Faculty of Mechanical Engineering

VIBRATION ANALYSIS OF FUSED DEPOSITION MODELING PRINTED LATTICE STRUCTURES CELLULAR MATERIAL

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DECLARATION

I declare that this thesis entitled " Vibration Analysis of Fused Deposition Modeling Printed Lattice Structures Cellular Material " is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ....

Name : Muhamad Syafwan bin Azmi

Date : ....

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Mechanical Engineering.

Signature : …………………………………...
Supervisor Name : Dr. Rainah binti Ismail
Date : …………………………………...

DEDICATION

“To my beloved mother and father”

ABSTRACT

This research presents a vibration analysis on the lattice structure material fabricated by utilizing fused deposition modeling (FDM) additive manufacturing (AM) for application as load-bearing lightweight body part in automated device. The work has been motivated by the need to explore the dynamic behaviour of the lattice structure material so that the real behaviour of the system, performance, suitability and limitations can be understood and which at the end can provide better safety of the structure in the real dynamic applications. This work has undertaken on clarifying issues related to weight and built quality of the manufactured lattice structure material samples prior to vibration testing. The four proposed topological designs namely simple cubic (SC), face centred cubic (FCC), body centred cubic (BCC) and body centred cubic with reinforced *z* pillars (BCC_z) are evaluated based on these two criteria which are from manufacturability and weight practicality. Based on the selection process, it is found that the BCC topological design of the lattice structure is more acceptable and henceforth used to represent the vibrational response study of the lattice structure cellular material with different strut diameter sizes. The results show that the natural frequency of the lattice structure material can be greatly affected by the strut diameter sizes due to increase in stiffness as the strut diameter increases. In addition, the mathematical equation is also derived to calculate the total area moments of inertia of the lattice structure model and the validity of this developed model is shown through comparison of the results with experimental work of the three-point bending test. From the calculation of total area moment of inertia, it is found that the lattice structure model with the highest strut diameter size yield highest value of total area moment of inertia. The results show a good agreement between the theoretical model and experimental work. The investigation on various effects of damage existence including damage locations and damage extents to the natural frequency values of the lattice structure material are also examined. The damage in the lattice structure is represented by a damage parameter η which indicates the ratio of missing unit cells to the total unit cells of the intact lattice structure. It is found that the natural frequency values decrease with the increase of damage parameter η from ratio of 0.00 to 0.50. Meanwhile, the natural frequency values increase as the damage location became farthest from the clamped edge. This indicates that the effect of damage on the natural frequency values become smaller as the damage zone moves from the clamped edge boundary condition to the free end. This research provides a good information on the influence of the strut diameter design parameter as well as the effects of damage existence to the natural frequency values of the lattice structure material and it can be seen that the results could constitute a useful information for subsequent investigation into the development of the lattice structure in order to fulfil the demand on the lightweight and cost reduction of materials.

ABSTRAK

Kajian ini membentangkan analisa getaran terhadap bahan berstruktur kekisi dibuat dengan pembuatan secara tambahan fused deposition modeling (FDM) untuk aplikasi bahagian badan menahan beban ringan pada peranti automatik. Kerja ini termotivasi oleh keperluan untuk meneroka tingkah laku dinamik bahan berstruktur kekisi agar tingkah laku sebenar sistem, prestasi, kesesuaian dan batasan difahami dan akhirnya memberikan keselamatan struktur lebih baik dalam aplikasi dinamik sebenar. Kerja ini juga melaksanakan penjelasan isu berkaitan berat dan kualiti pembinaan bahan berstruktur kekisi sebelum ujian getaran. Keempat rekabentuk topologi dicadangkan iaitu simple cubic (SC), face centred cubic (FCC), body centred cubic (BCC) dan body centred cubic dengan tiang z (BCCz) dinilai berdasarkan dua kriteria iaitu keterbuatan dan kepraktikan berat. Melalui proses pemilihan, didapati rekabentuk topologi BCC lebih baik dan digunakan mewakili kajian respon getaran bahan berstruktur kekisi dengan saiz garis pusat tiang berbeza. Hasil kajian menunjukkan frekuensi semulajadi bahan berstruktur kekisi amat dipengaruhi saiz garis pusat tiang kerana peningkatan kekakuan apabila saiz garis pusat tiang meningkat. Selain itu, persamaan matematik diperoleh untuk mengira jumlah kawasan momen inersia model bahan berstruktur kekisi dan kesahihan model diperoleh ini dibuktikan dengan perbandingan hasil kajian dengan esperimen lenturan tiga titik. Dari pengiraan jumlah kawasan momen inersia, didapati model bahan berstruktur kekisi dengan saiz garis pusat tiang tertinggi menghasilkan nilai jumlah kawasan momen inersia tertinggi. Hasil ini menunjukkan persetujuan baik antara model teori dan kerja esperimen. Kajian terhadap pelbagai kesan kerosakan termasuk lokasi dan keterukan kerosakan terhadap nilai frekuensi semulajadi bahan berstruktur kekisi juga dilaksanakan. Kerosakan bahan berstruktur kekisi diwakili parameter kerosakan η yang menunjukkan nisbah sel unit yang hilang berbanding sel unit struktur sempurna. Didapati nilai frekuensi semulajadi menurun dengan peningkatan parameter kerosakan η dari 0.00 hingga 0.50. Selain itu, nilai frekuensi semulajadi meningkat apabila lokasi kerosakan lebih jauh dari sisi dikapit. Ini menunjukkan kesan kerosakan terhadap frekuensi semulajadi bar bahan selular berstruktur kekisi menjadi lebih kecil apabila zon kerosakan bergerak dari sisi dikapit ke arah sisi bebas. Kajian ini memberikan maklumat baik mengenai pengaruh parameter rekabentuk saiz garis pusat tiang serta kesan kerosakan kepada nilai frekuensi semulajadi bahan berstruktur kekisi dan ianya boleh dilihat bahawa hasil kajian membentuk maklumat berguna untuk siasatan seterusnya ke atas pembangunan bahan struktur berbentuk kekisi dalam memenuhi permintaan untuk bahan ringan dan pengurangan kos bahan.

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Verily, With Hardship Comes Ease (Surah al-Sharh,94).

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LIST OF SYMBOLS

ω_n - Natural Frequency

ω - Frequency

x - Displacement

$\dot{x}$ - Velocity

$\ddot{x}$ - Acceleration

F - Driven Force

k - Stiffness

m - Mass

c - Damping factor

E - Elastic modulus

t - Time

L - Bar length

A - Cross sectional area

$W(x)$ - Mode shape function

k_nL - Eigenvalue of vibration mode

L - Unit Cell’s Length

θ_{xy} - Strut to Surface Angle

Ø - Strut Diameter

η - Damage Parameter

Hz - Hertz

V$_{rms}$ - Root Mean Square Voltage

N - Newton

dF - Frequency Resolution

° - Degree

ρ - Density

I - Total Area Moment of Inertia

I_x - Total Area Moment of Inertia in x Axis Direction

I_y - Total Area Moment of Inertia in y Axis Direction

I_z - Total Area Moment of Inertia in z Axis Direction

$\sum$ - Summation

N_{strut} - Number of Strut

N_{node} - Number of Node

i - *i*-th strut

j - *j*-th node

I_{xsi} - Area Moments of Inertia of *i*-th Strut in x Axis Direction

I_{ysi} - Area Moments of Inertia of *i*-th Strut in y Axis Direction

I_{zsi} - Area Moments of Inertia of *i*-th Strut in z Axis Direction

I_{xnj} - Area Moments of Inertia of *j*-th Node in x Axis Direction

I_{ynj} - Area Moments of Inertia of *j*-th Node in y Axis Direction

I_{znj} - Area Moments of Inertia of *j*-th Node in z Axis Direction

x_s - Strut distance in x Axis to The Origin

y_s - Strut distance in y Axis to The Origin

z_s - Strut distance in z Axis to The Origin

x_n - Node distance in x Axis to The Origin

y_n - Node distance in y Axis to The Origin

z_n - Node distance in z Axis to The Origin

θ - Angle

l_s - Strut's length

d_s - Strut's diameter

I'_{xsi} - Area Moments of Inertia of The *i*-th Strut In Horizontal Orientation After Rotation of Axes' Transformation in x Axis Direction With Respect to The Origin

I'_{ysi} - Area Moments of Inertia of The *i*-th Strut In Horizontal Orientation After Rotation of Axes' Transformation in y Axis Direction With Respect to The Origin

I'_{zsi} - Area Moments of Inertia of The *i*-th Strut In Horizontal Orientation After Rotation of Axes' Transformation in z Axis Direction With Respect to The Origin

O - Origin

a - Radius a

b - Radius b

LIST OF ABBREVIATIONS

3D - Three Dimensional

ABS - Acrylonitrile-Butadiene-Styrene

AM - Additive Manufacturing

BCC - Body Centred Cube

BCC_z - Body Centred Cube with Vertical Struts

CAD - Computer Aided Design

CFRP - Carbon Fibre Reinforced Polymer

EBM - Electron Beam Melting

ERC - Earth Return Capsule

ESA - European Space Agency

F2BCC - Boolean Combination of BCC and FCC

FBCC_z - Face and Body Centred Cubic with Z Struts

FCC - Face Centred Cube

FCC_z - Face Centred Cubic with Z Struts

FDM - Fused Deposition Modeling

FEM - Finite Element Method

FRF - Frequency Response Function

GFRP - Glass Fibre Reinforced Polymer

RMS - Root Mean Square

NDE - Non Destructive Evaluation

NDT	-	Non Destructive Testing
PBF	-	Powder Bed Fusion
PFCC	-	Face Centred Cube with Vertical Struts
PLA	-	Polylactic Acid
SC	-	Simple Cubic
SLA	-	Stereolithography
SLM	-	Selective Laser Melting
SLS	-	Selective Laser Sintering
STL	-	Standard Triangulation Language
TLPDB	-	Transient Liquid Phase Diffusion Bonding

LIST OF PUBLICATIONS

Journal Articles

Azmi, M.S., Hasan, R., Ismail, R., Rosli, N.A. and Alkahari, M.R., 2018. Static and dynamic analysis of FDM printed lattice structures for sustainable lightweight material application. *Progress in Industrial Ecology, an International Journal*, 12(3), pp. 247-259.

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LIST OF AWARDS

Bronze Award in Universiti Teknikal Malaysia Melaka Exhibition (UTeMEX 2017) for ‘New method to produce optimized ABS polymer lattice structure material manufactured using mid-end additive layer manufacturing’.

Bronze Award in Universiti Teknikal Malaysia Melaka Exhibition (UTeMEX 2017) for ‘A low-cost fire extinguisher using sound wave’.

Silver Award in Mini Universiti Teknikal Malaysia Melaka Exhibition (MiniUTeMEX 2016) for ‘Vibration characteristics for diesel engine oil mixed hexagonal boron nitride (hBN) nanoparticles.