NUMERICAL INVESTIGATION OF DVA IN ATTENUATING THE TRANSMITTED HAND-ARM VIBRATION FROM THE MOTORBOAT ENGINE

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DECLARATION

This work has not previously been accepted in substance for any degree and is notbeing concurrently submitted in candidature for any degree.

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This thesis is the result of my own investigations, except where otherwise stated. Other sources are acknowledged by giving explicit references. Bibliography/references are appended.

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AHMAD SYAFIQ NAZRI BIN SHA'ARI
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LIST OF SYMBOLS

Symbols	Description	Unit
m	Mass of motorboat engine handle	kg
m_a	Mass of DVA	kg
m_h	Mass of hand-arm	kg
k	Stiffness of motorboat engine handle	N/m
k_a	Stiffness of DVA	N/m
k_h	Stiffness of hand	N/m
c_h	Damping of hand	kg/s
f	frequency	Hz
F	Excitation force	N
ω_n	Natural frequency	rad/s
μ	Mass ratio	-

LIST OF ABBREVIATIONS

HAVs	Hand-Arm Vibration syndromes
VWF	Vibration White Finger
EAV	Exposure Action Value
ELV	Exposure Limit Value
SDM	Structural Dynamic Modification
DVA	Dynamic Vibration Absorber
FEM	Finite Element Method
SSA	State-Switched Absorber
HVAC	Heating, Ventilation and Air Conditioning
SDOF	Single Degree of Freedom
2DOF	2 Degree of Freedom
FFT	Fast Fourier Transform

ABSTRAK

Pendedahan terhadap getaran tahap tinggi dalam tempoh yang lama boleh mendorong kepada masalah kesihatan seperti sindrom getaran tangan. Oleh itu, dalam kajian ini, pelemahan getaran tangan-lengan yang terhantar semasa mengendalikan enjin motorbot dinilai menggunakan pendekatan simulasi menggunakan perisian MATLAB/Simulink. Salah satu kaedah pengubahsuaian dinamik struktur telah digunakan dalam kajian ini untuk melemahkan getaran pada pemegang enjin motorboat iaitu menerusi penggunaan penyerap getaran dinamik. Dua darjah kebebasan yang mewakili pemegang enjin motorbot bersama penyerap getaran dinamik telah dimodelkan dan dapatan daripada simulasi dibandingkan untuk menilai pelemahan untuk kedua-dua kes kelajuan enjin. Simulasi juga telah dijalankan ke atas penyerap getaran dinamik dengan pelbagai nisbah jisim. Nisbah jisim yang dihasilkan dalam kajian ini adalah berdasarkan julat efektifnya, iaitu $0.05<\mu<0.25$. Daripada dapatan simulasi, penyerap getaran dinamik dengan nisbah jisim, $\mu = 0.25$ memberikan hasil terbaik yang mana telah berjaya mengurangkan getaran di pemegang sehingga 98.5 % dan 99.8 % untuk enjin pada kelajuan 1 dan 2. Kemudian, sistem kebebasan darjah tunggal yang mana telah dibangunkan berdasarkan model yang dihasilkan oleh Reynolds and Soedel, (1972) telah digabungkan dengan model pemegang enjin motorbot untuk menyiasat keberkesanan penyerap getaran dinamik dalam mengurangkan getaran tangan-lengan terhantar. Dapatan kajian menunjukkan getaran tangan-lengan telah berjaya dikurangkan sehingga 88.6 % dan 95.3 % untuk enjin dengan kelajuan 1 dan 2. Kesimpulannya, kajian ini membuktikan bahawa penyerap getaran dinamik boleh menjadi salah satu kaedah yang efektif dalam mengurangkan getaran tangan-lengan untuk pemegang enjin motorbot.

ABSTRACT

Prolonged exposure to the high level of vibration from motorboat engine handle can lead to the health associated problems such as the Hand-arm Vibration syndromes (HAVs). Therefore, in this study, the attenuation of transmitted hand-arm vibration during operation of motorboat engine is evaluated using simulation approach in MATLAB/Simulink software. One of the Structural Dynamic Modification (SDM) method is applied in this study to attenuate the vibration of motorboat engine handle which is the use of Dynamic Vibration Absorber (DVA). A 2 degree of freedom (2DOF) system that represents the motorboat engine handle with DVA has been modelled and the simulation results are compared to evaluate the vibration attenuation for two cases of engine speeds. The simulation was also caried out for DVA with various mass ratios. The mass ratio designed in this study is based on its effective range, which is $0.05<\mu<0.25$. From the simulation results, the DVA with mass ratio of $\mu = 0.25$ shows the best performance and successfully reduced the vibration of handle by 98.5 % and 99.8 % for both engine speeds 1 and 2, respectively. Then, a SDOF model which based on Reynolds and Soedel, (1972) models is coupled with the motorboat handle model to investigate the effectiveness of the DVA in reducing the transmitted hand-arm vibration. The result shows that the hand-arm vibration is reduced by 88.6 % and 95.3 % for both engine speeds 1 and 2, respectively. As a conclusion, this study proved that DVA can be one of an effective way to reduce hand-arm vibration for motorboat engine handle.

CHAPTER 1

INTRODUCTION

1.1 Background Study

Motorboat engine which also known as outboard engine is commonly used for small-scale boat in Malaysia. This engine is mounted to the boat to provide the propulsion to move the boat. A handle is usually used to control the speed and direction of the boat. However, the transmitted vibration from the engine boat to the handle and workers hand could occurred and this involved a high level of vibration amplitude. From this, the worker will be exposed to variety of vascular and non-vascular disorders or it can be classify under Hand-Arm Vibration syndromes (HAVs) (Mansfield, 2005).

In EU Good Practice Guide HAV of Vibration Directive 2002/ 44/ EC, the guideline has set the daily vibration exposure that workers must not exceed; the daily Exposure Action Value (EAV) and Exposure Limit Value (ELV) of 2.5 m/s^2 and 5.0 m/s^2 , respectively. This guideline need to be followed in order to control the hand-arm vibration risks to the workers (Griffin et al., 2006).

Structural dynamic modification (SDM) is one of the alternatives that can be utilized to overcome the vibration problem. This method is used to improve the dynamic behaviour of the structure, which can be done by predicting the modified behaviour of a structure like lumped masses, rigid links, dampers, beams or by changing the configuration parameter of the structure itself (Kundra, 2000). Basically, this method can be done through simulation software such as MATLAB/Simulink software to predict the modified behaviour.

One of the famous SDM method that can be implemented is by using dynamic vibration absorber (DVA). DVA is a spring-mass system that mounted in a structure (primary mass) to eliminate the harmonic excitation at any given frequency (Sun, et. al., 2008).

For the case of motorboat engine handle, there is no study of SDM using DVA that been carried out. Therefore, this study will investigate the effectiveness of DVA in attenuating the vibration from the motorboat engine handle to the worker hand-arm by using a simulation method.

1.2 Problem Statement

Fisheries are one of the most important sectors in Malaysia. For rural area fisherman, the used of small-scale boat are common and operating the motorboat engine for a long time may expose them to HAVs due to the high vibration amplitude transmitted from the motorboat engine handle. DVA is one of the methods that can be used to absorb the vibration of the primary mass (handle) by shifting the motion to the secondary mass (DVA). Therefore, the main purpose of this study is to investigate the effectiveness of DVA in reducing the transmitted hand-arm vibration from the motorboat engine handle to the operators.

1.3 Objectives

- To construct the model of motorboat handle-DVA using MATLAB/Simulink software.

- To investigate the vibration of the motorboat handle and hand-arm with varies engine speeds using simulation.

- To investigate the effect of DVA in attenuating the transmitted hand-arm vibration from motorboat engine using simulation.

1.4 Project Scope

This final year project is conducted to reduce the hand-transmitted vibration from the motorboat engine using SDM technique, or specifically using a DVA. This project aims to investigate the transmitted hand-arm vibration in term of occupational safety and health and the effect of DVA in attenuating the vibration from motorboat engine handle.

This project is a simulation-based, whereby MATLAB/Simulink software will be used to simulate the vibration results. Firstly, the model that represents the motorboat engine handle and DVA will be created using the software. Then, the disturbance data will be included as input force to the model to simulate the effect of the DVA towards the primary system. After that, the simulation result will be collected for vibration analysis.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

This chapter will discuss on following topics:

- Small-scale motorboat and engine application
- Hand-Arm Vibration syndrome (HAVs) and guideline
- Hand-arm models
- Structural Dynamic Modification (SDM)
- Dynamic Vibration Absorber (DVA)

2.2 Small-scale motorboat and engine application

Fisheries is one of the main industries in Malaysia. This industry increasing steadily at 4.5% per year from 1985 to 1997. This increment trend not only come from large-scale fishers but also from a small scale fishers which mostly in the rural area in Malaysia. (Ahmad, et. al., 2003). Most of small-scale fishers choose smaller boat as their transport to the sea (Yusop, et. al 2018). In order to powering the boat, an outboard engine is needed to provide propulsion for the movement.

Basically, the outboard engine is the same as usual car engine which burn the gasoline or petrol mixing with oxygen to produce the motion in metal cylinder, and the motion is transferred to piston and crankshaft which eventually move the wheels. The main difference between the outboard engine and car engine is that it has fewer cylinders, two or four-stage cycles in its operation and use motor to power the propeller instead of gearbox. To steer the boat, operator need to use an extended handle to move and tilt the motor (explainthatstuff.com, 2020). The use of hand to steer the motorboat handle may expose the operator to the hand-transmitted vibration. Figure 2.1 shows the typical small-scale boat with a handle directly mounted to the engine. The vibration from the engine can be transmitted to the handle and operator hand directly without any protection.

Figure 2.1 Operator operate motorboat engine (nelsonsspeedshop.com , 2021)

2.3 Hand-Arm Vibration syndrome (HAVs) and guideline

HAVs is a potential disease to any workers involving in prolonged use of tools or machines. HAVs could affect sensory, vascular and musculoskeletal system (Campbell, et. al. , 2017). The signs of HAVs usually develop after long exposure to the vibrating tools or machines which could cause permanent injury, as well as long-lasting pain in the hand and arms which leads to difficulties in performing daily activities (Azmir, et. al., 2016). HAVs is a serious and continuous disorder which need an early prevention (Heaver, et. al., 2011). A proper vibration regulation needs to be complied in order to control the risk of vibration. Thus, employees can be protected from poor health caused by the vibration (Health and Safety Executive, 2005). Raynaud's phenomenon is one of the most common vascular signs of HAVs with finger blanching and vibration white finger (VWF) (Nieradko-Iwanicka, 2019), as shown in Figure 2.2.

Figure 2.2 Example of HAVs (Blanching)

Based on recent studies, it shows that workers those are dealing with the high vibration instruments have the high potential to be affected by HAVs. For example, there is a study conducted on a group of gold miners in South Africa with 156 workers been assigned to the vibration-exposed group. As a result, 13 of them suffered both vascular and neurological symptoms, 8 suffered the neurological symptoms and 3 suffered vascular symptoms (Nyantumbu *et al.*, 2007).

Based on EU Good Practice Guide HAV of Vibration Directive 2002/44/EC, the daily vibration exposure, EAV and ELV were set at 2.5 m/s^2 and 5.0 m/s^2, respectively. These values must not be exceeded in order to control the hand-arm vibration risks to the workers. (Griffin *et al.*, 2006).

2.4 Hand-arm models

Dynamic behaviour of hand-arm system such as motion and force, can be observe by using biodynamic hand-arm model (Dong, et. al., 2005). Various type of human biodynamic hand-arm model has been developed to measure and characterize the responses of human hand-arm towards the vibration (Rakheja et. al., 2002).

Rakheja et. al., 2002, suggested that human biodynamics hand-arm model can be classified into two category which is to-the-hand and through-the hand models. To-the-hand usually used to evaluate the driving point mechanical impedance (DPMI) of hand-arm and through-the hand used to investigate the vibration transmission to the hand-arm.

There are various hand-arm models that have been developed by researchers. For example, Wood, et. al., (1978) introduced hand and forearm distributed-parameter models, as well as the full hand-forearm upper arm systems. In 1972, Reynolds and Soedel has designed SDOF hand-arm model that considered all three orthogonal axes direction to characterize the vibration responses. Based on Rakheja et al., (2002), there are several researchers that developed 3DOF and 4DOF hand-arm models. For example, Mishoe and Suggs (1977), conducted research on human hand-arm and the experiment utilized 3DOF system. In similar literature, several researchers have developed 3DOF and 4DOF models (Daikoku and Ishikawa, 1990); (Reynolds and Falkenberg, 1984); (Gurram, 1993). All of them introduced the model that are identical to the Mishoe and Suggs.

However, since there is no specific method during hand-arm vibration measurement, there will be a significant different on the result obtained (Rakheja et al., 2002). There is one model that suitable for the motorboat engine application, which is the model developed by Reynolds and Soedel (1972) since the frequency range of study is within 20-500 Hz, as shown in Figure 2.3.

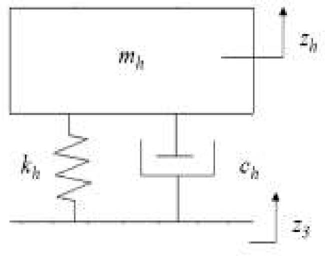

Figure 2.3 SDOF hand-arm equivalent model, (Mazlan et. al., 2015)

2.5 Structural Dynamic Modification (SDM)

SDM is a method used to identify the changes required in a structure in order to modify its dynamic characteristics which referring to the natural frequency and mode shape in the desired direction. One of the common goals of SDM is to enhance the structural or acoustic response which can be related to any of the following elements; the source of vibration, the transmission path or the noise radiating component (Sestieri, 2000).

Finite element method (FEM) is one of method that can be used to evaluate these characteristics. FEM is possible to be used to find the structural modification in terms of mass, stiffness and damping changes. However, for the real structure, it is more important to determine the modification in term of geometrical parameters (thickness, length, diameter) or material properties (damping coefficient, density, Young's modulus) changes (Nad, 2007).

In SDM method, DVA and state-switched absorber (SSA) are two common method that been used to control the vibration of structure. Based on research done by (Sun *et al.*, 2008), the performance of DVA and SSA are compared for the same primary system which have the same parameters, as shown in Figure 2.4. As a result, both systems have almost equal performance, except the dual DVA which have some advantages such as lower tuning frequencies, rapid optimization process and lower requirement for the anti-fatigue properties of the material.

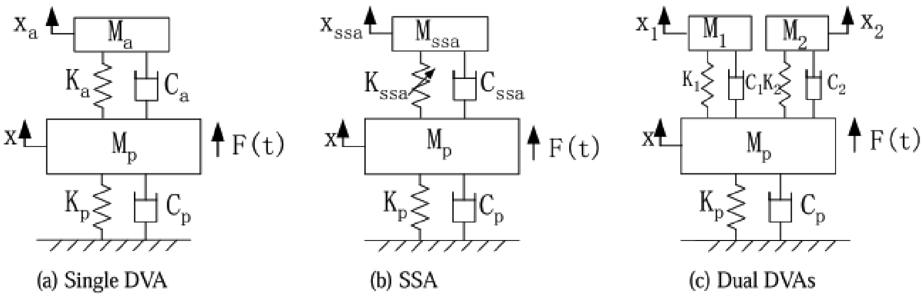

Figure 2.4 Single DVA, SSA and Dual DVA. (Sun et al., 2008)

In other study, the SDM technique has successfully reduced the acceleration level of grass trimmer up to 95 % (Hao, et.al, 2011). Also, another researchers found that by applying SDM technique on vehicle HVAC system, the resonance phenomenon can be avoided which indirectly reduced the vibration level of the whole system (Satar et al., 2019). Therefore, it can be said that SDM technique is one of the most effective techniques in reducing the vibration of the system.

2.6 Dynamic Vibration Absorber (DVA)

DVA is defined as a secondary or spring-mass system that attached to a primary system to absorb the vibration. DVA which also known as Tuned Vibration Absorber is commonly used to attenuate the structural vibration and noise radiation due to their simplicity, effectiveness and inherent stability characteristics. It is also used in suppressing vibration over a frequency band, generally in the targeted frequency range. Vibration reduction within the interested frequency band can be resulting a suppression of original peak and inducing of two newly emerged peaks by implementing the DVA into vibrating system (Yang, et. al, 2011). Figure 2.5 shows the theoretical model of the structure with DVA.

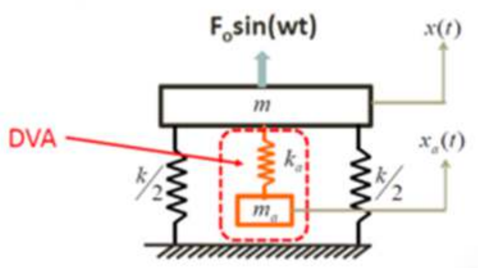

Figure 2.5 2DOF model of DVA attached to Primary system (Mazlan, 2019)

There is a research that been carried out to study the effectiveness of DVA in attenuating the vibration of grass trimmer. In this research, Dunkley's Equation was used to design the variable stiffness with dual masses vibration absorber. The study focusing on altering the effective stiffness in the system and its natural frequency by adjusting the absorber masses along the cantilever beam. As a result, the vibration of handle has successfully reduced by 80 % (Patil, 2019).

Another research has proved that by implementing DVA to the motorcycle handlebar, the vibration of handlebar can be attenuated by 59 % - 68 % on the speed of 30 -50 km/h. The study considered the vibration attenuation at different motorcycle's speeds in the x and z axis directions of the motorcycle handlebar (Saifudin, et. al, 2018). Figure 2.6 shows the detail comparison of handlebar vibration reduction at different speeds.

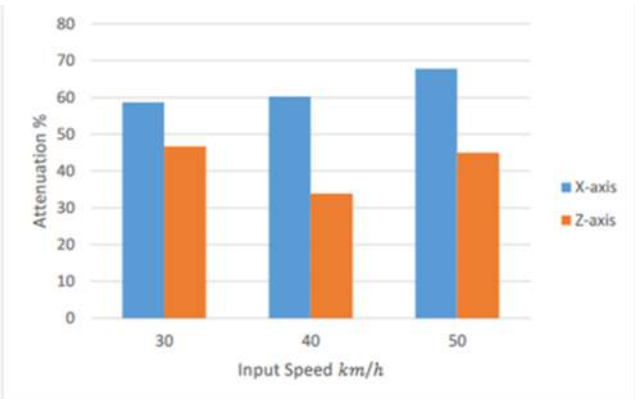

Figure 2.6 Vibration attenuation level at different motorcycle speed (Saifudin et al., 2018)

2.7 Summary

From the literatures, the following summary can be made:

- Small-scale boat and outboard engine are widely used in Malaysia for small-scale fishers that comes from rural area. The vibration from the engine can be transmitted to the operator due to direct mounted of handle to the engine.
- Prolonged exposure to the hand-transmitted vibration could lead to HAVs. EU Good Practice Guide HAV of Vibration Directive 2002/44/EC has set daily ELV and EAV threshold of 2.5 m/s^2 and 5.0 m/s^2, respectively and these values cannot be exceeded.
- There are a lot of hand-arm models that been developed which can be utilized to study the transmissibility of the handle-hand.
- SDM is one of the most effective method that can be used to attenuate the vibration by modifying its dynamic characteristics.
- DVA is one of SDM methods that can be applied to reduce the vibration by absorbing the vibration from the primary system to the DVA mass.

CHAPTER 3

METHODOLOGY

3.1 Overview

This chapter will discuss briefly on the following topics:

- 3D modelling of motorboat engine-handle
- Theoretical development of handle-DVA system
- Simulink model development
- Analysis of DVA performance
- Effect of DVA to the hand-arm vibration

3.2 3D modelling of Motorboat Engine-handle

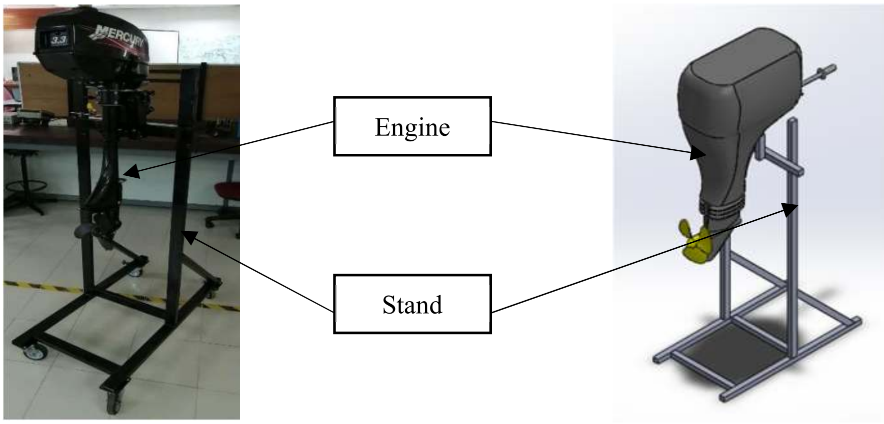

Figure 3.1 Real experiment setup for motorboat engine

Figure 3.2 Modelling of CAD for motorboat engine

Figures 3.1 and 3.2 show the real experiment setup and modelling of CAD for 3.3 Hp Mercury motorboat engine, respectively. In this study, the motorboat engine needs to be run and the input vibration data is recorded for the simulation purpose. A rig is built to hold the engine in position during operation. Therefore, a CAD design of the rig has been constructed which will be used as a stand to hold the engine.

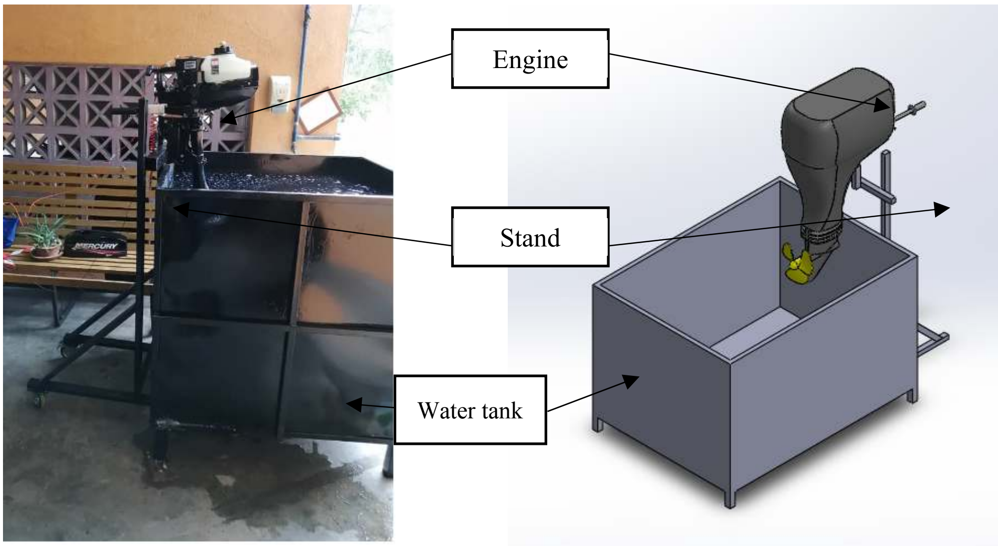

Figure 3.3 Real experiment setup for engine, stand and water tank

Figure 3.4 Modelling of CAD for engine, stand and water tank

Figures 3.3 and 3.4 show the real experiment setup and CAD modelling of the engine, stand and water tank, respectively. From the figure, when engine is running, it will pump the water to circulate through the engine system for cooling. Water is needed during the experiment, otherwise the engine will be broken due to overheating. Thus, a water tank was design in a CAD software as a container to store the water.

In this study, the simulation for the motorboat engine-handle is carried out using MATLAB/Simulink as in the experimental setup for the initial investigation of the DVA performance in attenuating the hand-transmitted vibration from the motorboat engine.

3.3 Theoretical development of handle-DVA system

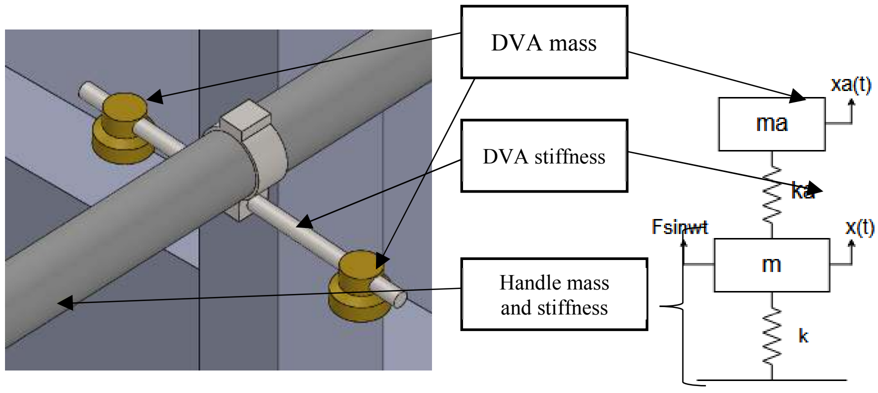

Figure 3.5 CAD design of DVA

Figure 3.6 Theoretical model of DVA with handle

Figure 3.5 shows the 3D model of DVA for motorboat engine handle. This DVA contain of two masses ($m_a = m_{a1} + m_{a2}$) connected by a rod (k_a) and attached to the motorboat engine handle. Meanwhile, Figure 3.6 shows the theoretical model of the DVA with the motorboat handle.

Based on Figure 3.6, the equation of motion for the system can be derived as follows:

$$\begin{bmatrix} m & 0 \\ 0 & m_a \end{bmatrix} \begin{Bmatrix} \ddot{x} \\ \ddot{x}_a \end{Bmatrix} + \begin{bmatrix} k + k_a & -k_a \\ -k_a & k_a \end{bmatrix} \begin{Bmatrix} x \\ x_a \end{Bmatrix} = \begin{Bmatrix} F sin\,\omega t \\ 0 \end{Bmatrix} \tag{3.1}$$

$$m\ddot{x} + x(k + k_a) - k_a x_a = F\, sin\,\omega t \tag{3.2}$$

$$m_a \ddot{x}_a + k_a x_a - k_a x = 0 \tag{3.3}$$

Divide Equations (3.2) and (3.3) by m and m_a, respectively:

$$\ddot{x} + \frac{x(k + k_a)}{m} - \frac{k_a x_a}{m} = \frac{F}{m} sin\,\omega t \tag{3.4}$$

$$\ddot{x}_a + \frac{k_a x_a}{m_a} - \frac{k_a x}{m_a} = 0 \tag{3.5}$$

Let $\frac{F}{m} sin\,\omega t = \frac{F}{m} e^{j\omega t}$ and assume the solution in form of :

$$X = x e^{j\omega t} \tag{3.6}$$

$$X_a = x_a e^{j\omega t} \tag{3.7}$$

By substituting Equations (3.6) and (3.7) into (3.4) and (3.5), hence :

$$X = \frac{\frac{F}{m}(\frac{k_a}{m_a} - \omega^2)}{\left(\frac{k + k_a}{m} - \omega^2\right)\left(\frac{k_a}{m_a} - \omega^2\right) - \frac{{k_a}^2}{m * m_a}} \tag{3.8}$$

$$X_a = \frac{\frac{k_a}{m_a}}{\left(\frac{k_a}{m_a} - \omega^2\right)} X \tag{3.9}$$

From Equation (3.8), the vibration displacement of primary system will become, $X = 0$ when $\frac{k_a}{m_a} = \omega^2$,whereby ω is the excitation frequency. Therefore, by tuning the natural frequency of DVA to be the same as excitation frequency, the internal energy of primary system can be transferred to the DVA significantly. Hence the vibration of primary system at its operating frequency can be reduced.

3.4 Simulink model development

In this section, the Simulink model for motorboat engine handle is modelled as single degree of freedom (SDOF) and the DVA is later included to the handle to become a 2 degree of freedom (2DOF) system. Firstly, the SDOF analysis is conducted to analyse the vibration of handle and later the result is compared with 2DOF vibration analysis results which include the DVA.

3.4.1 Modelling of SDOF motorboat handle

SDOF of motorboat handle is modelled using MATLAB/Simulink software as shown in Figure 3.7, which based on Equation (3.10). This model is developed to investigate the vibration of primary system (handle) without the DVA. Then, the outcome is compared with the vibration of the handle with DVA attachment.

$$m\ddot{x}(t) + kx(t) = F\ sin\omega t \tag{3.10}$$

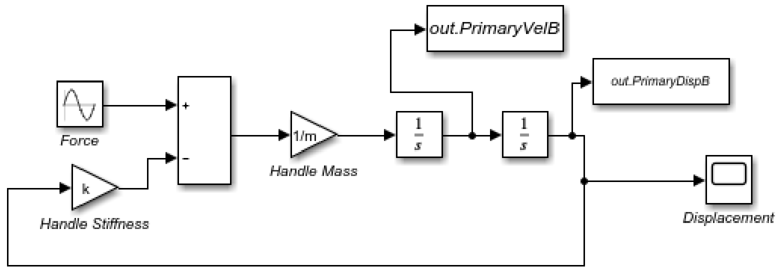

Figure 3.7 SDOF model of motorboat handle in Simulink software.

3.4.2 Modelling of 2DOF motorboat handle with DVA

2DOF of motorboat handle with DVA is modelled using MATLAB/Simulink software as shown in Figure 3.8. From the figure, the first degree of freedom is representing the motorboat handle and the second degree of freedom is referring to the designed DVA. This model is constructed based on Equation (3.4) and (3.5), previously. The model will be investigated using different DVA parameters in order to capture the effectiveness of the DVA to the motorboat handle.

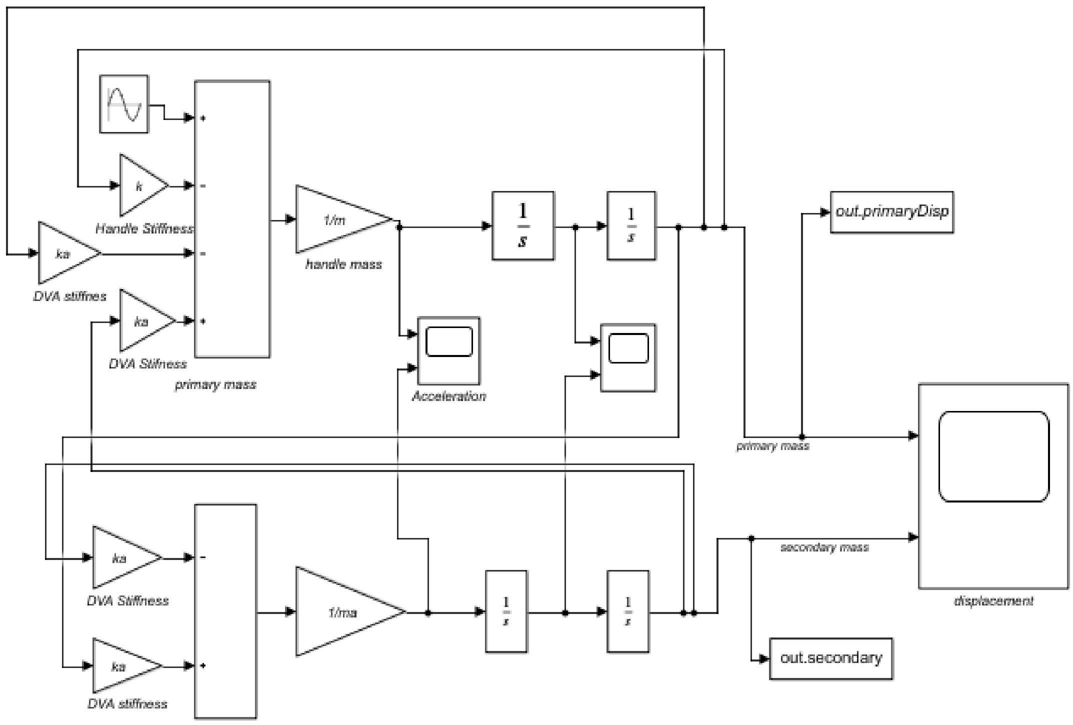

Figure 3.8 2DOF of handle-DVA system in Simulink

3.5 Analysis of DVA Performance

In this simulation, the disturbance measured data from motorboat engine will be used as an input force to the handle. Two engine speeds will be investigated in this study (speed 1 = 50 Hz and speed 2 = 100 Hz). In this simulation, the effect of DVA on the primary system (handle) will be investigates to determine the effectiveness of DVA.

Table 3.1 shows the parameter study for the handle and DVA systems. From the table, case study 1(a)-(c) use 50 Hz = 100π (rad/sec) of excitation frequency, which represent the operating frequency of engine at speed 1, while case study 2(a)-(c) use 100 Hz = 200π (rad/sec), which represent the operating frequency of engine at speed 2.

In this study, the mass of DVA designed based on the mass ratio, μ curve in Figure 3.9 and Equation (3.11) :

$$\mu = \frac{m_a}{m} \tag{3.11}$$

From the figure, if the mass ratio, μ is too high, the frequencies will split farther apart ($>\omega_2$) and if the μ is too small, the DVA will not be able to tolerate much fluctuation in driving frequency ($<\omega_1$), which will decrease the effectiveness of the DVA. Therefore, the mass ratio, μ designed for this study is based on its effective range, which is $0.05< \mu<0.25$.

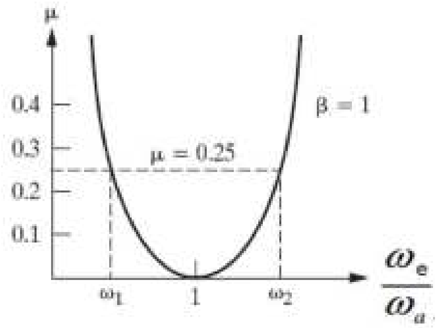

Figure 3.9 Effective range of mass ratio curve (Mazlan, 2019)

Table 3.1 Parameters used to test the system.

Case study		Excitation Force (N)	Frequency (rad/s)	Primary system mass, m (kg)	DVA mass, m_a (kg)	Mass ratio, μ	Primary system stiffness, k (N/m)	DVA stiffness, k_a (N/m)
1	a	30	100π	0.534	0.0267	0.05	57638	2635
	b	30	100π	0.534	0.0801	0.15	57638	7906
	c	30	100π	0.534	0.1335	0.25	57638	13176
2	a	30	200π	0.534	0.0267	0.05	210815	10541
	b	30	200π	0.534	0.0801	0.15	210815	31622
	c	30	200π	0.534	0.1335	0.25	210815	52704

3.6 Effect of DVA to the hand-arm vibration

In order to characterize the biodynamic reaction of the human hand-arm under particular vibration, a SDOF model (Reynolds and Soedel, 1972) is chosen to represent the hand-arm system. This model is based on the driving-point mechanical impedance (DPMI) response under various hand-arm postures and grip forces (Rakheja, et al., 2002). With the studied frequency range within 20-500 Hz, the model is considered valid to represent hand-arm in this study. The resulting mechanical equivalent model is shown in Figure 2.3, previously.

Based on the figure, a SDOF of motorboat handle is developed using MATLAB/Simulink software as shown in Figure 3.10, which based on Equation (3.12). This model is developed to investigate the transmitted hand-arm vibration from motorboat engine at speed 1 and 2, with and without the DVA.

$$m\ddot{x}_h(t) + c\dot{x}_h(t) + kx_h(t) = c\dot{x}(t) + kx(t) \tag{3.12}$$

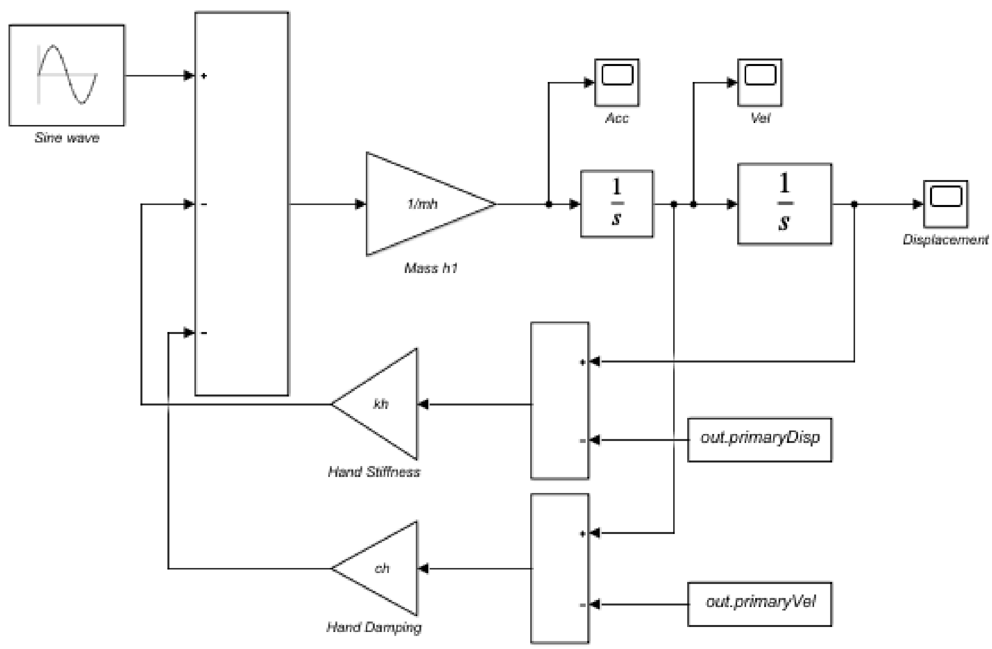

Figure 3.10 Hand-arm model in Simulink software

The hand-arm model parameters of SDOF Reynolds and Soedel, (1972) model in x_h, y_h, and z_h axis direction for frequency above 100 Hz are shown in Table 3.2, respectively. in this study only single axis vibration (z_h) is considered.

Table 3.2 Hand-arm model parameters of SDOF Reynolds and Soedel, (1972) model.

Direction	Hand mass, mh (kg)	Hand damping , ch (kg/s)	Hand stiffness, kh (N/m)
xh	2.19 x 10-2	85.6	5.38 x 104
yh	7.2 x 10-3	35.7	1.486 x 104
zh	9.5 x 10-3	62.9	2.96 x 104

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Overview

This chapter will discuss briefly on following topics:

- Disturbance models
- Handle vibration without DVA
- Handle vibration with DVA
- Effect of DVA to the hand-arm vibration

4.2 Disturbance models

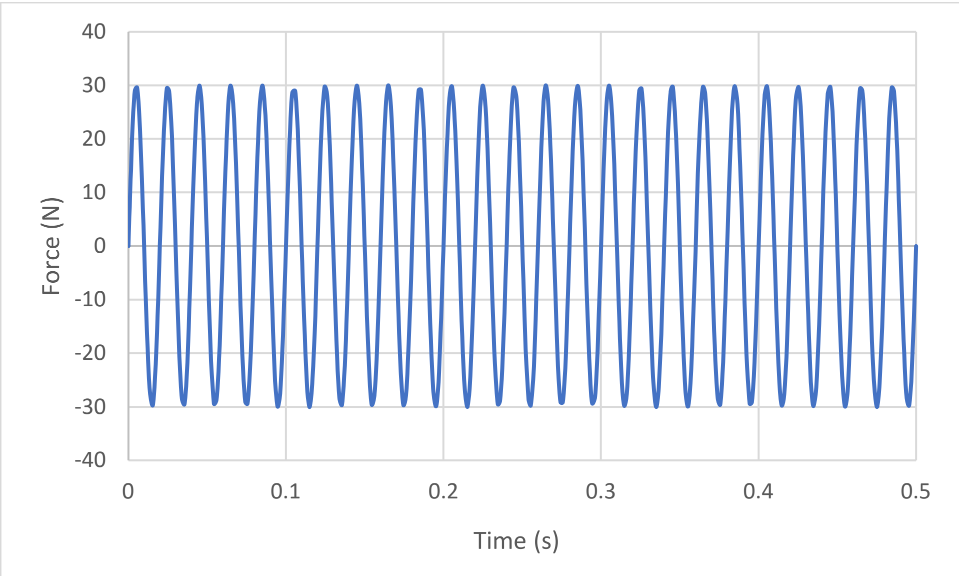

Figure 4.1 Time domain force excitation from the motorboat engine (Speed 1)

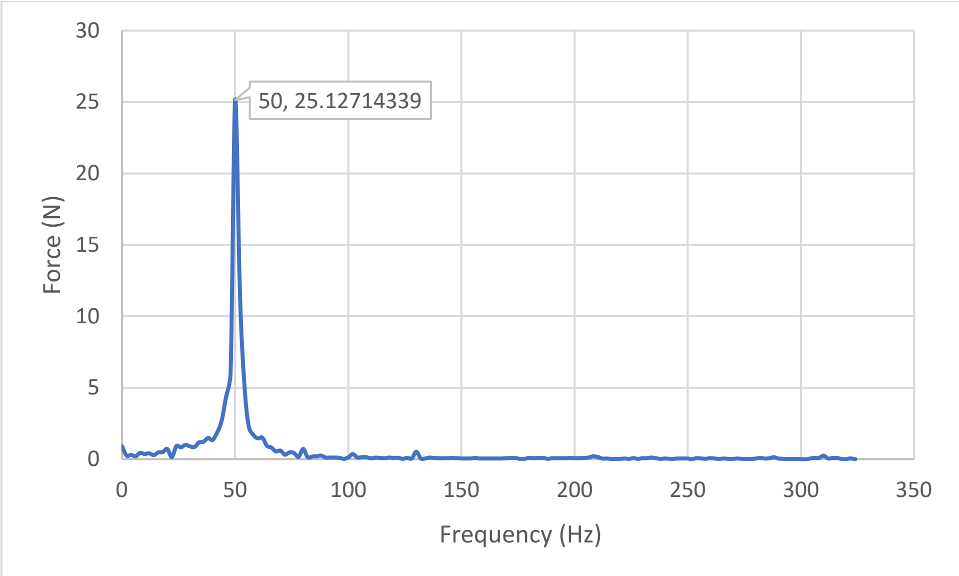

Figure 4.2 Frequency domain force excitation from the motorboat engine (Speed 1)

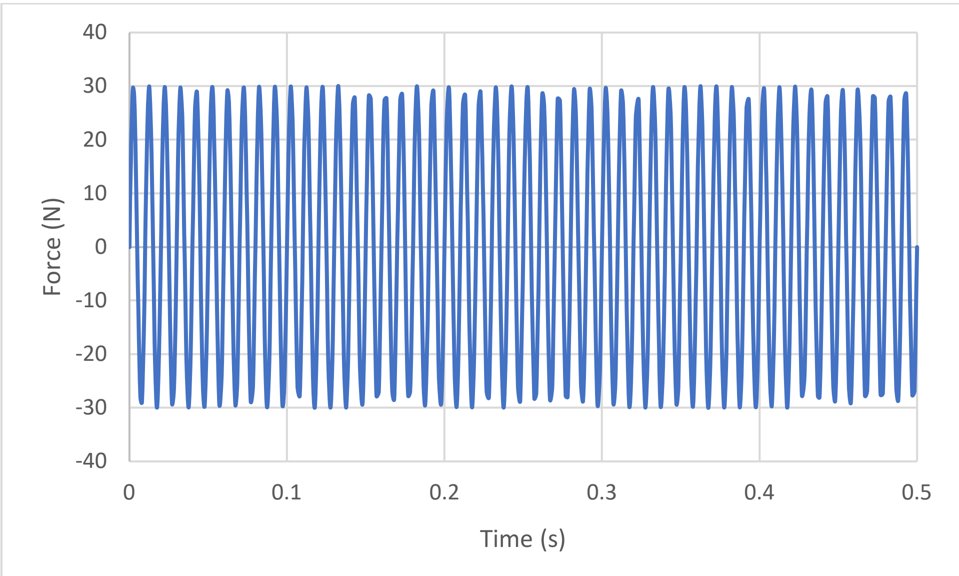

Figure 4.3 Time domain force excitation from the motorboat engine (Speed 2)

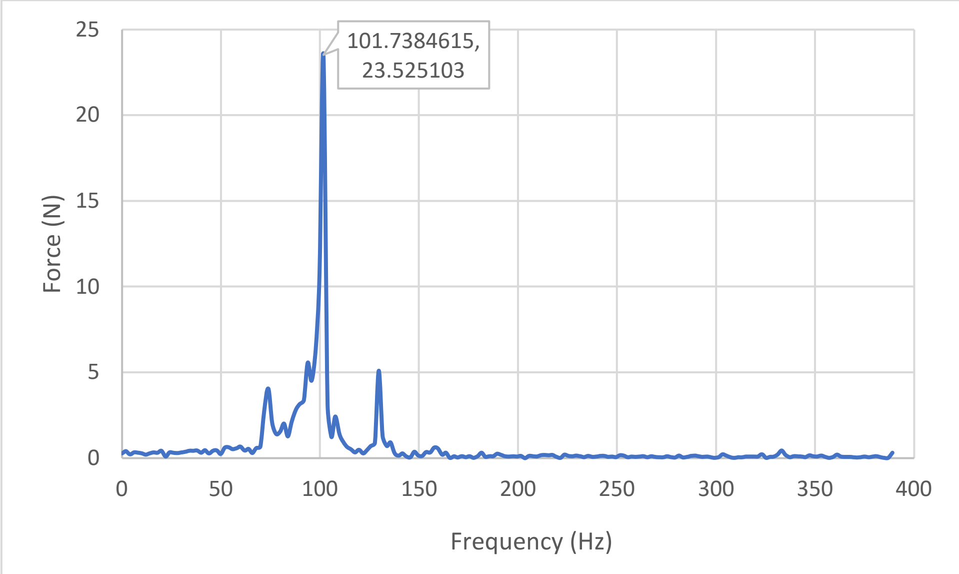

Figure 4.4 Frequency domain force excitation from the motorboat engine (Speed 2)

Figures 4.1 and 4.2 show the time and frequency domain (FFT) of force excitation from the motorboat engine at speed 1, respectively while Figure 4.3 and 4.4 highlighted the vibration for speed 2.

Based on both FFT graph, the engine speed 2 is observed to have higher frequency range. For engine speed 1, the highest amplitude is observed at 50 Hz with the peak vibration amplitude at 25.13 N. Meanwhile, for speed 2, the highest forcing amplitude occurred at 101.74 Hz with the peak force of 23.53 N.

Both forcing vibration are determined from the experiment and remodeled in the MATLAB/Simulink software for the analysis.

4.3 Handle vibration without the DVA

Figures 4.5 and 4.6 show the time and frequency responses of handle vibration at engine Speed 1, respectively, while Figures 4.7 and 4.8 show the vibration responses for speed 2. From the time domain graph of Figure 4.5, it is clearly shown that the vibration amplitude of the handle increased with time as its resonance with the operating frequency of speed 1 at 50 Hz. Same goes to time domain graph of Figure 4.7, the resonance also occurred at Speed 2 (101.74 Hz) which resulting an increment of vibration amplitude. Both FFTs showed highest peak of vibration at 0.006 m (Speed 1) and 0.011 m (Speed 2). In this study, the DVA is designed to counter both vibration operating amplitude at 50 Hz and 101.74 Hz, respectively.

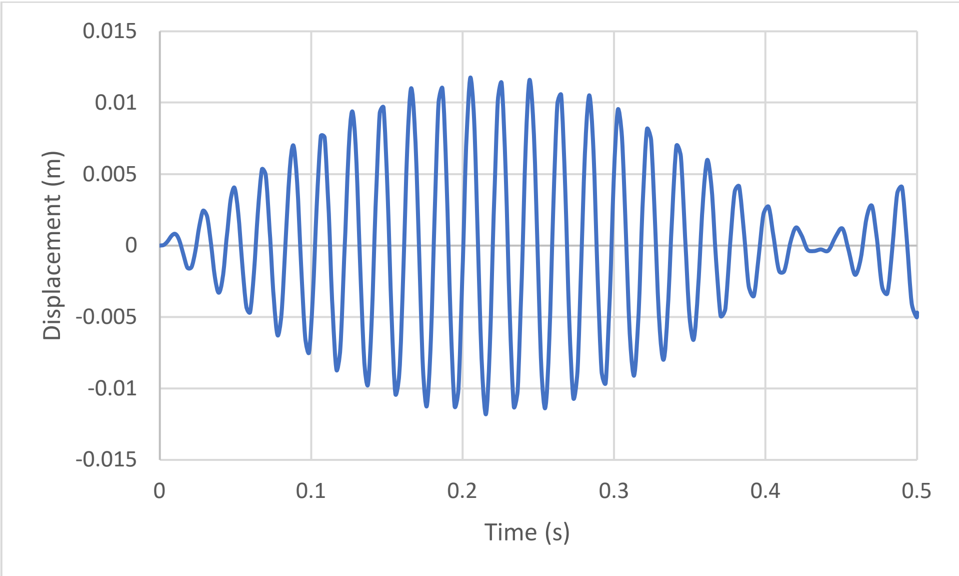

Figure 4.5 Time domain vibration of the motorboat handle without DVA (Speed 1)

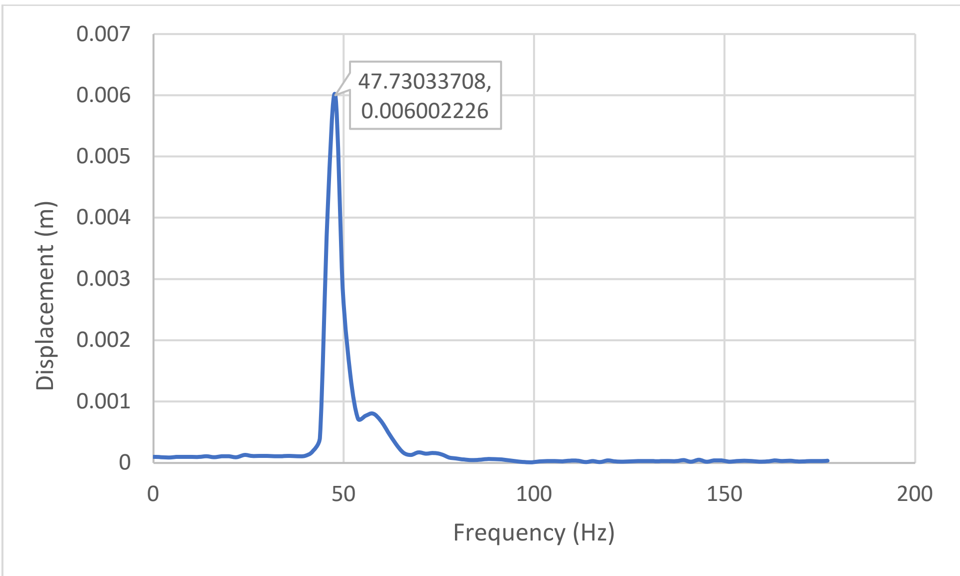

Figure 4.6 Frequency domain vibration of the motorboat handle without DVA (Speed 1)