Development of Vibration Test System to Measure Human Biodynamic Responses to Hand-Transmitted Vibration (HTV)

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Abstract. Workers commonly experience hand-transmitted vibrations (HTV) especially in industries involving power tools. Vibration exposure will differ by individuals where prolonged and unmonitored exposure can lead to the development of symptoms known as hand arm vibration syndrome (HAVS). A deep understanding of human response to HTV is required to provide feasible solutions to lessen its adverse effects. Research has been extensively conducted on exploring the vibration transmission to the hand-arm system. However, there is limited study on the effects of handles mounted on a damping material or suspension systems. The objective of this study is to develop a vibration test system to measure the human biodynamic response to hand-transmitted vibration. Engineering design theory were used to formulate the essential design requirements of the system. The evaluation and selection of concepts were done. The design was modelled, and frequency analysis was performed using Computer-Aided Engineering (CAE) software. The frequency analysis results showed the first 10 modes in the frequency range of 1320 – 5088 Hz and therefore will not have resonance issues in the 25 – 1250 Hz frequency excitation range as per requirement. The prototype design was shown to comply with the product design specification and final detail design drawings were approved for fabrication. In conclusion, an instrumented handle with a modular expansion slot had been appropriately designed to measure human biodynamic responses due to hand-transmitted vibration.

1. Introduction
Hand-transmitted vibration (HTV) are often experienced daily depending on the type of working environment that the individuals are exposed to. Industrial workers in various fields such as in agriculture and manufacturing operate hand power tools and machineries and are more susceptible to severe vibration exposure. The exposure if left unsupervised can adversely affect the health of these workers. Hand-arm-vibration syndrome (HAVS) are commonly reported amongst workers as a result of prolonged exposure especially in cold climates [1].

Ongoing research is conducted to investigate the four vibration components that can affect the amount of vibration exposure which are the vibration’s frequency, magnitude, duration and frequency [2]. A good understanding of human biodynamic response to HTV with the variation of these components can provide future solutions and create a better work environment.

Current vibration test systems are mostly developed in the area of research. There are various configurations such as the split handle design [3] and the suspended handle [4]. The types of sensors used to measure force and acceleration also differs among experimenters depending on the purpose of
their research. Besides that, there are instrumented handle designs as suggested by international standards and guidelines to evaluate the vibration transmissibility of gloves at the palm of the hand[5]. Some researchers utilise indenter rigs to measure dynamic stiffness of materials to predict vibration transmissibility based on human biomechanical models [6].

As of now, there are no instrumented handle designs which can be mounted on materials and suspension systems. This would be useful to further investigate the effects of materials or suspension systems on the human biodynamic response.

This paper addresses the design process of the development of a vibration test system to measure human biodynamic response to HTV which also have a modular expansion feature to accommodate for future experiments with materials and suspension systems.

2. Methodology
The basic methodology follows a standard engineering design process of conceptual design followed by the embodiment design phase and finally the detail design for fabrication [7].

2.1. Conceptual Design
This phase starts with defining the problem and generating the product design specification (PDS) as shown in Table 1. Table 2 shows the functional decomposition of the instrumented handle. Various concepts are then brainstormed, and conceptual drawings were produced. The evaluation of the concepts was done using a weighted rating method based on the selection criteria.
Table 1. Product design specifications for the instrumented handle.

| Aspect                  | Objective                     | Criteria                                      |
|-------------------------|-------------------------------|-----------------------------------------------|
| Materials               | Appropriate for design        | High stiffness to ensure structure rigidness |
| Weight                  | Low                           | Below 3 kg                                   |
| Safety                  | High                          | No sharp edges that can injure human subjects |
| Handle dimensions       | Convenient for gripping purposes | Diameter (40 – 50 mm) & minimum length 110 mm |
| Handle resonance        | Appropriate for design        | No modes in the range of 25 – 1250 Hz         |
| characteristics         |                               |                                               |

Table 2. Functional decomposition of instrumented handle.

| Part         | Function                                                                 |
|--------------|--------------------------------------------------------------------------|
| Base         | Acts as the foundation for the instrumented handle. Provide extension for modular feature. |
| Handle       | The core part of the assembly. Provide the housing for the sensors.      |
| Grip handle  | Allow for human subjects to grip the handle. Attached to the force sensor. |
| Front bracket| Secure alignment of the handle’s position.                               |
| Rear bracket | Secure alignment of the handle’s position. Provide extension for modular feature. |
| Force Sensors| Measure the dynamic force.                                               |
| Accelerometers| Measure the acceleration of the handle.                                  |
| Plate        | Connect the instrumented handle to the shaker.                           |

2.2. Embodiment Design
The next phase carried out in the arrangement and sizing of the physical parts of the chosen concept. The concept was then modelled in a computer-aided engineering (CAE) software to check out for function and spatial constraints. Selection of materials were also investigated to comply with the PDS. Finite element analysis (FEA) was conducted to simulate and predict the first 10 modes of the design.

2.3. Detail Design
This design phase involved the complete product engineering description of the instrumented handle. The detailed design drawings for each parts and overall assembly were prepared before it was sent for fabrication.

3. Results

3.1. Prototype Design
Figure 3 shows the various parts in the instrumented handle assembly design. All the main parts are fastened together via M8 socket button head cap screws while the grip handles are joined to the force sensors via ANSI ¼ - 28 screws. The sensors have their own stud mounting screws connected to the tapped holes in the handle part. The base part will be fixed to a plate using M8 screws. Materials for all parts excluding the accelerometer, force sensors, and screws are made of Aluminium Alloy 7075. It is
chosen based on its high stiffness, relatively lightweight and readily available in the market. The overall weight of the design is 2.62 kg. The grip diameter is 50 mm.

All sensors are placed inside the instrumented handle to minimise errors in the vibration path transmission. However, there is an extra accelerometer hole placement for future investigation of the vibration transmissibility of the instrumented handle structure. Cable holes are available to allow for best measurement practice in terms of safety, quality of sensors data acquisition and convenient for human subjects.

The instrumented handle had been designed with a modular feature. This is achieved by the split design of the rear bracket and the base parts. Any module can be attached here depending on the objectives of the experiment.

Figure 3. Exploded view of the instrumented handle assembly.

For the experimental setup of the vibration test system, the instrumented handle will be positioned on top of a plate component that are rigidly attached to the vibration shaker as shown in Figure 4. A vibration measurement and control system usually in the form of a personal computer, will control the vibration input of the shaker to the handle as well as measuring the data output from the accelerometers and force sensors measured from the instrumented handle. A data acquisition system converts the analog output signals into digital signals for further post processing. Human subjects will need to grip the handles at a constant grip and push force as required by the experimenter. Thus, the forces will be displayed on a monitor for the subjects.
3.2. Finite Element Analysis (FEA) for Frequency Analysis of the Handle

The frequency analysis of the handle was conducted to predict the handle resonance characteristics based on the PDS in Table 1. The criteria specified that the design shall not have any modes or natural frequencies in the range between 25 to 1250 Hz. The parameters that can affect the frequency analysis were the boundary conditions and the quality of meshing. The instrumented handle design was fixed at the bottom of the base part as that will be the configuration of the handle in the experiment. The quality of meshing was determined by doing a convergence plot and the final meshing parameters were shown in Table 3. The results of FEA from the CAE software shows the first 10 natural frequencies and their corresponding mode shapes as shown in Figure 5. It is calculated that the natural frequencies are in the range of 1320 Hz till 5088 Hz. The first mode shape is a translational mode shape to the sides of the handle. The second and the third mode shape represent a twisting pattern of the base and grip handles. Most of the subsequent mode shapes predict resonances occurring at the grip handles. This is coherent with the fact that the grip handles have small thickness dimensions and therefore are proved to be the weakest link of the instrumented handle design.

![Figure 4](image1.png)

**Figure 4.** Overall setup of the vibration test system to measure human biodynamic response to hand-transmitted vibration.

![Figure 5](image2.png)

**Figure 5.** The first 10 modes of the instrumented handle calculated using finite element method.

Figure 6 shows the convergence of the value of the first mode of the design. A convergence of FEA results is important to validate the accuracy of the study. It is shown that there is a convergence trend as the number of elements increases. A difference of 16 Hz was observed between the lowest quality mesh
at 1336 Hz and 1320 Hz for the final mesh. The computation time was quick at 1 minutes 46 seconds. The same convergence trend is also evident for the other nine modes. Therefore, the FEA results are accepted with confidence. Table 3 shows the parameters of the frequency analysis used for the simulation.

![Graph showing mode shape frequency against number of elements](image)

**Figure 6.** Convergence plot for the first mode of the instrumented handle.

**Table 3.** Meshing parameters used for frequency analysis.

| Parameters          | Value    |
|---------------------|----------|
| Number of elements  | 71,105   |
| Number of nodes     | 111,887  |
| Degree of freedoms  | 328,212  |
| Total solution time | 1:46 minutes |

4. Discussion

From the results, it is evident that the design achieved the PDS and functional requirements. The first mode occurs outside the maximum 1250 Hz. The detailed design drawings had been sent for fabrication. Once the handle is fabricated, experimental modal analysis (EMA) will be performed to validate the FEA results. This step is important to ensure there would be no resonances occurring during experimentation in the frequency range of interest [4]. Resonances will negatively affect outcomes and reduce the acceptable frequency range of measured vibration spectrums.

Figure 7 show the general configuration of modules containing a certain thickness of a variety of materials can be slotted between the rear bracket part and the base part of the instrumented handle. Likewise, suspension modules consisting of springs and damper can be designed and slotted in the same configuration. The purpose is to measure the human biodynamic response with the inclusion of these material or suspension variables and investigate the effects. Previous research employed several methods to understand the effects of materials in reducing HTV. Hamouda et al used the obvious method of human subjects wearing actual vibration reducing gloves whilst gripping an instrumented handle rig [8], [9]. Other researchers developed a more systematic approach by investigating the effects of numerous factors such as thickness of materials and effective contact area towards the human biodynamic response using an indenter rig [10]–[12]. The data can then be fitted to a biomechanical model to better predict vibration experienced by humans [13], [14].
5. Conclusions
The instrumented handle with a modular expansion feature was designed to be compatible with a vibration test system that can measure human biodynamic responses to hand-transmitted vibration. The design was modelled in a CAE software and a frequency analysis study was conducted using finite element method. The design was shown to comply with the product design specification and final detail design drawings were approved for fabrication.

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