
	Freq. (Hz)	Amp.	Freq. (Hz)	Amp.	Freq. (Hz)	Amp.	Freq. (Hz)	Amp.	Freq. (Hz)	Amp.	Freq.	Amplitude	
1	0		0		0		0		0		0	0	
2	25.25	0.00106	25	0.00084	26.25	0.00071	27.75	0.00059	30	0.00121	26.85	1.85	7%
3	49.5	0.00054	53	0.00084	51.5	0.00041	55.75	0.00102	48.75	0.00155	51.70	2.52	5%
4	256.75	0.00041	245.25	0.00005	238.25	0.00006	226.5	0.00002	242.25	0.00008	241.80	9.82	4%
Sample 3													
Mode	Data Set 1		Data Set 2		Data Set 3		Data Set 4		Data Set 5		Mean	SD	RSD
	Freq. (Hz)	Amp.	Freq. (Hz)	Amp.	Freq. (Hz)	Amp.	Freq. (Hz)	Amp.	Freq. (Hz)	Amp.	Freq.	Amplitude	
1	0		0		0		0		0		0	0	
2	27.5	0.00120	28.25	0.00082	26.75	0.00125	28.5	0.00070	27.5	0.00072	27.70	0.62	2%
3	48.75	0.00136	44.00	0.00033	49	0.00076	49	0.00059	54.5	0.00058	49.05	3.33	7%
4	224	0.00003	203.75	0.00001	201.25	0.00004	202.25	0.00002	188	0.00002	203.85	11.55	6%
Sample 4													
Mode	Data Set 1		Data Set 2		Data Set 3		Data Set 4		Data Set 5		Mean	SD	RSD
	Freq. (Hz)	Amp.	Freq. (Hz)	Amp.	Freq. (Hz)	Amp.	Freq. (Hz)	Amp.	Freq. (Hz)	Amp.	Freq.	Amplitude	
1	0		0		0		0		0		0	0	
2	28	0.00082	27.5	0.00191	28	0.00064	34.75	0.00053	26.75	0.00045	29.00	2.91	10%
3	54.5	0.00189	57.75	0.00078	52	0.00048	41	0.00059	53.5	0.00060	51.75	5.70	11%
4	236	0.00002	279.50	0.00002	235.25	0.00004	287.75	0.00005	218.75	0.00005	251.45	27.11	11%
Sample 5													
Mode	Data Set 1		Data Set 2		Data Set 3		Data Set 4		Data Set 5		Mean	SD	RSD
	Freq. (Hz)	Amp.	Freq. (Hz)	Amp.	Freq. (Hz)	Amp.	Freq. (Hz)	Amp.	Freq. (Hz)	Amp.	Freq.	Amplitude	
1	0		0		0		0		0		0	0	
2	27.75	0.00496	26.75	0.00118	26.25	0.00059	29	0.00117	27.25	0.00114	27.40	0.94	3%
3	46	0.00059	56	0.00153	57.75	0.00035	54.25	0.00051	52.25	0.00118	53.25	4.06	8%
4	239	0.00004	257.75	0.00003	250	0.00005	217.75	0.00002	229.5	0.00005	238.80	14.24	6%

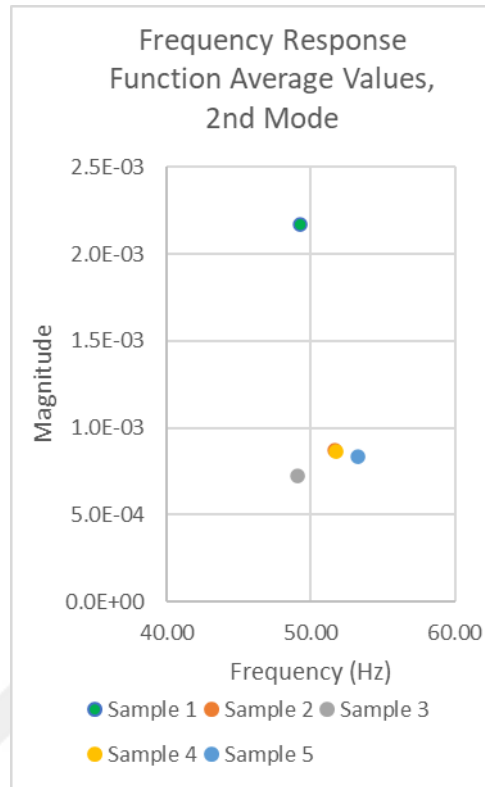


Figure 5.3: FRF average values vs. frequency for 2nd mode.

The highest decrease in the frequency response magnitude compared to control sample was observed in the 2nd mode. Fig. 5.3. shows that the frequency response magnitude drop is around 60% compared to beam sample 1's frequency response magnitude. This result can also be seen in Table 5.4., which also shows the difference of 1st and 2nd mode frequency response magnitudes ratios of defective samples from the control sample.

Table 5.4. 2nd mode magnitude ratios of defective samples, and 1st mode 2nd mode magnitude ratios with respect to beam sample 1.

2nd mode magnitude ratio		1st mode /2nd Mode Magnitude	
S2	0.40	S1	1.01
S3	0.33		1.30
S4	0.40	0.3	1.00
S5	0.38		2.17

Table 5.5: Percentile differences of modal frequency values of defective samples with respect to beam sample 1.

	S2	RSD	S3	RSD
1st mode	7%	7%	10%	2%
2nd mode	5%	5%	1%	7%
3rd mode	18%	4%	1%	6%
	S4	RSD	S5	RSD
1st mode	15%	10%	9%	3%
2nd mode	5%	11%	8%	8%
3rd mode	22%	11%	16%	6%

Table 5.5. shows the percentile differences of modal frequency values of defective samples with respect to beam sample 1, and their relative standard deviations, which shows that the changes in the 1st mode frequency value can be an indicator of a defective sample, ranging from 7% to 15% with respect to defect-free sample.

The interpretation of the coherence analysis results is given in Table 5.6. Which, are again the culmination of the results from 5 different measurements for each individual beam sample. From this table it can be seen that 1st mode frequency values change significantly in defective samples with respect to control sample, ranging from 8.9% to 10.9%.

Table 5.6: Coherence analysis modal frequency values and defective samples percentile differences with respect to beam sample 1.

Frequency (hz)				
S1	25.25	Diff.	49.75	Diff.
S2	-	-	-	-
S3	27.5	8.9%	48.75	2.0%
S4	28	10.9%	54.5	9.5%
S5	27.75	9.9%	-	-

6. CONCLUSION

This work's objective was to introduce a novel approach to non-destructive testing for defect detection in additively manufactured parts, via a low-cost, and fast setup that employs a laser displacement sensor, which is used to measure the vibration signals of the several AM beam samples. The samples are excited with an impact hammer, which is capable of measuring the force input to the test setup. These input and output signals, captured real time from multiple measurements, are then processed and analyzed to determine the presence of a defect in the beam sample. The experimental results were also compared to finite element analysis results, with 2 different boundary conditions.

Finite element analysis with free-free boundary conditions and the comparison of this analysis' results with the mean values of the experimental analysis were compared to yield a near-identical result for the 1st modal frequency value. This outcome from combined results is a proof that the finite element analysis results with realistic boundary conditions can eliminate the need for a defect-free sample to use the coherence analysis results given in table 5.6. to detect a defective sample from the change in its 1st modal frequency.

In the presence of a defect-free sample, additional results such as frequency response magnitude values of different modal frequencies can be investigated for defect detection without the need for constructing a finite element model for analysis, which can be beneficial in terms of speed and simplicity.

In conclusion, the hypothesized methodology was found to be applicable and yielded useful results combined with different techniques of modal analysis, for instance, finite element analysis. However, there is room for future development such as utilizing multiple locations for measurements, to not only detect defective parts, but also locating the defect inside the part. Also, different boundary conditions and part geometries can be analyzed to further enhance the defect detection capabilities.

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BIOGRAPHY

Mustafa Ozan Ayverdi graduated from Işık University, with a bachelor's degree in mechanical engineering, in 2020. He continued his education with a master's degree in mechanical engineering, Graduate School, Gebze Technical University, since 2020. He currently works as a mechanical design engineer in iHoy electronics, which he started in 2022.



APPENDICES

APPENDIX A: MATLAB CODES FOR FRF AND COHERENCE ANALYSES

%FRF code for Distance and Force data

% Step 1: Retrieve experimental data

```
Displacement=S2Vib5(:, "VarName4");
Displacement=Displacement-Displacement(1,1); %mean extraction
a=table2array(Displacement);
fft_x=fft(a)/(height(Displacement)/2);

Hammer=H25(:, "VarName3");
force=table2array(Hammer);
```

% Step 2: Create a time vector

```
dt = 1 / 4000; % Sampling interval (inverse of sampling rate)
time = 0:dt:(length(force)-1)*dt; % Time vector
```

% Step 3: Perform the Fourier Transform

```
N = length(force); % Length of the signal
f = (0:N-1) / (dt * N); % Frequency axis
```

```
force_fft = fft(force);
```

% Step 4: Compute the magnitude of the spectrum

```
force_magnitude = abs(force_fft);
vib=abs(fft_x);

FRF=vib./force_magnitude;

res=abs(FRF);
```

% Step 5: Plot the results

```
figure;
plot(f,res);
% plot(f,log10(res));
title('FRF vs. Frequency');
xlabel('Frequency (Hz)');
ylabel('Magnitude');
```

```
%FRF code for Distance and Force data
```

```
% Step 1: Retrieve experimental data
```

```
Displacement1=S2Vib1(:, "VarName4");  
Displacement1=Displacement1-Displacement1(1,1); %mean extraction  
a1=table2array(Displacement1);  
fft_x1=fft(a1)/(height(Displacement1)/2);
```

```
Displacement2=S2Vib2(:, "VarName4");  
Displacement2=Displacement2-Displacement2(1,1); %mean extraction  
a2=table2array(Displacement2);  
fft_x2=fft(a2)/(height(Displacement2)/2);
```

```
Displacement3=S2Vib3(:, "VarName4");  
Displacement3=Displacement3-Displacement3(1,1); %mean extraction  
a3=table2array(Displacement3);  
fft_x3=fft(a3)/(height(Displacement3)/2);
```

```
Displacement4=S2Vib4(:, "VarName4");  
Displacement4=Displacement4-Displacement4(1,1); %mean extraction  
a4=table2array(Displacement4);  
fft_x4=fft(a4)/(height(Displacement4)/2);
```

```
Displacement5=S2Vib5(:, "VarName4");  
Displacement5=Displacement5-Displacement5(1,1); %mean extraction  
a5=table2array(Displacement5);  
fft_x5=fft(a5)/(height(Displacement5)/2);
```

```
Hammer1=H21(:, "VarName3");  
force1=table2array(Hammer1);
```

```
Hammer2=H22(:, "VarName3");  
force2=table2array(Hammer2);
```

```
Hammer3=H23(:, "VarName3");  
force3=table2array(Hammer3);
```

```
Hammer4=H24(:, "VarName3");  
force4=table2array(Hammer4);
```

```
Hammer5=H25(:, "VarName3");  
force5=table2array(Hammer5);
```

```
% Step 2: Create a time vector
```

```
dt = 1 / 4000; % Sampling interval (inverse of sampling rate)  
time = 0:dt:(length(force1)-1)*dt; % Time vector
```

```

% Step 3: Perform the Fourier Transform

N = length(force1); % Length of the signal
f = (0:N-1) / (dt * N); % Frequency axis

force_fft1 = fft(force1);

force_fft2 = fft(force2);

force_fft3 = fft(force3);

force_fft4 = fft(force4);

force_fft5 = fft(force5);

% Step 4: Compute the magnitude of the spectrum

force_magnitude1 = abs(force_fft1);
vib1=abs(fft_x1);

force_magnitude2 = abs(force_fft2);
vib2=abs(fft_x2);

force_magnitude3 = abs(force_fft3);
vib3=abs(fft_x3);

force_magnitude4 = abs(force_fft4);
vib4=abs(fft_x4);

force_magnitude5 = abs(force_fft5);
vib5=abs(fft_x5);

FRF1=vib1./force_magnitude1;
res1=abs(FRF1);

FRF2=vib2./force_magnitude2;
res2=abs(FRF2);

FRF3=vib3./force_magnitude3;
res3=abs(FRF3);

FRF4=vib4./force_magnitude4;
res4=abs(FRF4);

FRF5=vib5./force_magnitude5;
res5=abs(FRF5);

% Ensure equal lengths for all signals
% if length(y) ~= length(x1) || length(y) ~= length(x2) || ...
%     length(y) ~= length(x3) || length(y) ~= length(x4)
%     error('Signals must have the same length.');
```

```

% Calculate FFTs for all signals
Fy = res1;
Fx1 = res2;
Fx2 = res3;
Fx3 = res4;
Fx4 = res5;

% Calculate autospectral densities
Gyy = abs(Fy).^2;
Gxx1 = abs(Fx1).^2;
Gxx2 = abs(Fx2).^2;
Gxx3 = abs(Fx3).^2;
Gxx4 = abs(Fx4).^2;

% Calculate cross-spectral densities
Gxy1 = Fy .* conj(Fx1);
Gxy2 = Fy .* conj(Fx2);
Gxy3 = Fy .* conj(Fx3);
Gxy4 = Fy .* conj(Fx4);

% Calculate multiple coherence using optimized formula
denominator = prod(Gxx1 .* Gxx2 .* Gxx3 .* Gxx4) .* Gyy.^2;
% Avoid division by zero (replace with small epsilon if necessary)
denominator(denominator == 0) = eps;

% Reshape Gxy1 to a matrix with matching dimensions for multiplication
Gxy1_matrix = reshape(Gxy1, size(Gxy2, 1), []);

% Perform matrix multiplication to combine cross-spectral densities
numerator = (abs(Gyy - (Gxy1_matrix .* Gxy2 .* Gxy3 .* Gxy4 .* Gxy1))).^2;

Coh2 = numerator ./ denominator;
Coh3= Coh2./(1.6*10^6);
Coh=1-Coh3;

plot(f, Coh2); % Plot multiple coherence
title('Coherence');
xlabel('Frequency (Hz)');
ylabel('Coherence');
% xlim([0 250])
% ylim([0 1])

```

APPENDIX B: COHERENCE ANALYSIS PLOTS

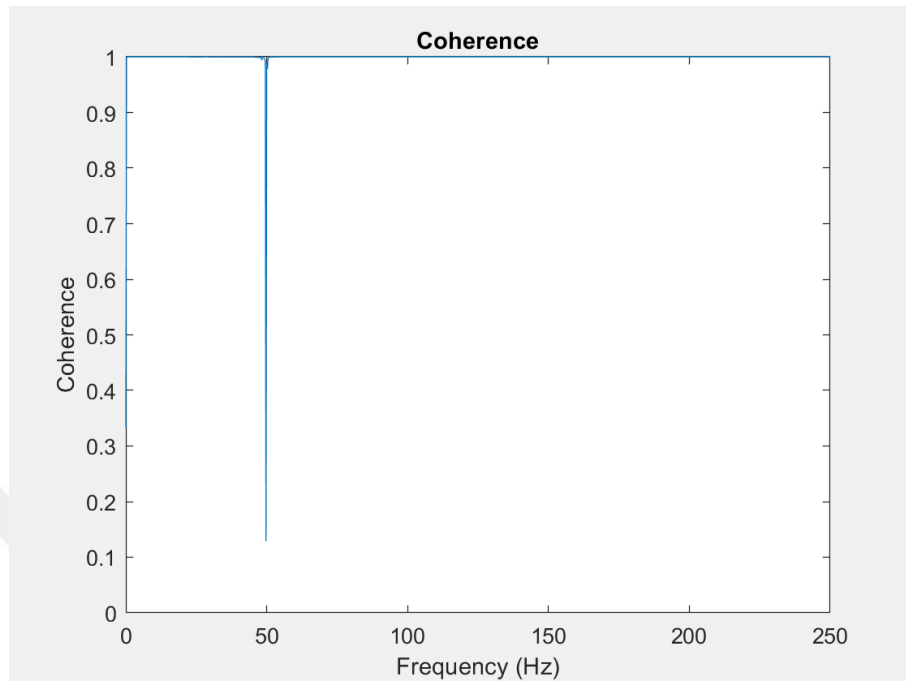


Figure B.1: Coherence Plot 1.

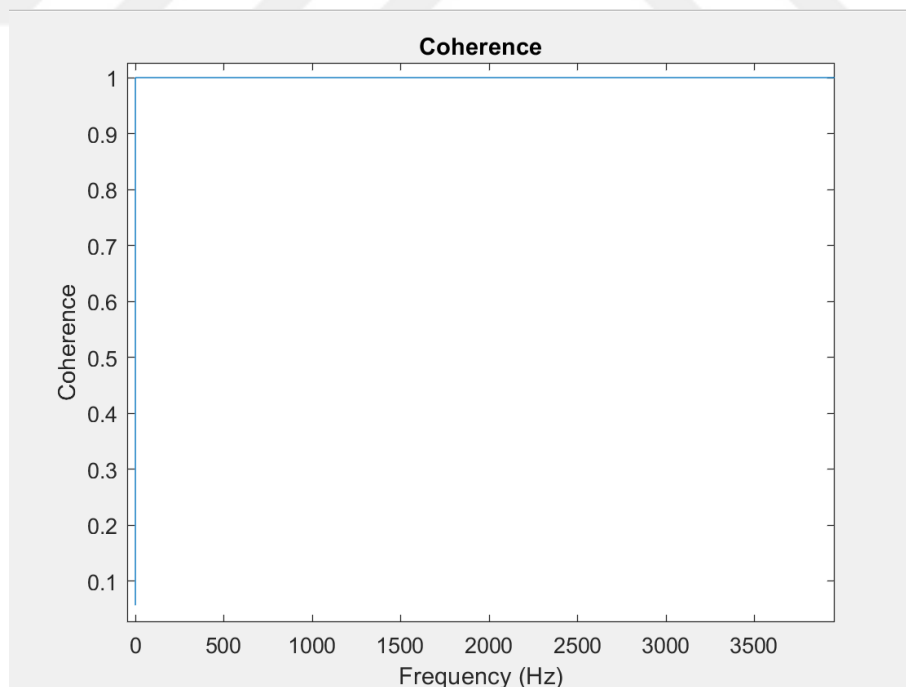


Figure B.2: Coherence Plot 2.

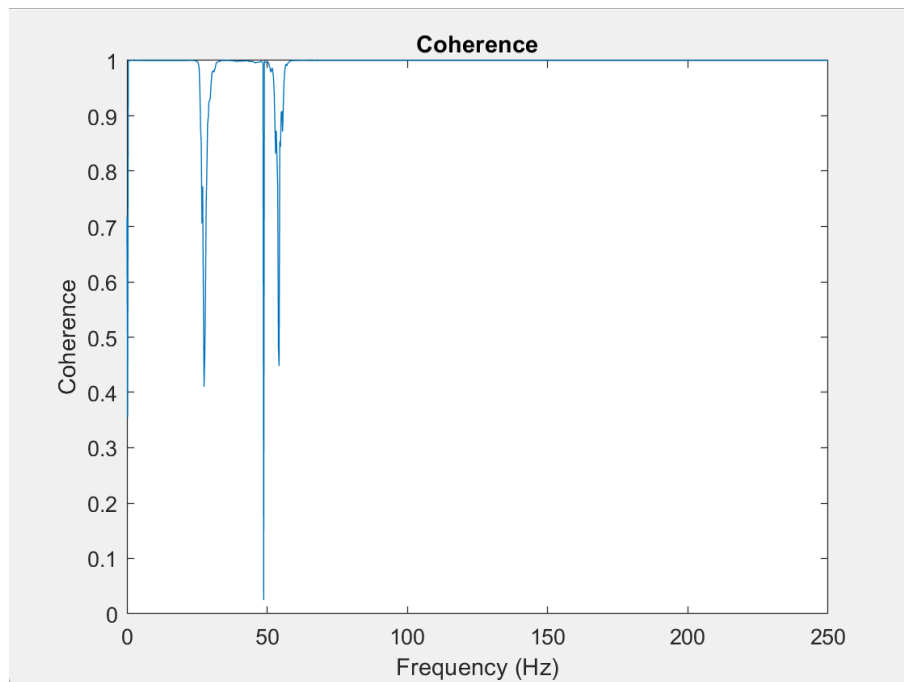


Figure B.3: Coherence Plot 3.

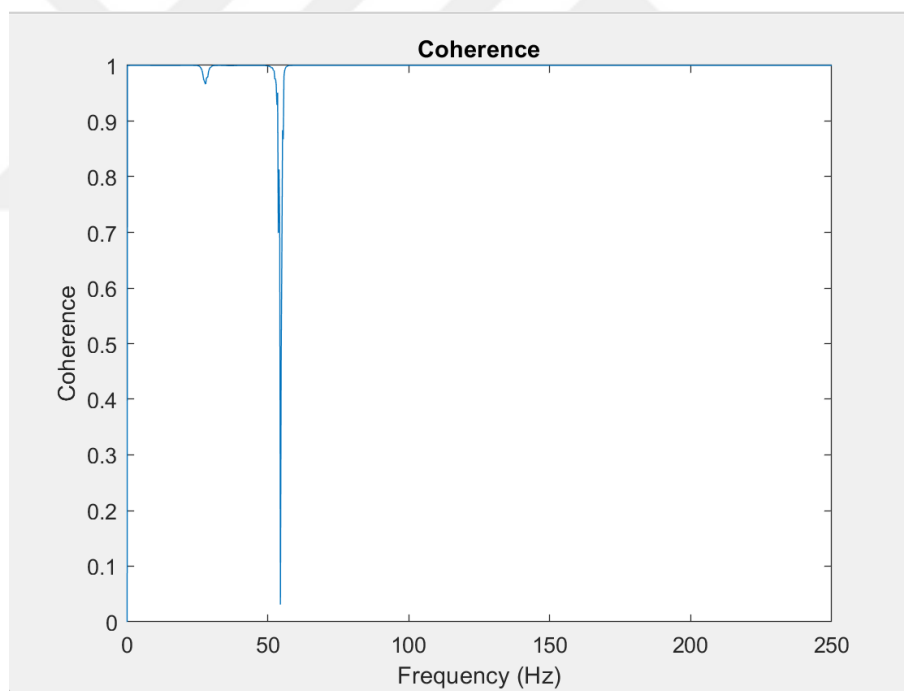


Figure B.4: Coherence Plot 4.

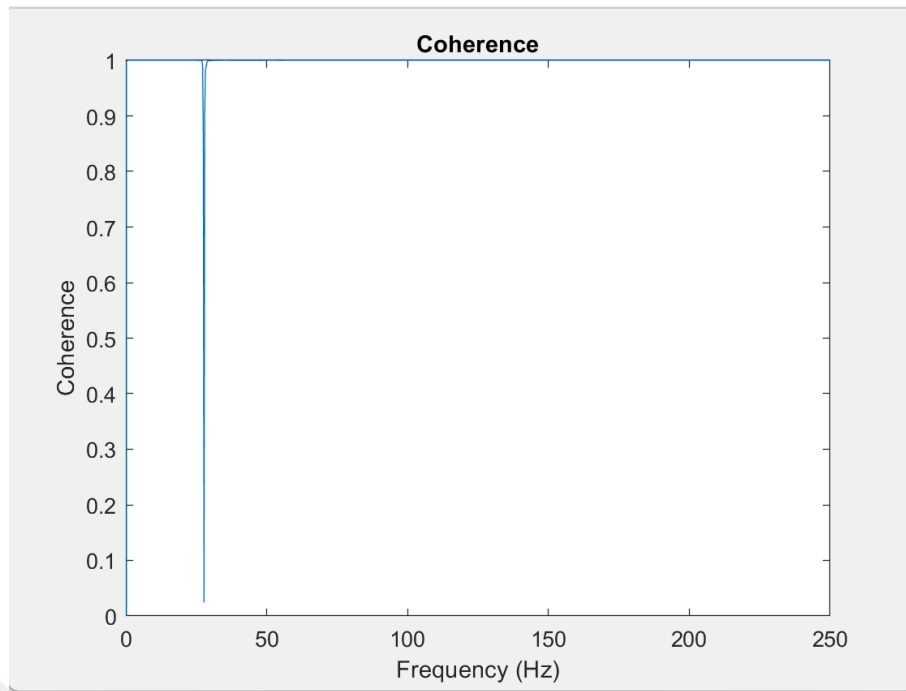


Figure B.5: Coherence Plot 5.

APPENDIX C: TECHNICAL DRAWINGS OF SAMPLES

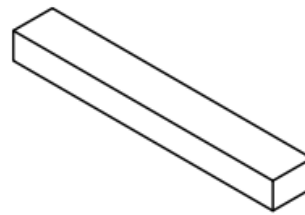
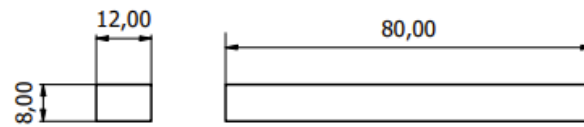


Figure C.1: Sample 1.

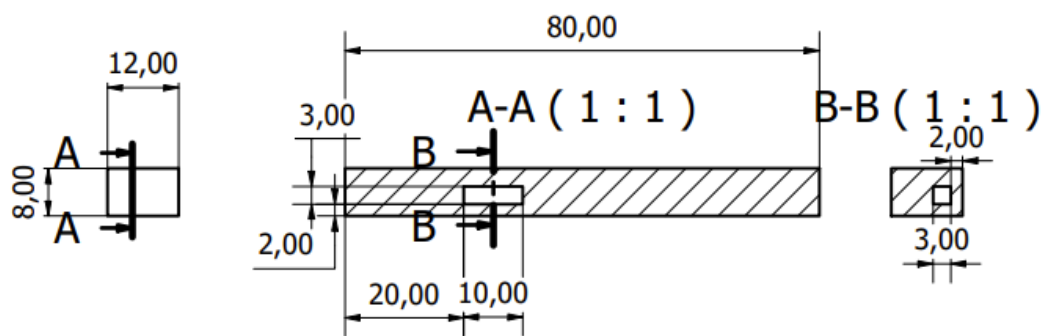


Figure C.2: Sample 2.

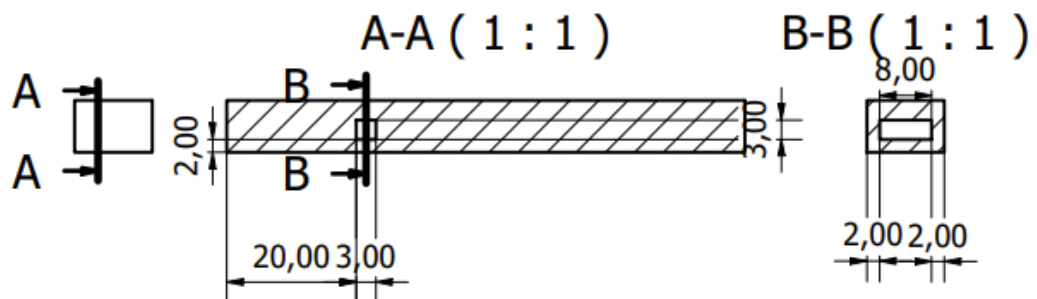


Figure C.3: Sample 3.

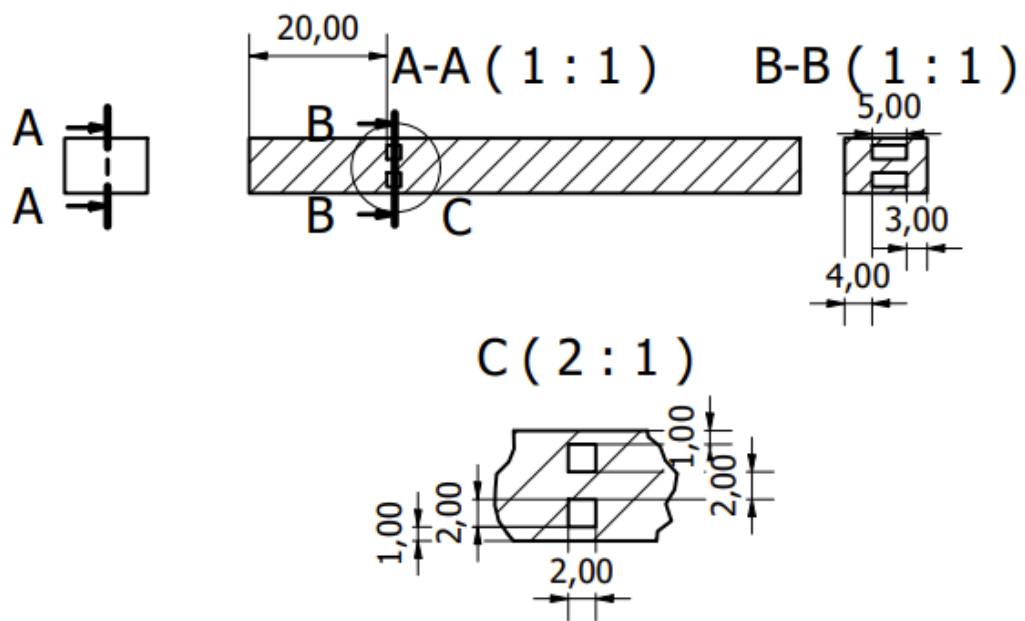


Figure C.4: Sample 4.

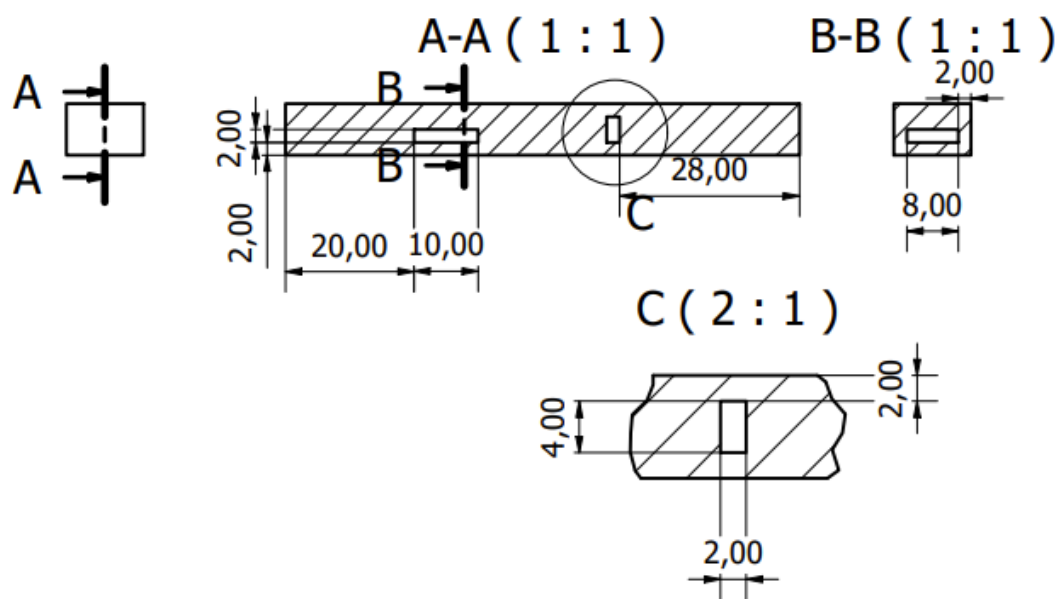


Figure C.5: Sample 5.

APPENDIX D: FRF PLOTS

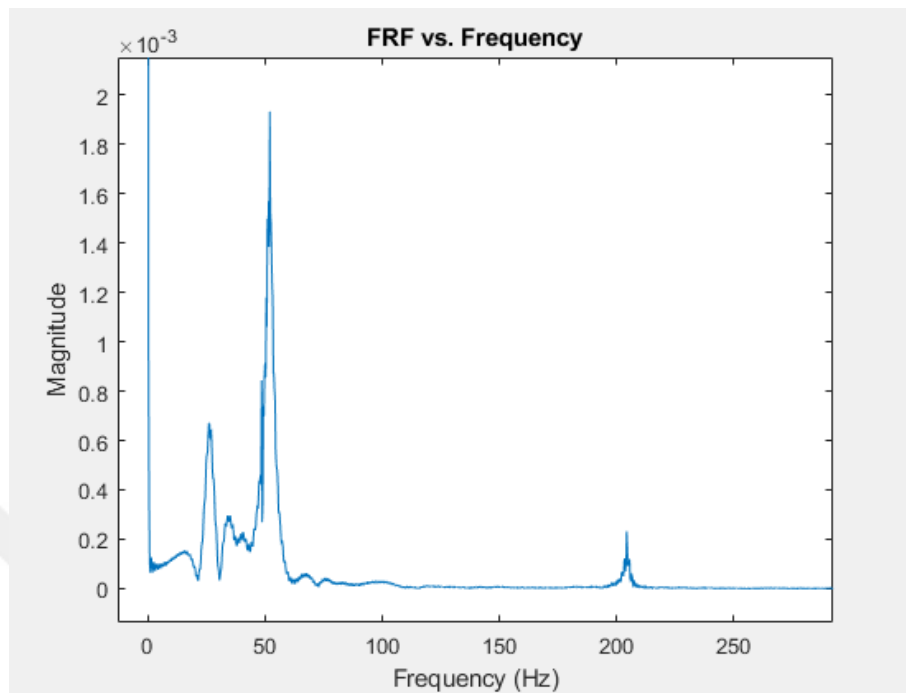


Figure D.1: FRF Plot 1.

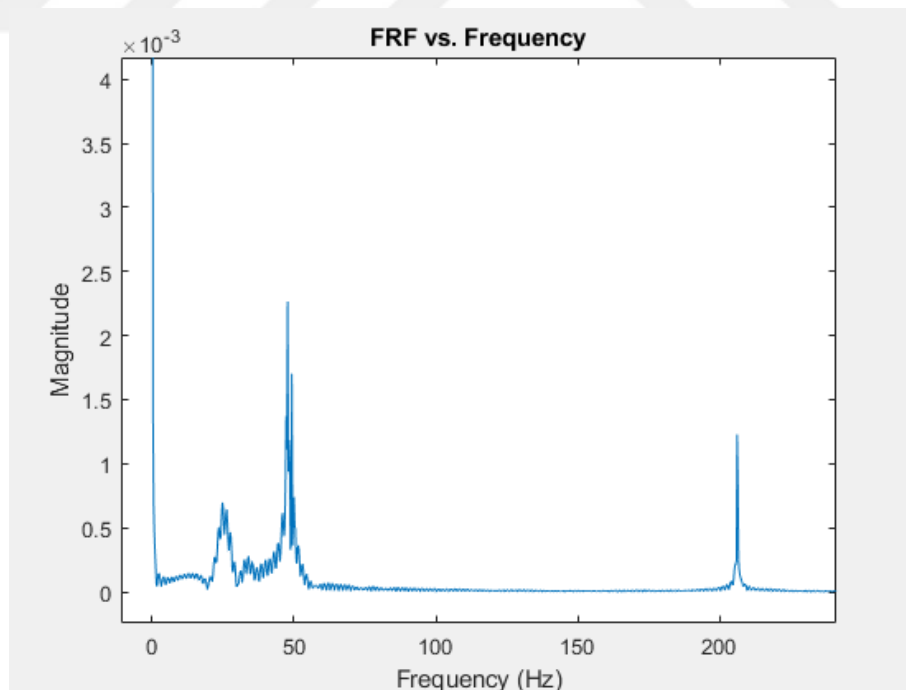


Figure D.2: FRF Plot 2.

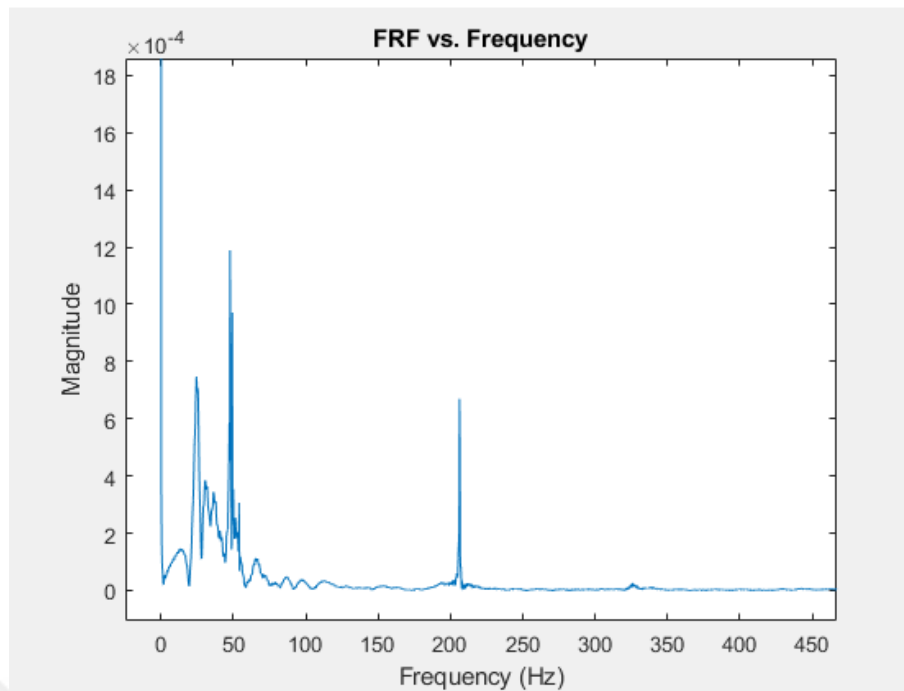


Figure D.3: FRF Plot 3.

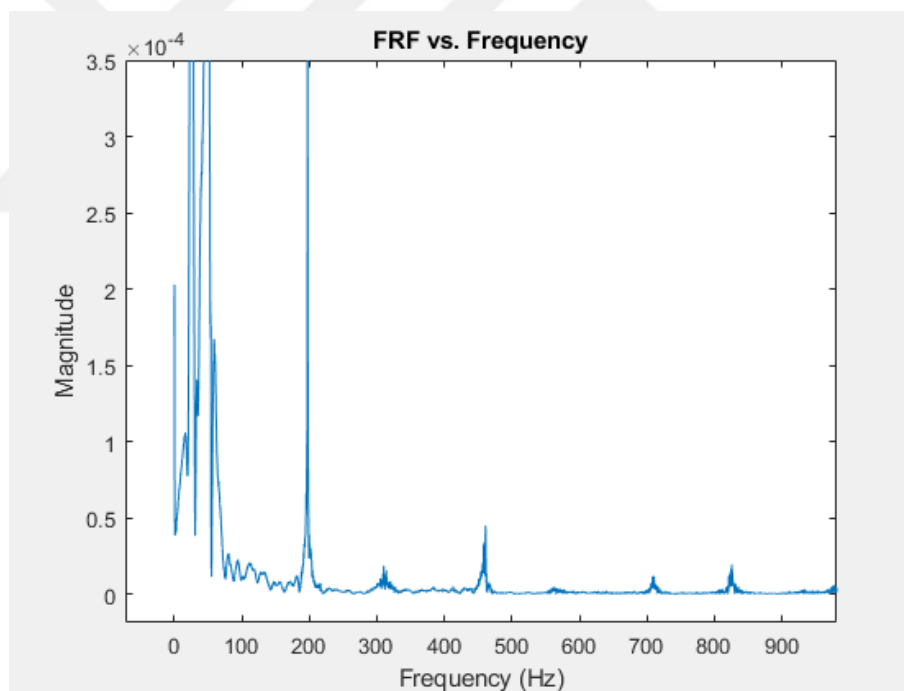


Figure D.4: FRF Plot 4.

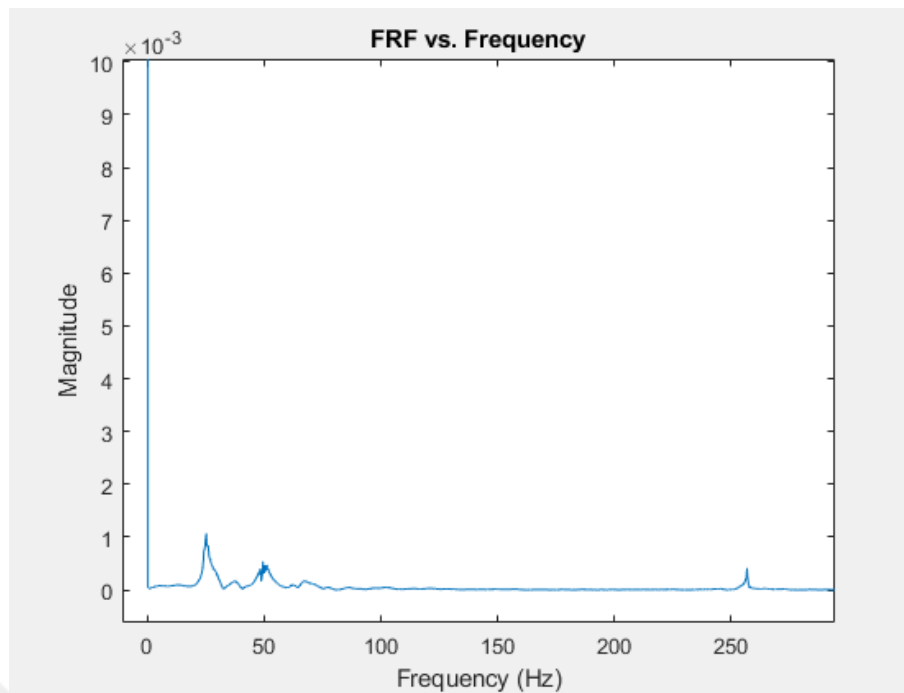


Figure D.5: FRF Plot 5.

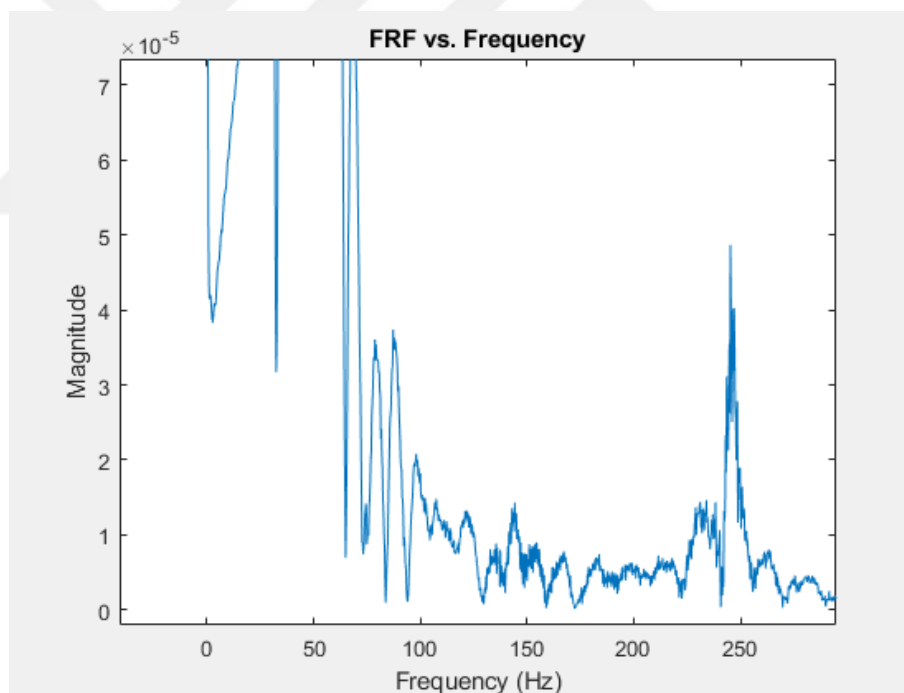


Figure D.6: FRF Plot 6.

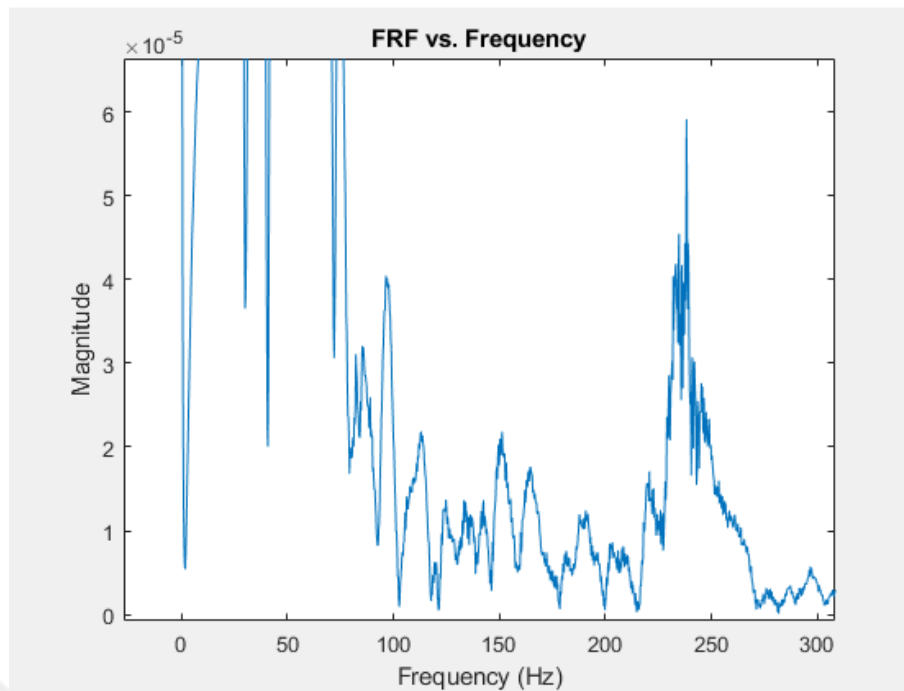


Figure D.7: FRF Plot 7.

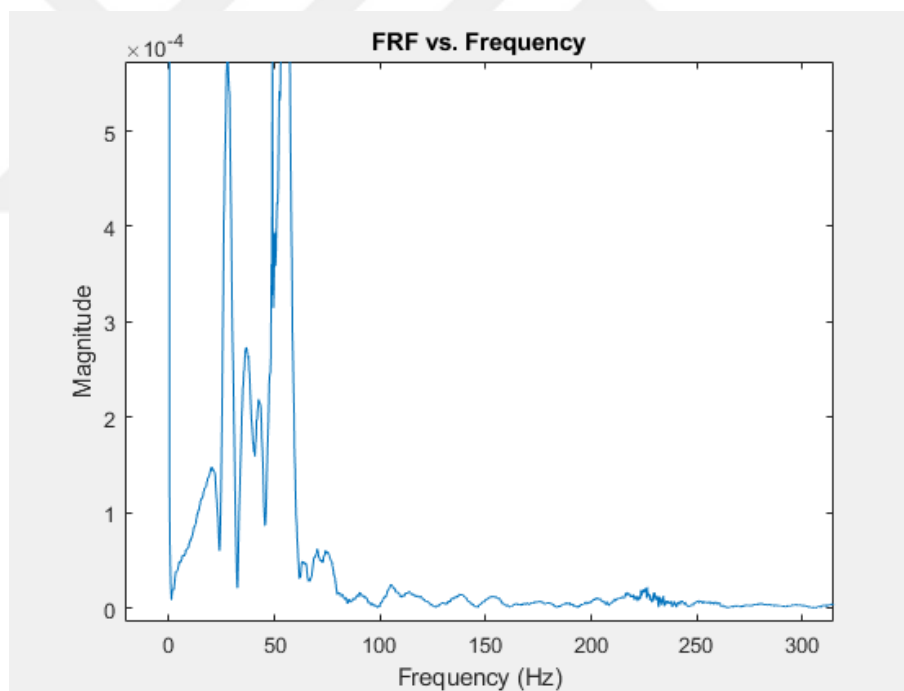


Figure D.8: FRF Plot 8.

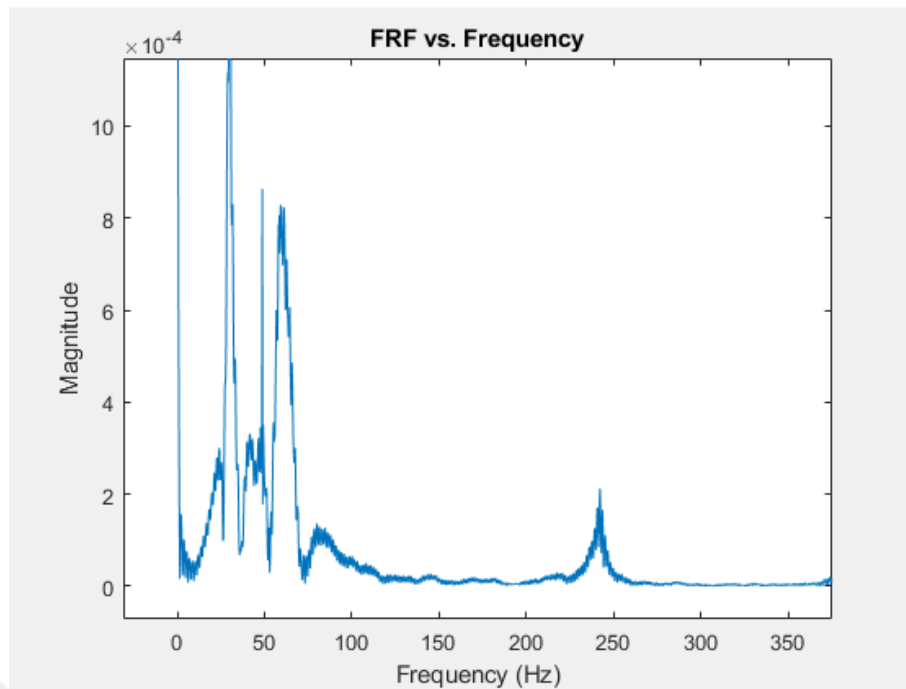


Figure D.9: FRF Plot 9.

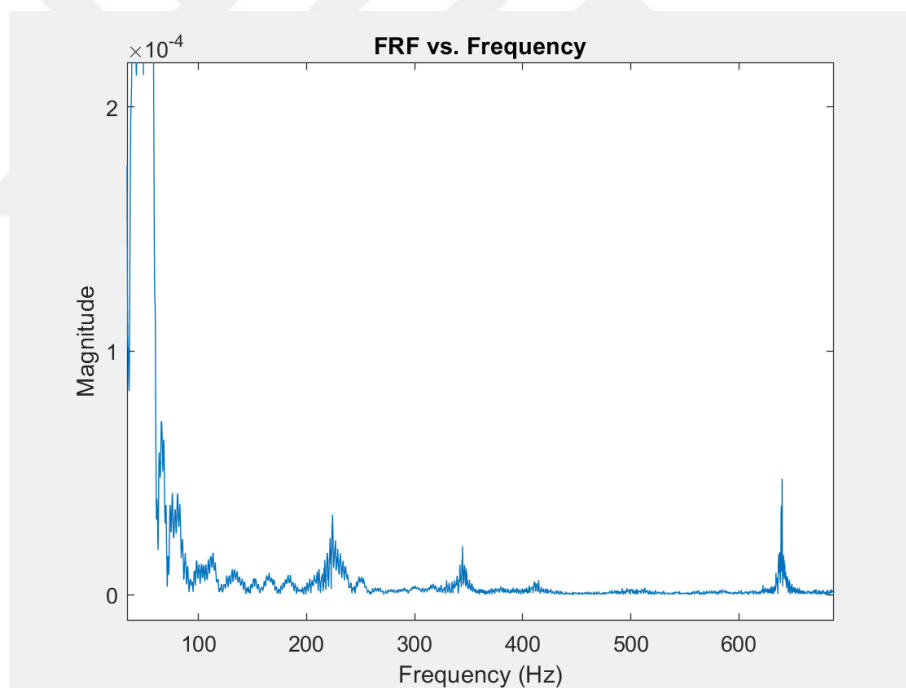


Figure D.10: FRF Plot 10.

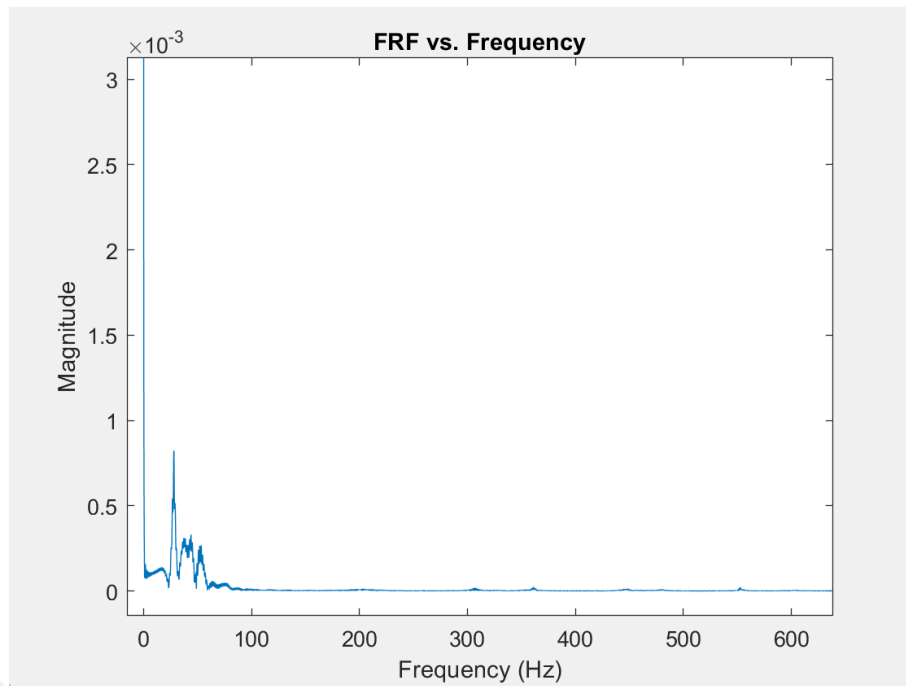


Figure D.11: FRF Plot 11.

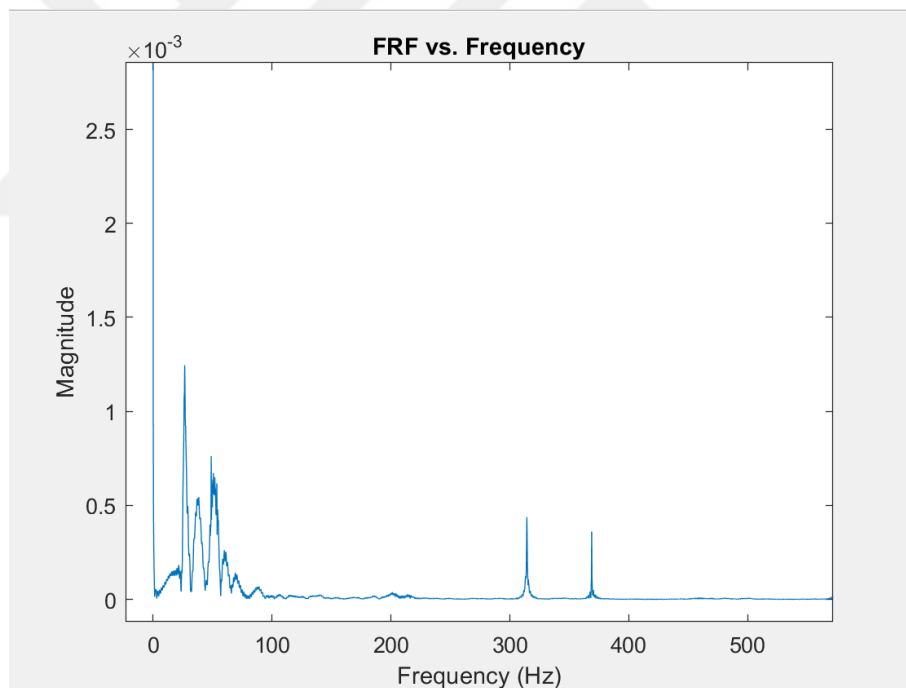


Figure D.12: FRF Plot 12.

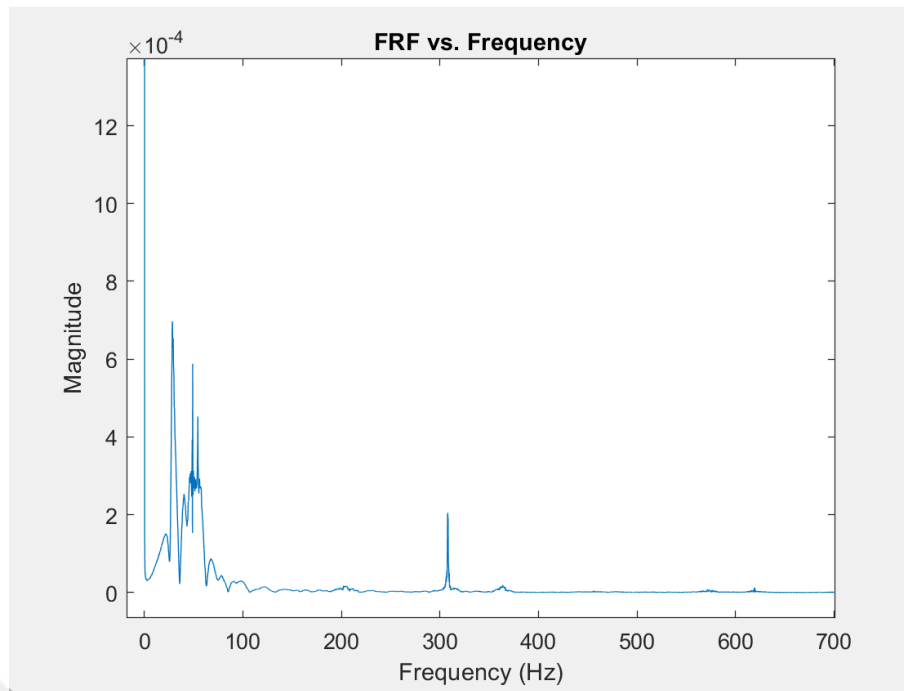


Figure D.13: FRF Plot 13.

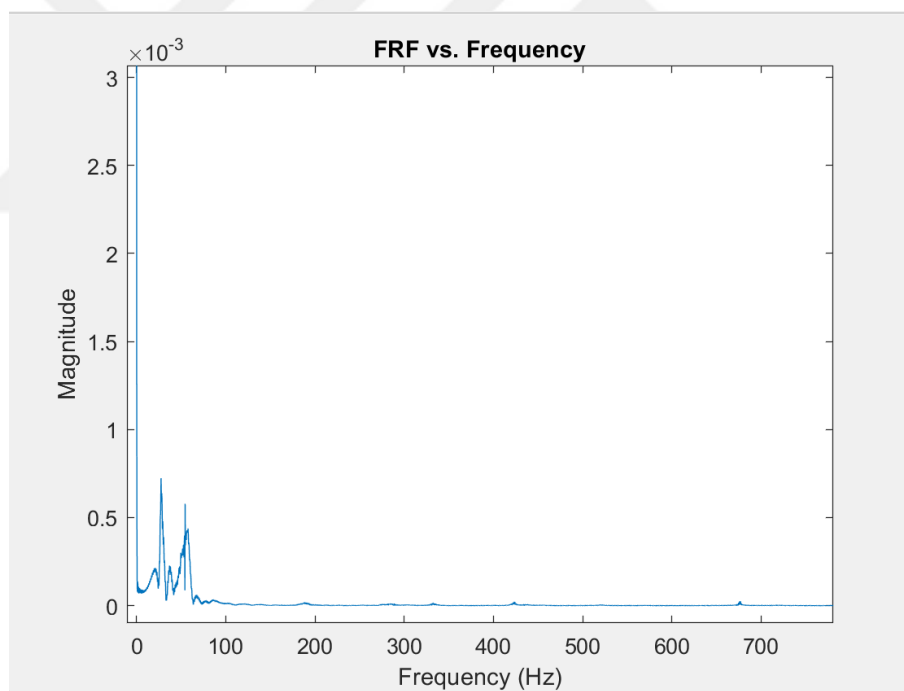


Figure D.14: FRF Plot 14.

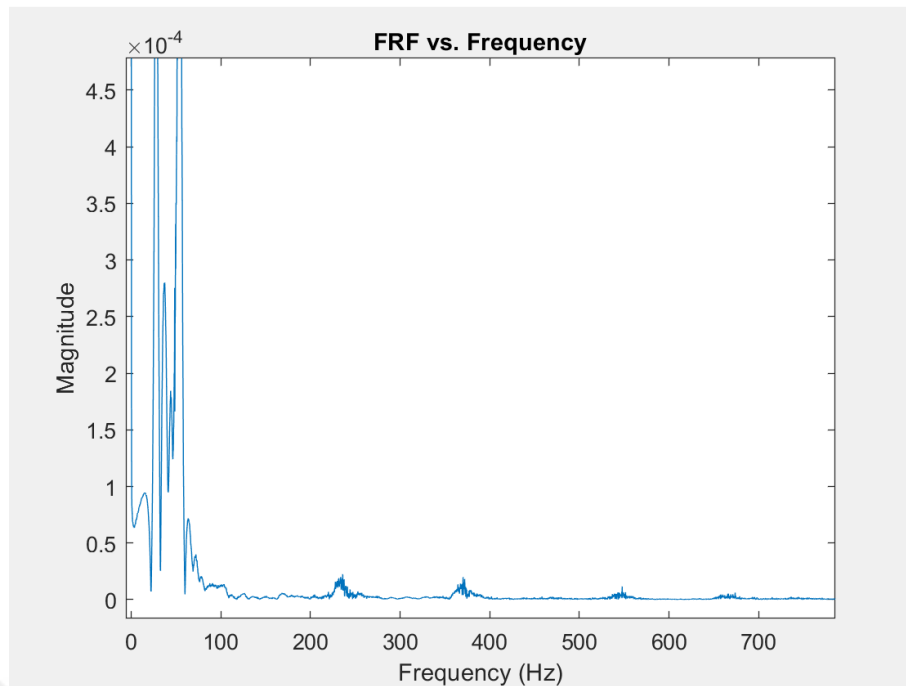


Figure D.15: FRF Plot 15.

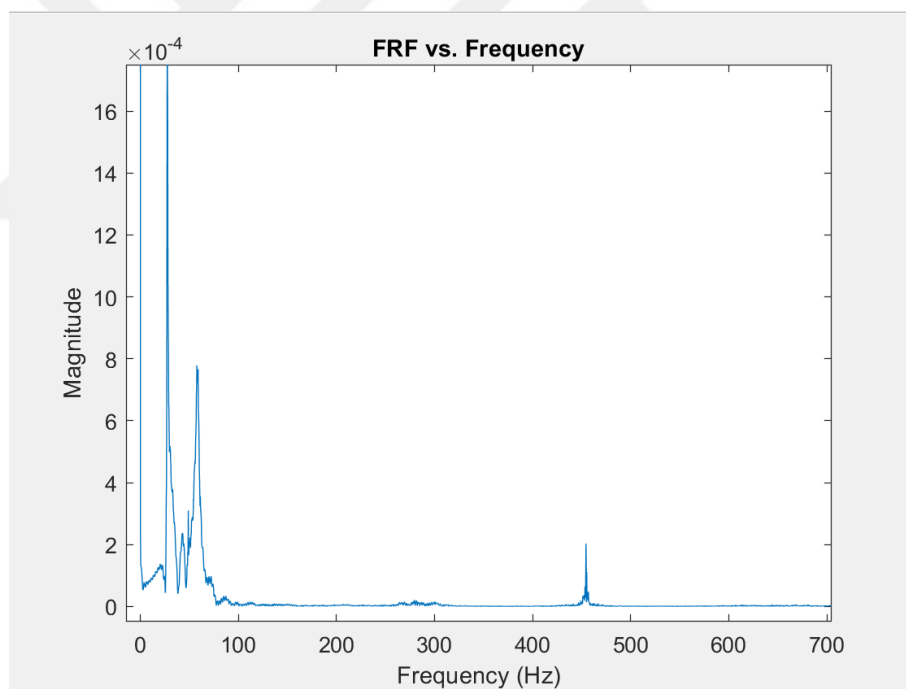


Figure D.16: FRF Plot 16.

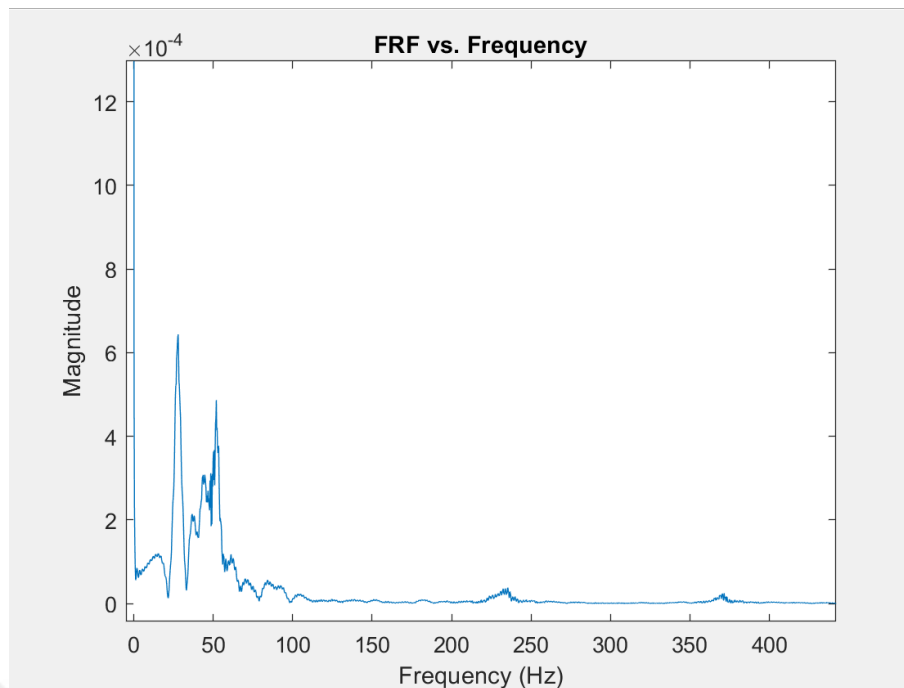


Figure D.17: FRF Plot 17.

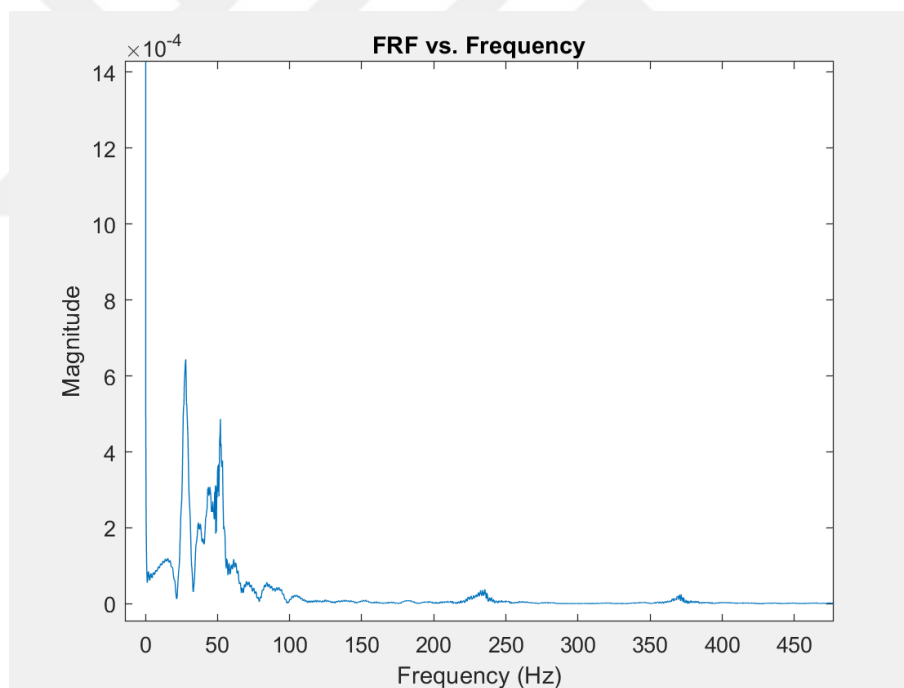


Figure D.18: FRF Plot 18.

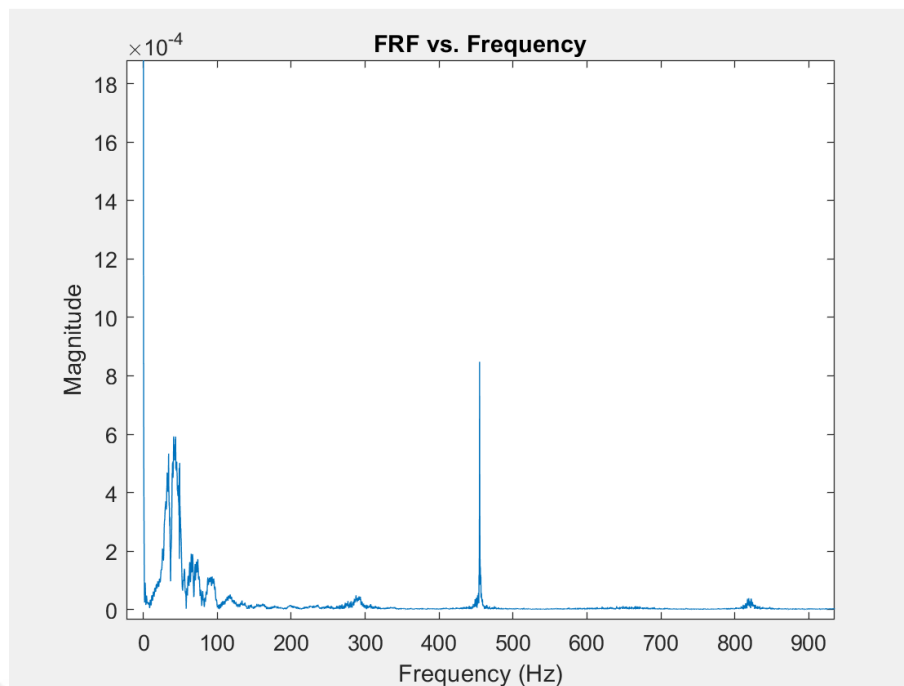


Figure D.1: FRF Plot 19.

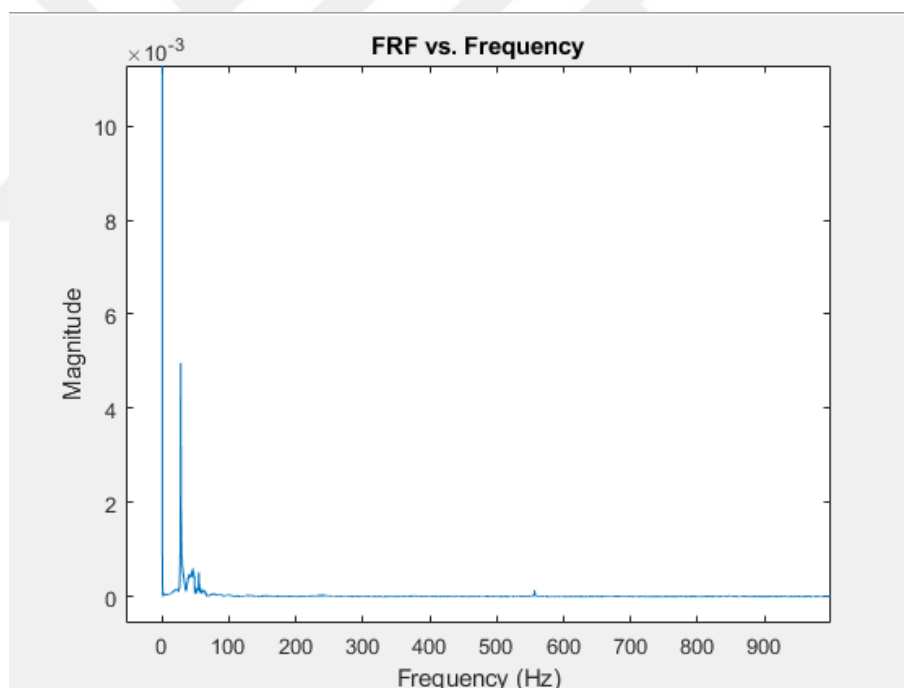


Figure D.20: FRF Plot 20.

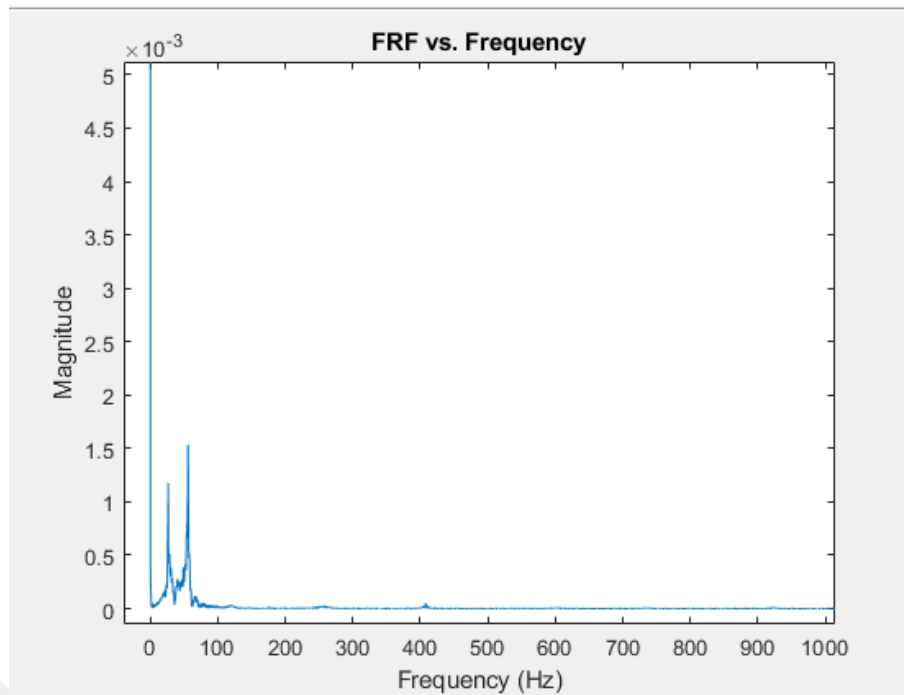


Figure D.21: FRF Plot 21.

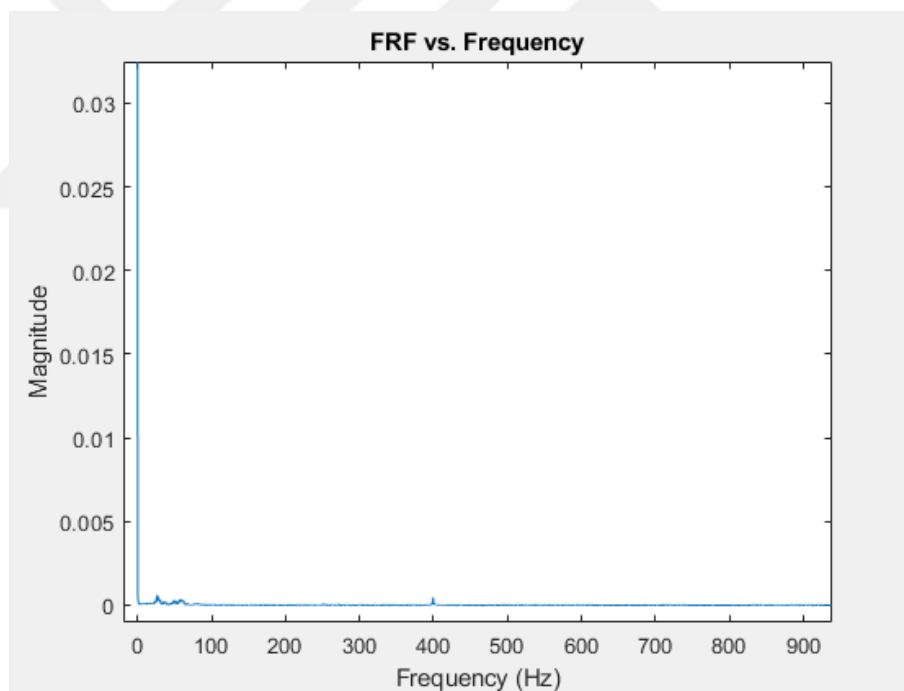


Figure D.22: FRF Plot 22.

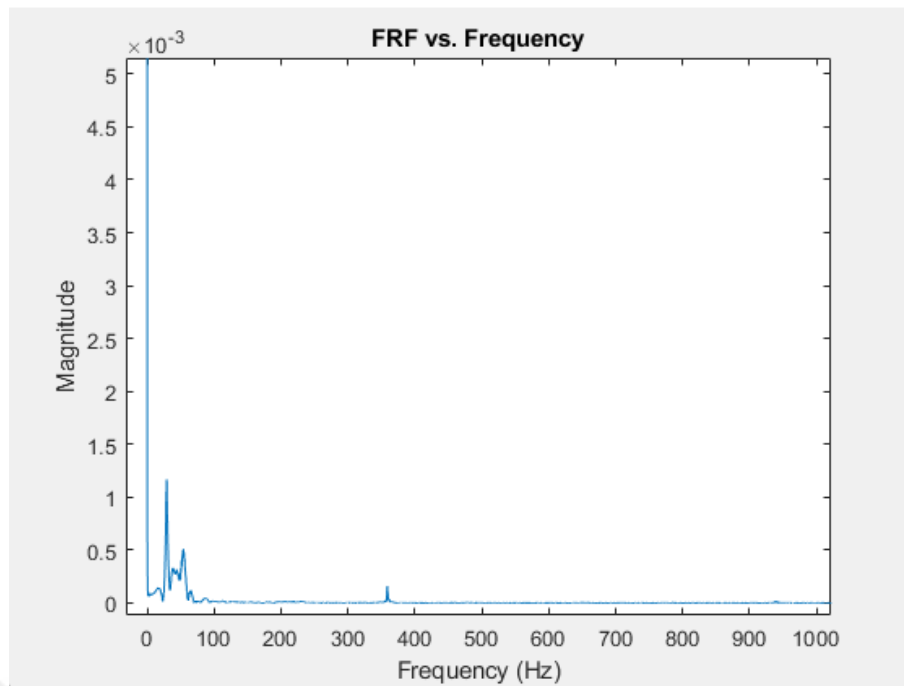


Figure D.23: FRF Plot 23.

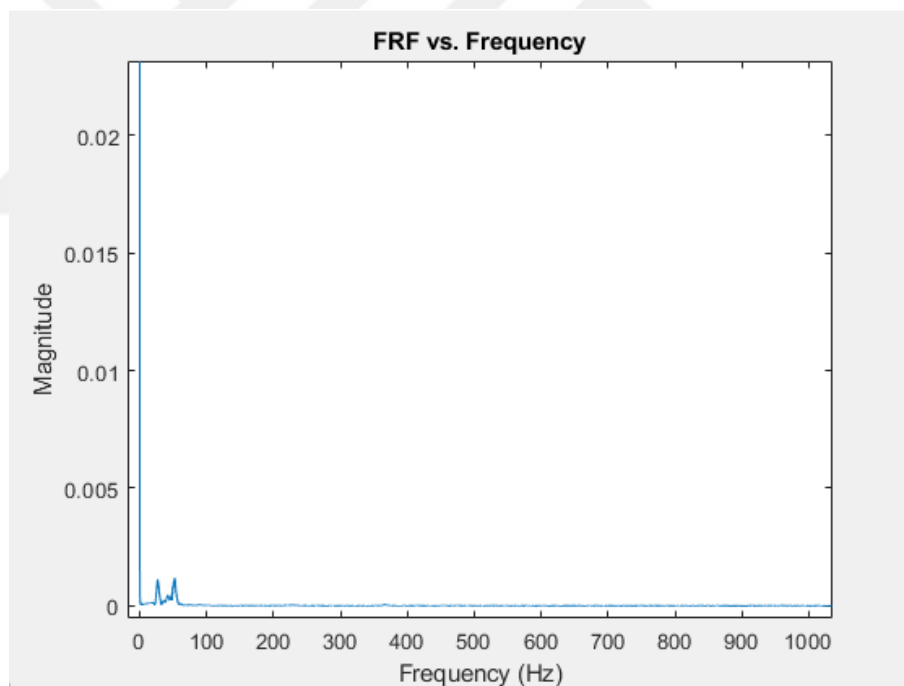


Figure D.24: FRF Plot 24.

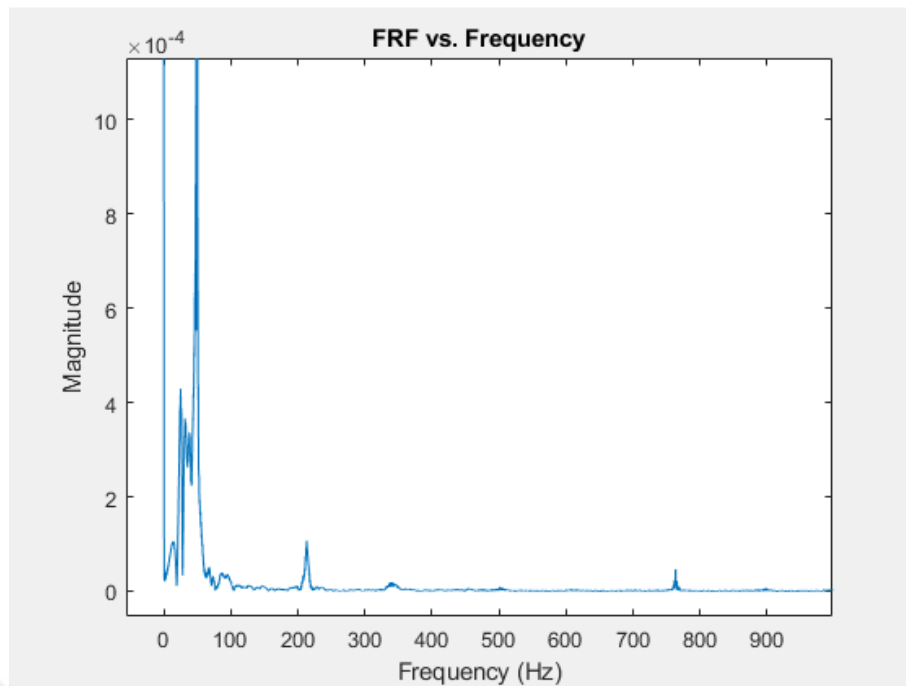


Figure 25: FRF Plot 25.