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UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Faculty of Mechanical Engineering

STUDY OF TRANSMISSIBILITY OF LAMINATED RUBBER-METAL SPRING

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Doctor of Philosophy of Mechanical Engineering

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DECLARATION

I declare that this thesis entitled "Study of Transmissibility of Laminated Rubber-Metal Spring" 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 : Mohd Azli bin Salim

Date : 4 Nov 2016

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 Doctor of Philosophy in Mechanical Engineering.

Signature : ....

Supervisor Name : A.P. Dr. Azma Putra

Date : 4/11/2016

DEDICATION

To my father and to my mother and

most importantly my beloved wife

ABSTRACT

Laminated rubber-metal bearing has been well-known as a vibration isolator to dissipate vibration energy. However, most of existing works on the bearing especially the mathematical models consider only the performance of the bearing due to the static force. The main objective of this study is therefore to develop mathematical model to characterize the isolation performance of the bearing; called here laminated rubber-metal spring (LRMS). Mathematical models for 'transmissibility' are developed by using three different approaches: (i) lumped parameter system, (ii) distributed parameter system and (iii) discrete lumped parameter system. The first approach uses assumption of massless rubber, where the rubber layers are simply modelled by using spring and damper elements. The second approach employs impedance technique derived from wave propagation across a cylindrical rubber. In this approach, the internal resonances can be predicted. And the third approach uses a method of dividing a rubber layer into multiple elements of masses and springs in order to predict the equivalent internal resonance as in the second approach. It is found that by adding more metal plates in the rubber, more resonances exist in the transmissibility which can degrade the isolation performance. However, the isolation at high frequencies is improved compared with that of the spring without embedded metal plates. The resonances can be reduced by adding more damping to the rubber. For the experimental work, the LR-MS samples with five different number of embedded metal plates were fabricated using Standard Malaysian Rubber Constant Viscosity (SMR-CV). A test rig for this purpose was also fabricated based on international standards. The measured data of force transmissibility shows good agreement with the proposed mathematical model. Last but not least, there parametric study is also discussed in this thesis.

ABSTRAK

"Laminated rubber-metal spring (LR-MS)" telah dikenali sebagai pemencil getaran, bertujuan untuk menghalang pergerakan tenaga getaran. Pemencil getaran pada masa kini hanya mempunyai model matematik untuk mengkaji prestasi pemencil getaran pada daya statik sahaja. Oleh yang demikian, pembangunan model matematik daya dinamik masih jauh ketinggalan. Model matematik untuk kebolehpindahan dibangunkan dengan menggunakan tiga pendekatan yang berbeza: (i) sistem parameter teragih dan (ii) sistem parameter tergumpal diskret. Pendekatan pertama menggunakan andaian getah tanpa jisim, di mana lapisan getah hanya dimodelkan dengan menggunakan unsur pegas dan peredam. Pendekatan kedua menggunakan teknik galangan dari perambatan gelombang untuk silinder getah. Dalam pendekatan ini resonan dalaman boleh diramalkan. Untuk kaedah ketiga, lapisan getah dibahagikan kepada elemen kecil yang dikenali sebagai jisim dan peregas, ini bertujuan untuk menjangka salunan dalaman yang terhasil dari kaedah kedua. Dapat disimpulkan bahawa apabila menambah kepingan logam di dalam getah, salunan dalaman yang terhasil telah bertambah. Salunan dalaman ini akan mengurangkan prestasi pemencil getaran. Pada frekuensi tinggi, prestasi pemencil getaran dapat ditingkatkan dengan memasukkan kepingan logam ke dalam getah. Salunan dalaman dapat dikurangkan apabila nilai kepingan logam ditambah. Di dalam eksperiman, sampel LR-MS telah di bangunkan dengan menggunakan "Standard Malaysian Rubber Constant Viscosity (SMR-CV)". Sebanyak lima sampel berjaya dibangunkan, di mana setiap sampel mempunyai nilai kepingan logam yang berlainan. Pelantar ujian telah dibangunkan dengan rujukan piawaian antarabangsa. Hasil keboleh-pindaan daripada eksperimen telah dibandingkan dengan model matematik, dan hasilnya adalah menyokong antara satu sama lain. Analisis parameter turut di jalankan di dalam kajian ini.

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LIST OF ABBREVIATIONS

LR-0MS	Laminated rubber-metal plate without metal plate
LR-1MS	Laminated rubber-metal plate with one metal plate
LR-2MS	Laminated rubber-metal plate with two metal plate
LR-3MS	Laminated rubber-metal plate with three metal plate
LR-4MS	Laminated rubber-metal plate with four metal plate
SMR CV-20	Standard Malaysia Rubber Constant Viscosity - 20
SMR CV-40	Standard Malaysia Rubber Constant Viscosity - 40
SMR CV-60	Standard Malaysia Rubber Constant Viscosity - 60
SMR CV-80	Standard Malaysia Rubber Constant Viscosity - 80

LIST OF SYMBOLS

f_n	Vertical natural frequency
x_y	Static deflection of the spring
f	Distributing frequency
f_e	Internal force
y	Displacement
$\dot{y}$	Velocity
$\ddot{y}$	Acceleration
m	Mass of the motor
c	Damping constant
k	Stiffness constant
ω	Frequency at harmonic motion
F_e	Complex amplitude at the excitation force
Y	Complex amplitude at the displacement
f_t	Injected force
T_F , T	Transmissibility force
F_t	Transmitted force
F_e	Excitation force
ω_n	Natural frequency at harmonic motion
ξ , η	Damping loss factor
ω/ω_n	Normalized frequency
m_2	Mass of the rigid foundation
D	Outer diameter
L	Height
d	Inner diameter
K	Static stiffness

G	Shear modulus
B	Numerical factor
B_S	Short numerical factor
B_L	Long numerical factor
E	Young's modulus
A	Area
r	Radius
u_1	Displacement of the loaded mass
u_2	Displacement of the embedded plate
U	Complex amplitude
M	Working mass
$\mathbf{M}$	Mass matrix
$\mathbf{C}$	Damping matrix
$\mathbf{K}$	Stiffness matrix
$\tilde{\mathbf{U}}$	Vectors of complex displacement amplitude
$\tilde{\mathbf{F}}$	Vectors of complex force
$\mathbf{A}$	Matrix A
$\mathbf{A}^{-1}$	Inverse matrix A
N	Layer of metal plates
A, B	Complex wave amplitude
k_l	Longitudinal wavenumber
c_l	Longitudinal wave speed
ρ	Density
$Z_{11}, Z_{12}, Z_{21}, Z_{22}$	Localized impedance
S	Cross sectional area
κ_l	Longitudinal rigidity
Z	Impedance matrix
K	Stiffness matrix
R	Outer radius
r	Inner radius
$K_{11}, K_{12}, K_{21}, K_{22}$	Localized stiffness
F_1, F_2, F_3	Internal force

Z_1	Input impedance
Z_2	Impedance matrix for non-dispersive finite rod
E^*	Complex Young's modulus
k_l^*	Complex longitudinal wavenumber
Ω	Ratio of the driving frequency ω to the system's fundamental natural frequency ω_1
ω_1	Fundamental natural frequency
μ_1	Ratio of the mass of the non-dispersive finite rod to the working mass
c_{eq}	Damping coefficient equation
$\tau_{x\theta}$	Shear stress at x-axis
$\tau_{y\theta}$	Shear stress at y-axis
U_0	Displacement at the middle of vibration isolator
$\bar{\tau}_{xy}$	Shear stress at the vibration isolator bonded with metal plate.
ε	Compressive strain
I_0	Modified Bessel function
S_f	Shape factor
I_1	Modified Bessel function of order one.

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