Hand-arm vibration transmissibility measurement from the petrol driven motorboat engine

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Abstract. Petrol driven motorboat engine consisted of direct handle-engine mounting mechanism which exposed the operators to the high level of vibration and can lead to the Hand-arm Vibration syndrome (HAVs). The transmitted vibration from the engine to the handle with natural frequency excitation making the transmitted vibration worsen. This study is focusing on the vibration analysis of the 3.3 HP motorboat engine and the transmitted vibration to the operator handle in specific directions and frequency ranges. A lab-scale experimental rig with motorboat engine is set-up to represent the actual operation of the motorboat engine. Experimental Modal Analysis (EMA) is conducted at the motorboat handle to obtain the natural frequencies in y and z axis directions. Two levels of engine speed (Speed 1: Low and Speed 2: High) are taken into consideration for the vibration measurement of both engine and handle in x, y and z axis directions. From this study, the natural frequencies of the handle are determined within 75 – 80 Hz. For the vibration spectral measurement, the engine has produced high vibration in x and y axis directions, whereby the transmitted vibration to the handle is worst in y axis direction. At Speed 1, the engine excited the vibration within frequency range of 45 – 50 Hz while by increasing the engine to Speed 2, the vibration peak shifted to 95 – 100 Hz with higher vibration amplitude. In overall, the vibration transmissibility at the handle are significant between the frequency range of 0 – 100 Hz (above 1) which can result the HAVs among the operators if no necessary action been taken.

1. Introduction
Mechanical vibration from the running engine or motor is a well-known issue for ages and a lot of methods have been studied to eliminate or reduce this issue. Mechanical vibration can contribute to wear and tear of the engine components. Moreover, the vibration produced by the engine can also be transferred to the operator which can affect the human body. Engine vibration is likely to occur due to the rotational irregularities by changes of torque which is resistive and active during engine cycle [1]. Mainly, there are two types for engine vibration, torsional and longitudinal vibrations which produced due to crankshaft rotation inside the engine [2]. Vibration of engine is depending on the unbalanced reciprocating and rotating parts, cyclic variation in gas pressure, shaking forces and the mounting of the engines itself [3].

Some engine, like motorboat engine has a simple mechanism that required direct contact between human hand and handle to operate and control the engine. A small motorboat engine is a popular choice for fisherman that lived in a rural area. This small engine usually has a direct hand-handle mechanism and the fisherman can be exposed to the high level of vibration which can lead to Hand-arm Vibration syndrome (HAVs) [4]. Vibration from the engine can be transferred directly to operator and
increase the risk of tendon and nerve disorder [5]. A long-term exposure to the vibration while using hand-held machine can resulting the neurological and vascular symptoms in fingers and hand [6] and cause the development of vibration induced disability [7]. In general, HAVs is not possible to be cured, hence a proper method is required in reducing the vibration magnitude that generated by the machine or tools. The methods are listed in ISO 5349-1 which has been documented on 2001.

As engine is running, the vibration will be transferred to other components and human hand-arm, which known as vibration transmissibility. Vibration transmissibility is defined as a ratio of vibration at selected point of the hand-arm system to the vibration from the tool [8]. There are several methods that have been conducted for vibration transmissibility measurement. An accelerometer is used to measure the hand-held tool vibration for 48 workers and the measurement is done based on frequency-weighted and unweighted methods with the absorption of vibration energy is measured in three mutually orthogonal direction [9]. In other study, testing on human subject has been conducted to identify the basic characteristic of system response from grinding tools to human grip [10]. One study shows that a mono-axial accelerometer is used on tools handle for vibration measurement and Laser Doppler Vibrometer is used to measure vibration on several points of subject hand [11]. Other than that, vibration transmissibility of the gloves at human finger are measured as output and the vibration in glove interior are recorded as input [12].

This study is targeting the citizens lives in a rural area which mostly work as a fisherman and used small motorboat engine capacity that has direct hand-handle mechanism compared to high engine capacity that occupied with power steering mechanism. This basically will increase the potential risk of HAVs. As present, there is a lack of study regarding the vibration exposure issue from the motorboat engine. Hence, this study proposed the vibration measurement of the small motorboat engine capacity and vibration transmissibility of the handle for the future improvement of the HAVs among the fisherman.

2. Methodology
The study begins by identifying the vibration of the motorboat engine. To obtain the vibration data, a tri-axial accelerometer is used and connected to the IMC device to determine the frequency spectrum using IMC software. The raw data from IMC software is then transferred to the Microsoft Excel for more detail analysis.

The second measurement conducted is an Experimental Modal Analysis (EMA) to obtain the natural frequencies of related components. Natural frequencies data are required to study the effect of resonance on the vibration level of selected components. Impact hammer and accelerometer are used in this measurement and connected to the LMS SCADAS. The data is interpreted by LMS Test.Lab software. The general connection for this instrumentation is shown in Figure 1.

![Figure 1. General connection for vibration measurement and EMA instrumentation](image)

2.1. Design and Experimental Setup
A typical motorboat engine is running with a water-cooling system to encounter overheat of the engine. The engine contains water pump to draw in water and circulate through the engine system and the intake is located near to the propeller as shown in Figure 2. To run the engine, the propeller and water inlet must sink into the water, otherwise the engine might be broken due to overheat. Hence, for the testing purpose, a portable stand and water tank are designed and fabricated and the vibration measurement
direction of the overall structure is set-up as shown in Figure 3. For both vibration measurement and EMA of the motorboat engine are referring to this direction.

![Figure 2. The position of water inlet for engine cooling system](image1)

![Figure 3. The measurement direction of the overall structure](image2)

2.2. Experimental Modal Analysis of the Handle

The handle of motorboat engine is the main component that has a direct connection between the engine and operator hand-arm. This component is selected for the EMA to determine its natural frequencies in $y$ and $z$ axis directions. The handle is tested as a complete system, whereby the overall engine is clamped in upward position on the stiff mounting. An accelerometer is attached on the handle based on the selected direction and the impact hammer is used to apply the external force on the handle as shown in Figure 4(a). The data is then analysed using LMS Test.Lab software, whereby the natural frequencies
and mode shapes are obtained using this software. Figure 4(b) shows the geometry of the handle in the LMS software.

![Figure 4. (a) EMA set up for the engine handle and (b) The geometry of the handle in LMS software](image)

Theoretically, natural frequency is depending on mass and stiffness of the component and can represented as follows:

$$\omega_n = \sqrt{\frac{k}{m}}$$  \hspace{1cm} (1)

$$\omega_n = 2\pi f$$  \hspace{1cm} (2)

$$Speed = \omega_n \times 0.159155 \times 60$$  \hspace{1cm} (3)

where, $\omega_n$ is the natural frequency in (rad/s), $k$ is the stiffness, $m$ is the mass and $f$ is the frequency in (Hz). Equation (3) shows the speed unit conversion to rpm from natural frequency obtained.

2.3. Vibration Transmissibility Measurement

Vibration transmissibility measurement is conducted to study the vibration behaviour between the engine and handle. Tri-axial accelerometer is used to obtain the vibration data in all directions ($x$, $y$ and $z$ axis). These accelerometers are attached on top of the engine cover and the handle as shown is Figure 5(a) and (b). The data logger and software used for this vibration measurement is IMC device and IMC Software, respectively. The test is conducted in two speed conditions which is Speed 1 (Low) and Speed 2 (High) as labelled at the engine speed indicator in Figure 5(c). In this measurement, the engine is running at the natural gear condition and the collected data is then transferred and analysed in Microsoft Excel.

The vibration transmissibility is then calculated using the collected data from the engine and handle using following equation:

$$Vibration\ Transmissibility\ (T) = \frac{a_{handle}}{a_{engine}}$$  \hspace{1cm} (4)

where, $a_{handle}$ is the handle acceleration and $a_{engine}$ is the engine acceleration. The vibration transmissibility is calculated for both Speed 1 and Speed 2 and then been compared.
3. Results and Discussion

3.1. Natural Frequencies of the Motorboat Handle

The natural frequencies of the handle are summarized in Table 1. The first natural frequency of the handle in $z$ and $y$ axis directions are almost equal and at this frequency range the resonance can be occurred in both directions. The natural frequency value is considered low due to the hollow handle structure (low in mass and stiffness). The amplitude for first natural frequency in $z$ axis direction is slightly higher than $y$ direction as shown in Figure 6. The handle is adjustable in $z$ axis direction and mounted rigidly in $y$ direction, which indicates that the handle is more easily deflected in $z$ direction when external force is applied.

| No | Direction | Frequency Range (Hz) | First Natural Frequency (Hz) |
|----|-----------|----------------------|-----------------------------|
| 1  | $z$       | 0-1900               | 79.87                       |
| 2  | $y$       |                      | 75.49                       |

Figure 6: EMA results for motorboat handle in $z$ and $y$ axis directions
3.2. Vibration Measurement Results

3.2.1 Time and Frequency Domain Vibration of the Engine and Handle

The vibration measurement has been conducted at two different speeds (1 and 2) to study the effect of vibration transmitted from the engine to the handle. The raw data of time domain measurement in x, y and z axis directions between engine and handle for Speed 1 and 2 are shown in Figure 7(a) ~ (d). In general, the vibration acceleration of the engine at Speed 2 is higher compared to Speed 1 and the similar trend also been observed for the vibration acceleration of the handle. This proved that by increasing the speed of the engine, more vibration will be transmitted to the handle. At Speed 1, the vibration of the engine in y axis direction is the highest and this effect can be observed also at the handle. As the speed is increased to 2, the vibration of the engine and handle are still significant in y axis direction and become more uniform.

![Figure 7](image)

Figure 7. (a) Time domain graph of engine at Speed 1 (b) Time domain graph of handle at Speed 1 (c) Time domain graph of engine at Speed 2 (d) Time domain graph for handle at Speed 2

The vibration is then analysed in term of frequency spectrum (FFT) graph to determine the frequency range that contribute to the high vibration for both engine and handle. In this analysis, the frequency ranges up to 1000 Hz are taken into consideration for further analysis. Figure 8(a) and (b) shows the FFT graph of the engine and handle at the running Speed 1.
From Figure 8(a), the engine has a high peak between 45-50 Hz of frequency range, whereby x axis direction produced the highest peak at frequency 48.83 Hz. From FFT graph of the handle, there are significant high peaks below 100 Hz of frequency. Handle produced the highest acceleration in y axis direction at frequency of 48.83 Hz, followed by x direction in the same frequency range. The acceleration of handle is higher which is more than 16 m/s² in y direction, compared to the engine acceleration below 9 m/s². This result shows that at the operating frequency 48.83 Hz, vibration in x direction from engine is transferred and amplified the vibration of the handle in both x and y axis directions within same frequency range.

Figure 9(a) and (b) shows the FFT graph of the engine and handle at the running Speed 2. From the table, the engine has an obviously highest peak in frequency range of 95-100 Hz. The vibration in x axis direction has conquered the engine vibration with the highest peak at frequency 97.66 Hz, followed by y and z axis directions. The engine vibration acceleration at Speed 2 is higher compared to Speed 1 due to increase in engine speed. From the handle FFT graph, all three axis directions showed the significant high peaks between 95-100 Hz of frequency range. Like Speed 1, the vibration in y axis direction dominates the handle vibration at frequency 97.66 Hz, followed by x and z directions. The vibration acceleration of the handle is slightly lower than engine but way higher than the handle at Speed 1, which is nearly 60 m/s². At Speed 2, the vibration of engine at frequency of 97.66 Hz is transmitted to the handle in y axis direction.
From the vibration measurement results of Speed 1 and 2, the vibration from the engine is well transmitted and lead to the vibration of the handle. The operating frequency ranges are determined between 45-50 Hz for Speed 1 and 95-100 Hz for Speed 2. The vibration acceleration of the handle is amplified and higher than engine at Speed 1, while the vibration acceleration is almost equal for the engine and handle at Speed 2 (almost 60 m/s²). The handle vibration has the highest vibration in y axis direction because the handle is mounted to the engine structure in this direction at one end and free on the other end. The hollow structure of the handle also contributed to the high vibration in y direction.

3.2.2 Transmissibility Vibration of the Handle
The vibration transmissibility from the engine to handle is calculated and the graph is plotted as shown in Figure 10(a) and (b) for Speed 1 and 2, respectively. The analysis is carried out based on the red dot line indicator at $T_s = 1$ for the vibration transmissibility, whereby the value higher than 1 shows a high (worst) vibration transmissibility from the engine to handle. In frequency range of 0-100 Hz, Speed 1 shows high vibration transmissibility value in all directions with y direction has the highest peak. Meanwhile at Speed 2, y and z axis directions showed the high vibration transmissibility but opposed to x direction with low vibration transmissibility value. In frequency range of 100-200 Hz, the transmissibility value at Speed 1 in x and z direction are increased while for y direction, the significant decrement in transmissibility value is observed. Between 200-400 Hz, x and z axis directions are begun to decrease in transmissibility value as y direction is consistently low in this frequency range. However, above frequency 400 Hz, the vibration transmissibility in all directions are begun to increase and consistently above the value of 1. The transmissibility value at Speed 2 also showed a decrement trend in the frequency range of 100-400 Hz and started to increase above 400 Hz. This study proved that between the frequency range of 100-400 Hz, there is low vibration transmissibility from the engine to handle in all axis directions and then become ineffective after 400 Hz.

![Figure 10. (a) Vibration transmissibility graph between engine and handle at Speed 1 and (b) Vibration transmissibility graph between engine and handle at Speed 2](image-url)

3.2.3 Filtered Hand-arm Vibration (HAV) based on ISO 5349-1
Based on the handle vibration time domain signals at both Speed 1 and 2 in Figure 17, the signals are then filtered using the ISO 5349-1: HAV frequency-weighting function that available in the IMC software. The purpose of this study is to determine the vibration that occurred on the operator (human)
hand based on the ISO 5349-1 standard and regulation. Figure 11 (a) and (b) show the result of the HAV at Speed 1 and 2 during the engine running time from 0-0.05 s.

![Figure 11. Filtered HAV based on ISO 5349-1 for (a) Speed 1 and (b) Speed 2](image)

From Figure 12(a), the HAV in \( y \) axis direction is the most significant at Speed 1 with a moving average HAV amplitude of 9 m/s\(^2\) in the 0-0.05 s period of time and the amplitude is increased to the maximum of 12 m/s\(^2\) when the speed of engine is increased to 2. This result is corresponded to the handle vibration signals in time domain graph, whereby the vibration is significant in \( y \) axis direction for both Speed 1 and 2. As mentioned in ISO 5349-1 standard and regulation, the vibration that operated by the human should be below than 5 m/s\(^2\) (A8), which also been discussed in [9]. This experimental result proved that the vibration that transmitted to the human hand is exceeded the allowable amplitude in the regulation and necessary action should be taken in order to avoid the risk of getting the HAVs among the operators of the motorboat engine.

4. Conclusion
In this study, the vibration analysis of the petrol driven motorboat engine and handle have been conducted. The natural frequencies of the handle have been determined in the range of 75-80 Hz, which considerably low due to the hollow structure. For the vibration measurement, the \( y \) axis vibration has produced the most significant vibration amplitude and the level increased as the speed of the engine increased. At Speed 1, the operating frequency range occurred between 45-50 Hz while for Speed 2, the range has been shifted to 95-100 Hz. In term of vibration transmissibility, all three axes showed a high vibration transmissibility below 100 Hz and then started to reduce significantly between 100-400 Hz. Above, 400 Hz, the transmissibility become ineffective. The HAV measurement based on ISO 5349-1 also shown that the vibration transmitted to the operator hand is exceeded the allowable vibration amplitude that been stated in the regulation. In further study, an improvement of the handle should be made focusing in the frequency range below 100 Hz since the range involved both engine operating speeds. By improving the handle, the risk of getting the HAVs can also be avoided.

5. References
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