A COMPARISON OF DESIGN APPROACH USING TOPOLOGY OPTIMIZATION DESIGN AND PARAMETRIC DESIGN OF SUSPENDED HANDLE WITH MULTI CONSTRAINTS OPTIMIZATION FOR VIBRATION ATTENUATION

LEE WING SIONG

UNIVERSITI SAINS MALAYSIA

2021

A COMPARISON OF DESIGN APPROACH USING TOPOLOGY OPTIMIZATION DESIGN AND PARAMETRIC DESIGN OF SUSPENDED HANDLE WITH MULTI CONSTRAINTS OPTIMIZATION FOR VIBRATION ATTENUATION

By:

LEE WING SIONG

(Matrix no.: 137819)

Supervisor:

Professor Dr. Zaidi Bin Mohd Ripin

July 2021

This dissertation is submitted to
Universiti Sains Malaysia
As partial fulfilment of the requirement to graduate with honors degree in
BACHELOR OF ENGINEERING (MECHANICAL ENGINEERING)

UNIVERSITI SAINS MALAYSIA

School of Mechanical Engineering
Engineering Campus
Universiti Sains Malaysia

DECLARATION

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

Signed……………………………………………………………（LEE WING SIONG）

Date ……………9-7-2021……………………………….

STATEMENT 1

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.

Signed……………………………………………………………（LEE WING SIONG）

Date ……………9-7-2021……………………………….

STATEMENT 2

I hereby give consent for my thesis, if accepted, to be available for photocopying and for interlibrary loan, and for the title and summary to be made available to outside organizations.

Signed……………………………………………………………（LEE WING SIONG）

Date ……………9-7-2021……………………………….

ACKNOWLEDGEMENT

Firstly, I wish to give my greatest appreciation to my supervisor Professor Dr. Zaidi Bin Mohd Ripin for giving me this opportunity to carry out the project, his immense knowledge and the endless guidance in finishing the project. This paper would have never been accomplished without his assistance and support throughout the academic year. It has been a blessing and honour to have him as my supervisor.

Apart from that, I would also like to extend my thanks to the research officer of School of Mechanical Engineering Mr. Wan Mohd Amri Wan Mamat Ali for his help in giving guidelines in fabricating the prototype required for the research and giving me advice on conducting the experiments.

Besides from academic support, I wish to thank my fellow course mates for their unwavering personal and professional support during the time of project even when they were busy to carry out their project.

Most importantly, I would like to show my endless appreciation to my family that supporting me spiritually throughout the studies in Universiti Sains Malaysia. This thesis stands as a testament to their care and encouragements at all the time.

TABLE OF CONTENTS

ACKNOWLEDGEMENT .... **iii**

TABLE OF CONTENTS .... **iv**

LIST OF FIGURES .... **vii**

LIST OF TABLES .... **xi**

LIST OF ABBREVIATIONS .... **xiii**

ABSTRAK .... **xiv**

ABSTRACT .... **xv**

CHAPTER 1 INTRODUCTION **16**

1.1 Research Background 16

1.2 Problem Statement 18

1.3 Objectives 19

1.4 Scope of Research 19

CHAPTER 2 LITERATURE REVIEW **20**

2.1 Hand Arm Vibration 20

2.2 Common Vibration Control Techniques 22

2.2.1 Vibration Control in Grass Trimmer 23

2.3 Topology Optimization Design 25

2.3.1 Vibration Control using Topology Optimization 26

CHAPTER 3 RESEARCH METHODOLOGY **28**

3.1 Preparation for Topology Optimization Process 28

3.1.1 Digitization of the Model 28

3.1.1(a) 3D Model for Unguided Topology Optimization 29

3.1.1(b) 3D Model for Guided Topology Optimization 30

3.1.2 Defining Material Properties 31

3.1.3 Preliminary Check before Topology Optimization 32

3.1.3(a) Frequency Analysis 32

3.1.3(b) Static Analysis 34

3.2 Topology Optimization using Solidworks 35

3.3 Validation of Topology Optimization Result 39

3.4 Parametric Design of Machined Spring Model 40

3.4.1 Topology Optimization of Selected Parametric Design Model 43

3.5 Harmonic Analysis 43

3.6 Fabrication of Prototype 45

3.7 Experimental Analysis 46

3.7.1 Experimental Modal Analysis 46

3.7.2 Acceleration Transmissibility Test 47

CHAPTER 4 RESULT AND DISCUSSION 49

4.1 Preliminary Check Result 49

4.1.1 Preliminary Check Result for Unguided Topology Optimization Model 49

4.1.2 Preliminary Check Result for Guided Topology Optimization Model 50

4.2 Topology Optimization Result 51

4.2.1 Unguided Topology Optimization Result 51

4.2.2 Guided Topology Optimization Result 53

4.3 Validation of Topology Optimization Result 54

4.3.1 Validation of Unguided Topology Optimization Result 54

4.3.2 Validation of Guided Topology Optimization Result 56

4.4 Parametric Design Model Result 57

4.4.1 Static and Frequency Analysis of Parametric Design Model 57

4.4.2 Topology Optimization Result of Selected Parametric Design Model 59

4.5 Harmonic Analysis Result 60

4.6 Experimental Analysis Result 64

4.6.1 Modal Analysis Result 64

4.6.2 Acceleration Transmissibility Test Result 66

CHAPTER 5 CONCLUSION AND FUTURE WORK 71

5.1 Conclusion.. 71

5.2 Future Work 72

REFERENCES.. 74

APPENDICES 78

Appendix A: Static and Frequency Analysis Result for Unguided Topology Optimization Design Models 78

Appendix B: Static and Frequency Analysis Result for Guided Topology Optimization Design Models.. 83

Appendix C: Static and Frequency Analysis Result for Parametric Design Models. 88

Appendix D: Static and Frequency Analysis Result for Parametric Design Model (4d) after Topology Optimization.. 92

Appendix E: Acceleration at the shaft and handle computed from LMS Test Lab Software in X_h, Y_h, and Z_h axes for the case with and without prototype...... 93

LIST OF FIGURES

Page

Figure 1.1: Threshold Limit Values for Exposure of the Hand to Vibration in Either X_h, Y_h and Z_h (Department of Occupational Safety and Health Malaysia) 17

Figure 1.2: Universal Suspended Handle Adaptor for Petrol Engine Grass Trimmer.. 17

Figure 2.1: One-third octave band spectra on 20 powered hand tools such as (A) Pneumatic rock drill; (B) pneumatic road breaker; (C) petrol-driven Wacker compressing road surface after mending; (D) a non-antivibration chain saw; (E) an antivibration chain saw; (F) a pneumatic metal-chipping hammer; (G) pole scabbler; (H) needle gun; (I) random orbital sander; (J) impact wrench; (K) riveting gun; (L) dolly used with riveting gun; (M) nutrunner; (N) metal drill; (O) wire swaging; (P) etching pen; (Q) electric 9-in angle grinder; (R) pneumatic rotary file; (S) pneumatic 5-in straight grinder; (T) pneumatic 7-in vertical grinder: continuous lines, unweighted spectra; dashed lines, weighted spectra. (Disorders, 2001) 20

Figure 2.2: Vibration white finger (Voelter-Mahlknecht et al., 2012)....................... 21

Figure 2.3: Schematic diagrams of vibration isolation system 23

Figure 2.4: Advantages and disadvantages of each method in topology optimization (Zargham et al., 2016).. 27

Figure 3.1: Existing baseline design 28

Figure 3.2: 3D models for unguided topology optimization: (a) 100mm cube; (b) 150mm cube; (c) 120mm x 40mm x 40mm cuboid; (d) 100mm sphere; (e) 150mm sphere 29

Figure 3.3: 3D models for guided topology optimization: (a) X-shaped; (b) vertical cylinder; (c) horizontal cylinder; (d) washer spring; (e) machined spring 30

Figure 3.4: Define material properties for ABS plastic 32

Figure 3.5: Apply fixed constraint to the surface of top section cylinder..........33

Figure 3.6: Create meshing and run the simulation 33

Figure 3.7: Sample result of frequency analysis 33

Figure 3.8: Frequency analysis resonant frequencies listing 34

Figure 3.9: Apply fixed constraint to the surface of top section cylinder..........34

Figure 3.10: Apply the forces to the 26mm hole at the bottom section..........35

Figure 3.11: Sample result of static analysis..........35

Figure 3.12: Apply fixed constraint and forces to the model..........36

Figure 3.13: Define Goals and Constraints for topology study 36

Figure 3.14: Define the preserved regions 37

Figure 3.15: Define the symmetry plane..........37

Figure 3.16: Sample result of topology optimization..........38

Figure 3.17: Export the result as solid smooth mesh 38

Figure 3.18: Exported smooth mesh with small imported body 39

Figure 3.19: Recognize feature automatically using 'FeatureWorks'..........39

Figure 3.20: Smoothen the constraint and forces applied surfaces..........40

Figure 3.21: Parameters of machined spring design 41

Figure 3.22: Parametric design model: (a) 2-bend arm; (b) 2-flat arm; (c) 3-bend arm; (d) 3-flat arm & cuboid at bottom section; (e) 3-bend arm; (f) 3-bend arm & cuboid at bottom section..........41

Figure 3.23: Frequency analysis of assembly model 43

Figure 3.24: Define damping ratio and base excitation for harmonic analysis..........44

Figure 3.25: Define acceleration responses graph 45

Figure 3.26: Fabrication of prototype using Ender 3D printer.................................45

Figure 3.27: Experiment setup for modal analysis...46

Figure 3.28: Hanging the prototype for modal analysis...46

Figure 3.29: Test points for modal analysis...47

Figure 3.30: Experiment setup for transmissibility test 48

Figure 3.31: Hitting cutter head in X_h, Y_h and Z_h directions using impact hammer 48

Figure 4.1: Stress concentrates at the intersection region...50

Figure 4.2: Topology optimization result for 100mm cube model with different mass reduction constraints: (a) 5%; (b) 10%; (c) 30%; (d) 50% 52

Figure 4.3: Topology optimization result for 150mm cube model with different mass reduction constraints: (a) 5%; (b) 10%; (c) 30%; (d) 50% 52

Figure 4.4: Topology optimization result for 100mm sphere model with different mass reduction constraints: (a) 5%; (b) 10%; (c) 30%; (d) 50% 52

Figure 4.5: Topology optimization result for 150mm sphere model with different mass reduction constraints: (a) 5%; (b) 10%; (c) 30%; (d) 50% 52

Figure 4.6: Topology optimization result for cuboid model with different mass reduction constraints: (a) 5%; (b) 10%; (c) 30%; (d) 50% 52

Figure 4.7: Topology optimization result for X-shaped model with different mass reduction constraints: (a) 5%; (b) 10%; (c) 30%; (d) 50% 53

Figure 4.8: Topology optimization result for vertical cylinder model with different mass reduction constraints: (a) 5%; (b) 10%; (c) 30%; (d) 50% 53

Figure 4.9: Topology optimization result for horizontal cylinder model with different mass reduction constraints: (a) 5%; (b) 10%; (c) 30%; (d) 50% 54

Figure 4.10: Topology optimization result for washer spring model with different mass reduction constraints: (a) 5%; (b) 10%; (c) 30%; (d) 50% 54

Figure 4.11: Topology optimization result for machined spring model with different mass reduction constraints: (a) 5%; (b) 10%; (c) 30%; (d) 50% 54

Figure 4.12: Topology optimization result for parametric design model (4d) with different mass reduction constraints: (a) 5%; (b) 10%; (c) 30%; (d) 50% 59

Figure 4.13: Resultant acceleration at base excitation and handle for unguided topology optimization model from harmonic analysis 61

Figure 4.14: Resultant acceleration at base excitation and handle for guided topology optimization model from harmonic analysis 62

Figure 4.15: Resultant acceleration at base excitation and handle for parametric design model from harmonic analysis.. 62

Figure 4.16: Acceleration transmissibility of parametric design, guided and unguided topology optimization design models from harmonic analysis.. 63

Figure 4.17: Frequency response function computed from LMS Test Lab software 65

Figure 4.18: Acceleration transmissibility in X_h-axis from transmissibility test....... 67

Figure 4.19: Acceleration transmissibility in Y_h-axis from transmissibility test....... 67

Figure 4.20: Acceleration transmissibility in Z_h-axis from transmissibility test 68

Figure 4.21: HAV weighting factor (ISO 5349-1:2001)... 69

Figure 4.22: Weighted acceleration at shaft and handle based on ISO 5349-1:2001 while using baseline design.. 70

LIST OF TABLES

Page

Table 3.1: Detail of each 3D model for unguided topology optimization 30

Table 3.2: Detail of each 3D model for guided topology optimization 31

Table 3.3: Detail of each 2-bend arm design 3D model 42

Table 3.4: Detail of each 2-flat arm design 3D model 42

Table 3.5: Detail of each 3-flat arm design 3D model 42

Table 3.6: Detail of each 3-bend arm design 3D model 42

Table 4.1: Preliminary check result for unguided topology optimization model 49

Table 4.2: Preliminary check result for guided topology optimization model 51

Table 4.3: Frequency analysis for unguided topology optimization design result 55

Table 4.4: Static analysis for unguided topology optimization design result 55

Table 4.5: Frequency analysis for guided topology optimization design result 56

Table 4.6: Static analysis for guided topology optimization design result 56

Table 4.7: Static and frequency analysis result for 2-bend arm design model 57

Table 4.8: Static and frequency analysis result for 2-flat arm design model 58

Table 4.9: Static and frequency analysis result for 3-bend arm design model 58

Table 4.10: Static and frequency analysis result for 3-flat arm design model 59

Table 4.11: Frequency analysis for design model (4d) after topology optimization 60

Table 4.12: Static analysis for design model (4d) after topology optimization 60

Table 4.13: Acceleration transmissibility at 103Hz for parametric design, guided and unguided topology optimization design models from harmonic analysis 64

Table 4.14: List of modes from Solidworks frequency simulation............................ 65

Table 4.15: Acceleration transmissibility at 103Hz for the case with and without prototype from transmissibility test 69

LIST OF ABBREVIATIONS

3D	Three dimensions
A(8)	Daily vibration exposure
ABS	Acrylonitrile Butadiene Styrene
CAD	Computer Aided Design
CSV	Comma-separated values
COC	Constrained optimality criteria
DoSH	Department of Occupational Safety and Health
ESO	Evolutionary structural optimization
EU	European Union
FE	Finite element
HAV	Hand-arm vibration
HAVs	Hand-arm vibration syndrome
SIMP	Solid isotropic material with penalization
STL	Standard Template Library
TVA	Tuned vibration absorber

PERBANDINGAN KAEDAH REKA BENTUK MENGGUNAKAN REKA BENTUK PENGOPTIMUMAN TOPOLOGI DAN REKA BENTUK PARAMETRIK DALAM PEMEGANG SUSPENSI DENGAN PELBAGAI KEKANGAN UNTUK MENGURANGKAN GETARAN

ABSTRAK

Mesin rumput merupakan alat yang biasa untuk memotong. Walau bagaimanapun, getaran tangan yang tinggi telah dilaporkan semasa menggunakan mesin rumput. Pendedahan kepada getaran tangan yang tinggi dalam jangka masa yang panjang boleh menyebabkan sindrom getaran tangan. Terdapat bukti saintifik menunjukkan bahawa penggunaan penyesuai pemegang suspensi boleh mengurangkan getaran tangan dengan berkesan. Bagi memperbaik reka bentuk, penyesuai pemegang suspensi baru yang dibuat dengan plastic ABS akan direka bentuk melalui kaedah pengoptimuman topologi dan kaedah reka bentuk parametrik. Dari aspek kekerapan semulajadi dan tahap tekanan, model reka bentuk dari kaedah pengoptimuman topologi berpandu dan tidak berpandu mempunyai kekerapan semulajadi dan tahap tekanan yang tinggi kecuali model reka bentuk spring bermesin. Sebaliknya, model reka bentuk dari kaedah reka bentuk parametrik mempunyai kekerapan semulajadi dan tahap tekanan yang rendah terutamanya model reka bentuk tiga lengan. Dari aspek penghantaran getaran, keputusan simulasi menunjukkan bahawa model reka bentuk jenis spring bermesin yang terbaik dari kaedah pengoptimuman topologi dan kaedah reka bentuk parametrik berkemampuan untuk mengurangkan tahap pecutan pada sekitar pemegang mesin rumput sebanyak 78.36% and 93.61% pada frekuensi operasi yang dominan (103Hz). Berdasarkan keputusan simulasi, model reka bentuk (4d) dari kaedah reka bentuk parametrik telah dipilih untuk pembuatan prototaip. Keputusan eksperimen juga menunjukkan bahawa menggunakan prototaip boleh mengurangkan penghantaran pecutan dengan ketara pada paksi X_h, Y_h and Z_h. Penghantaran pecutan pada frekuensi operasi yang dominan bagi kes yang memakai prototaip adalah lebih rendah sebanyak 63.99%, 86.67% and 87.09% pada paksi X_h, Y_h and Z_h berbanding kes yang tidak memakai prototaip.

A COMPARISON OF DESIGN APPROACH USING TOPOLOGY OPTIMIZATION DESIGN AND PARAMETRIC DESIGN OF SUSPENDED HANDLE WITH MULTI CONSTRAINTS OPTIMIZATION FOR VIBRATION ATTENUATION

ABSTRACT

Grass trimmer is a very common tool to clear the weeds. However, the high hand-arm vibration level has been reported when using the grass trimmer which is undesired as long-term exposure to the high hand-arm vibration level could lead to hand-arm vibration syndrome. There is scientific evidence that shows the use of suspended handle adaptor can reduce the hand-arm vibration effectively. In order to further improve the design, new suspended handle adaptors were designed with ABS plastic through topology optimization approach and parametric design approach. In term of natural frequency and stress level, the designs models from the guided and unguided topology optimization approach have a high natural frequency and stress level except the machined spring design. Whereas the machined spring type design models from parametric design approach have a relatively low natural frequency and stress level especially the 3 arm design models. From the vibration transmission aspect, the simulation result shows that the best machined spring type design models from guided topology optimization approach and parametric approach were able to reduce the acceleration level at the loop handle by 78.36% and 93.61% at the dominant operating frequency (103Hz). Based on the simulation result, design model (4d) from parametric design approach was chosen for prototype fabrication. The experimental result also has showed that using the prototype was able to reduce the acceleration transmissibility significantly in X_h, Y_h and Z_h axes. The acceleration transmissibility at the dominant operating frequency for the case with prototype was 63.99%, 86.67% and 87.09% lower in X_h, Y_h and Z_h axes as compared to the case without prototype.

CHAPTER 1 INTRODUCTION

1.1 Research Background

In many countries including Malaysia, grass trimmer is a very common tool which is used to clear the weeds. The portable grass trimmer has a single nylon string that is attached to its rotating head is rotationally unbalanced. The vibration generates by the rotating nylon string will be transmitted to the handle through the shaft and then the vibration will be transmitted to human hands directly. Long term exposure to the high level of hand arm vibration is undesired and can lead to hand-arm vibration syndrome (HAVs) if the operator does not equip any protection tools.

Hand-arm vibration (HAV) is vibration transmitted from a work process into human hands which is usually caused by operating hand-held power tools, hand-guided equipment, or by holding materials being processed by machines. Long term exposure to the high HAV level can cause the complex vascular, neurological and musculoskeletal disorder, collectively named hand-arm vibration syndrome (HAVs) which is a widespread hazard in many industries and occupations. Thus, it is important to control the vibration at the handle or equip the protection tool in order to prevent HAVs.

According to the Guidelines on Occupational Vibration, 2003 by the Department of Occupational Safety and Health (DoSH) Malaysia, the maximum component acceleration at each direction (X_h, Y_h and Z_h) is 4 m/s^2 for the duration of 4 hours and less than 8 hours (Department of Occupational Safety and Health Ministry of Human Resources Malaysia, n.d.). In addition, European Union (2005) also has defined the exposure action value of 2.5 m/s2 and exposure limit value of 5.0 m/s2 for daily vibration exposure A(8). However, the measurement of the current grass trimmer has recorded a vibration total value (a_{hv}) of 11.30 m/s^2 (3.88 m/s^2 in X_h, 9.24 m/s^2 in Y_h and 3.96 m/s^2 in Z_h) which has exceed the exposure limit value of 4 m/s^2 (Ko et al., 2011).

Total Daily Exposure Duration#	Values of the Dominant,* Frequency - weighted, rms, Component Acceleration Which Shall not be Exceeded a_K, (a_{Keq})	
	m/s²	g^
4 hours and less than 8	4	0.40
2 hours and less than 4	6	0.61
1 hours and less than 2	8	0.81
less than 1 hour	12	1.22

\# The total time vibration enters the hand per day, whether continuously or intermittently.

* Usually one axis of vibration is dominant over the remaining two axes. If one or more vibration axes exceeds the Total Daily Exposure then the TLV has been exceeded.

^ $g = 9.81 m/s^2$

Figure 1.1: Threshold Limit Values for Exposure of the Hand to Vibration in Either X_h, Y_h and Z_h (Department of Occupational Safety and Health Malaysia)

There are many techniques for controlling vibration at the handle such as mounting a dynamic vibration absorber on the source of vibration, isolate the hand from the vibrating handle with the use of anti-vibration gloves and isolate the tool handle from the vibrating source by using isolators. In 2011, the use of suspended handle has showed that vibration level is reduced by 76% which is an effective tool to suppress the vibration level at the handle of the grass trimmer. After that, some researchers have tried other techniques to reduce the vibration level at the handle, but the vibration attenuation effect is not as good as the suspended handle. Thus, topology optimization design approach will be used in this present research to find a new possible and effective solution in reducing the vibration level at the handle. Besides that, parametric design approach will be used as well to compare the effectiveness of using topology optimization approach.

Figure 1.2: Universal Suspended Handle Adaptor for Petrol Engine Grass Trimmer

The natural frequency of the design is a very important parameter to be controlled and it should be far away from the operating frequency of the grass trimmer. The natural frequency of an object is mainly depended on its mass and stiffness. For example, lower mass and stiffer object increases natural frequency whereas higher mass and softer object lowers natural frequency (Fundamentals of Vibration, n.d.). Besides that, the natural frequency of an object is also affected by the material and the geometry as well (Kamath et al., 2014). Thus, various designs with different size, length and structures will be created in parametric design approach and a best optimum design could be found.

In addition, by using the topology optimization design approach such as topology study in Solidworks, all the important parameters can be controlled and set as the constraints for topology optimization. After that, a best optimum design can be created as well based on the result generated in the topology study. The best optimum design might have a very complex shape which is not able to fabricate easily through the traditional manufacturing way due to the complex geometry. However, it can be produced easily by using the additive manufacturing such as 3D printer with high precision.

A comparison will be made between the designs produced by the topology optimization design approach and parametric design approach. Only a best optimum design will be selected for additive manufacturing. The best design will be printed with ABS plastic using 3D printer. Originally, the adapter was made of mild steel and natural rubber that is strong enough to withstand high stress and able to attenuate the vibration level at the handle. This adapter served as the base design to compare with the new design and the several experiments will be conducted to test the prototype. Ideally, the new design must be strong enough to lift up the shaft of grass trimmer without any deformation and able to attenuate the vibration level at the handle.

1.2 Problem Statement

The portable grass trimmer has a single nylon string that attached to its rotating head is rotationally unbalanced. Thus, high level of vibration will be produced which is undesired as the operator might be suffered to the large magnitude of hand arm vibration (HAV) and may cause complex vascular and neurological and musculoskeletal disorder, collectively named as hand-arm vibration syndrome. The commercial handle of the petrol engine driven grass trimmer has a vibration total level of 11.30 ms-2 which has exceed the maximum exposure limit of 8 hours as stated in DoSH and EU's action limit for HAV.

1.3 Objectives

This research aims to achieve the objectives as listed:

1. To optimize the current suspended handle adaptor using topology optimization design and parametric design approach.
2. To compare the outcomes from the topology optimization design approach and parametric design approach in term of stress level and natural frequency.
3. To determine the acceleration transmissibility of the best optimum design obtained from different approaches using harmonic analysis simulation.
4. To fabricate a prototype with the best optimum design model obtained from different design approaches using additive manufacturing.
5. To verify the prototype through experimental approaches such as modal analysis and acceleration transmissibility test.

1.4 Scope of Research

In this research, different design model was created using parametric design approach and topology optimization design approach. For parametric design approach, different machined spring type designs were created. For the topology optimization approach, it was divided into two part which were guided and unguided topology optimization design. The unguided topology optimization design uses the simple shape model whereas the guided topology optimization design uses the baseline design as the reference for topology optimization. All the design models were validated using static and frequency analysis in Solidworks. Comparison between the outcomes from different approaches was made and the best design model from each approach was selected to perform harmonic analysis simulation to study the acceleration transmissibility of each design. Then, fabrication of prototype was done using additive manufacturing and verification was done by conducting experimental modal analysis and acceleration transmissibility test.

CHAPTER 2 LITERATURE REVIEW

In this section, relevant resources are reviewed to obtain sufficient knowledge about hand-arm vibration, vibration control techniques and topology optimization design.

2.1 Hand Arm Vibration

When the hands or fingers hold or grasp the vibrating objects, the vibration can be transmitted from the vibrating objects into human hand. This process is known as the harm arm vibration (HAV). Nowadays, there are many machines or powered hand-held tools have high vibration level as shown in Figure 2.1 which are undesired as long-term exposure to these vibration sources can cause serious health issue and diseases such as white finger, carpel tunnel syndrome, sensory nerve damage, muscle and joint damage in the hands and arm, collectively known as hand-arm vibration syndrome (HAVs).

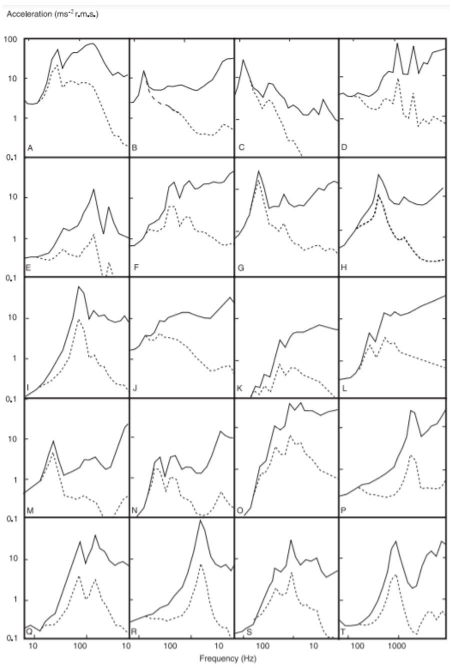

Figure 2.1: One-third octave band spectra on 20 powered hand tools such as (A) Pneumatic rock drill; (B) pneumatic road breaker; (C) petrol-driven Wacker compressing road surface after mending; (D) a non-antivibration chain saw; (E) an antivibration chain saw; (F) a pneumatic metal-chipping hammer; (G) pole scabbler; (H) needle gun; (I) random orbital sander; (J) impact wrench; (K) riveting gun; (L) dolly used with riveting gun; (M) nutrunner; (N) metal drill; (O) wire swaging; (P) etching pen; (Q) electric 9-in angle grinder; (R) pneumatic rotary file; (S) pneumatic 5-in straight grinder; (T) pneumatic 7-in vertical grinder: continuous lines, unweighted spectra; dashed lines, weighted spectra. (Disorders, 2001)

Harm-arm vibration syndrome (HAVs) is an occupational hazard which must be controlled to avoid long term health problems. Workers affected by HAVs might loss of light touch, feel pain and cold during white finger attacks and loss of grip strength. Long exposure to the hand-arm vibration (HAV) from the grass trimmer have been associated with the increase of signs of occupational diseases related to the harm-arm vibration syndrome (HAVs). However, most of the workers are not aware of the health issues caused by the vibration exposure. In a study to investigate the prevalence of hand-arm vibration symptoms among employees at a mechanical company, it was found that 21% of the employees were judged to have vibration-related problems even though the exposure to vibrations was judged to be relatively low (Azmir et al., 2018). From the Italian National Vibration Database, it has showed that the vibration values for a brush-cutter can go up from 1.5 m/s^2 to 16 m/s^2 which is very high and exceed the exposure limit as stated in DoSH and EU's action limit for HAV (Vihlborg et al., 2017). In a statistical study about the prevalence of HAVs among hand-held grass-cutting workers in Malaysia, it has showed that there were positive HAVS symptoms relationships between the low–moderate exposure group and the high exposure group among hand-held grass-cutting workers. The prevalence ratio was 3.63 which was considered high and 36.3 of the workers have experienced finger colour changes and numbness (Azmir et al., 2016). Thus, it is important to impose some technique or equipment to attenuate the vibration level at the handle of the grass trimmer to prevent HAVs.

Figure 2.2: Vibration white finger (Voelter-Mahlknecht et al., 2012)

2.2 Common Vibration Control Techniques

Generally, the vibration control can be done by controlling the vibration from the source, path and receiver. In the case of using hand-held tools, the source was referred to a mechanical disturbance generated by the machine such as rotationally unbalanced forces from the rotating component. The path is the structural medium that transmit the vibration to the receiver. The path and receiver were referred to the shaft and the handle that grip the shaft. Any or all of these areas were studied and modified based on some common vibration control techniques in order to reduce the vibration level and transmissibility.

Vibration control can be done by reducing the excitation input due to the unbalance or misalignment (5 Vibration Control, n.d.). This can be done by improving the balance of the rotating part. The center of gravity should be moved to the center of rotation and the net dynamic force acting on the shaft and moments about any point should be closer to zero to prevent rotationally unbalanced (Stevensen, 1972). Besides that, mass addition is another method which reduces the constant excitation forces by adding mass. This method obeys the principle of Newton's second law as the mass of a system is increased while the forces are remained constant, the acceleration which is the vibration response will be decreased (Geiss, 1956).

Next, vibration isolation is a commonly used technique as well to suppress the undesired vibrations in a system. A simple vibration isolation system is shown Figure 2.3. The isolator is an additional medium that keep the vibration apart between two surface which are in contact and one of them is vibrate continuously. The effectiveness of an isolator can be determined by calculating the transmissibility. The transmissibility is the ratio of the amplitude at the system to the amplitude of the vibration source. For example, if x(t) is the amplitude response of the system and y(t) is the amplitude from vibration source. Then the transmissibility would be x(t) divided by y(t) as shown in the figure below. The smaller the transmissibility implied that the less vibration is transmitted to the system, and vice versa.

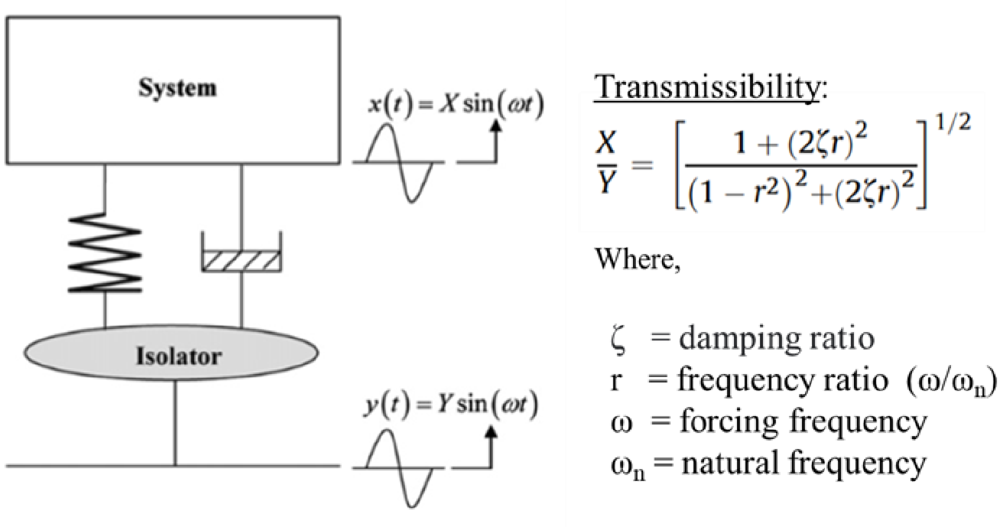

Figure 2.3: Schematic diagrams of vibration isolation system

Besides that, changing the natural frequency of a system by modified the stiffness of the system or manipulate the mass of the system is able to eliminate or reduce the amplification due to the resonance (Clarke, 1999). Once the natural frequency of the system was far away from the operating frequency, the magnitude of vibration can be reduced effectively. Furthermore, introducing damper into the system such as using vibration absorber as a secondary mass to dissipates the mechanical energy and converts io thermal energy which is also an effective way for vibration attenuation (Craig, n.d.).

Generally, these are the common techniques most of the designer and engineer were used for controlling the vibration. Most of the techniques mentioned here have also been applied to the grass trimmer to reduce the vibration level that will be transmitted to the human hands. The detail of the application of vibration control techniques in grass trimmer will be discussed in the next section.

2.2.1 Vibration Control in Grass Trimmer

It has been reported that the grass trimmer has the high vibration total value which can lead to HAVs. Therefore, vibration control in grass trimmer is essential and necessary to ensure that the vibration transmissibility from the grass trimmer to the human hands is maintained at a safe level.

In the past, anti-vibration gloves are used to isolate the hand from the vibrating handle (Brown, 1990). However, most of the commercial anti-vibration gloves are not able to attenuate the low frequency vibration (below 100 Hz) and only effective to attenuate the high frequency vibration (Dong et al., 2003). Thus, it is not suitable to use as the protection equipment as most of the hand-held tool has the low operating frequency including the grass trimmer. In addition, the vibration perception are different at different locations on the hand such as fingers and palm with the use of anti-vibration gloves (Dong et al., 2010). Thus, using anti-vibration gloves to attenuate the vibration level at the handle is not a feasible solution.

Insertion of anti-vibration systems could be a possible solution to attenuate the vibration level at the handle. For example, a tuned vibration absorber (TVA) can be applied to the grass trimmer to suppress the HAV. One of the studies has showed that install the tuned vibration absorber to the electric grass trimmer was able to reduce the vibration total value by 67% which has significantly reduced the risk of hand-arm vibration syndrome (Hao et al., 2011). In other study also has showed that the TVA installed at the particular location was effective in reducing acceleration level of vibration which has successfully reduce the vibrations of the handle by 80%. for both cutter head position (P, 2011). However, in practical the petrol engine of the brush cutter can operate in a wide range of frequency. For example, it can be varied from 6000 rpm to 10000 rpm. In a recent study, it has showed that the TVA was effective for small speed range only (up to about 40% vibration reduction), otherwise the absorber resonance frequency needs to be changed (Patil, 2018). Therefore, TVA might not be suitable for all type of grass trimmer as well if the operating frequency range is very wide. However, if the operating frequency was fixed at certain level, using multi-axial vibration absorber was able to further suppress the hand-arm vibration from grass trimmer as compared to the single direction absorber (Patil, 2019).

Other than using TVA, inserting rubber mounts between the handle and the source of excitation (suspended handle) was a feasible solution to isolate the handle from the vibrating source. From a study in 2011, different handle prototypes were designed with different material and the distance between the rubber mounts were varied and compare with the existing commercial handle (Ko et al., 2011). It can be noticed that the commercial handle has the highest vibration total value whereas the handle that was made of mild steel with rubber mount has the lowest vibration total value of 2.69 m/s^2 which was 75% reduction in vibration level. In addition, the distance between the rubber mounts will affect the vibration attenuation performance as well.