DYNAMIC ANALYSIS OF MAGNETORHEOLOGICAL ELASTOMER ENGINE MOUNT SYSTEM

BY

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ABSTRACT

Passive, semi-active and active mounts have been used to isolate vibration in engines. However, due to changes in materials used for engine construction, there is a need to improve the performance of engine mounts. These improvements require sophisticated computation software, experimentation difficulties and cost. On the other hand, smart materials applications in engineering is growing but with lesser research on the analysis of models used for simulating behaviors of these smart materials. With proper analysis of mathematical models, isolation of engine vibrations can be improved in modern vehicles using smart materials. One of such smart materials is Magnetorheological Elastomer (MRE). Usually, dynamic responses of visco-elastic materials are observed using phenomenological experiments which include creep, stress relaxation and rheological models. The simulations of these dynamic responses and characterization of engine mounts using Magnetorheological Elastomers (MREs) are limited in literature. These have contributed largely to the absence of commercial MRE mounts albeit their characteristics and performance in theory. The aim is to develop characteristics equation for MREs and simulate its behavior as MRE mount. In this research, the comparison between the Standard Linear Solid (SLS) model and the MRE model reveals the mechanical properties of MREs. These mechanical properties are utilized in the simulation of dynamic behaviors of MRE mount. Sensitivity Analysis (SA) is then used to determine the importance of the parameters which contribute to the performance of MRE mount. The SA reveals that that magnetic field input is more important than characteristic constituents' stiffness of MREs. With this knowledge, MRE mount is controlled to reduce low frequency and high frequency vibration in half car model. It is shown by using different vibration measurement criteria, that there is significant reduction of vibration by using MRE mount. The results obtained when the Passive rubber mount was replaced with MRE mount shows 27% reduction in vibration in low frequency and 25% reduction in vibration in high frequency. The performance of the MRE in nonlinear model is however less promising as shown in the simulation results and further studies are needed. The values identified in this study can be useful in the subsequent design of MRE mounts in engine mount systems.

خلاصة البحث

تستخدم المثبتات النشطة وشبه النشطة لعزل الاهتزاز في المحركات. على أي حال، نتيجة للتغيرات في المواد المستخدمة في بناء المحرك، فإن هناك حاجة لتحسين أداء مثبتات المحرك. هذه التحسينات تحتاج إلى برمجيات حساب معقدة، وتواجه صعوبات اختبارية بالإضافة إلى التكاليف المادية. ومن ناحية أخرى، فإن تطبيقات المواد الذكية في الهندسة هي في تطور مستمر، ولكن هناك عدد قليل من الأبحاث في مجال تحليل النماذج المستخدمة في سلوكيات المحاكاة لهذه المواد الذكية. وبتحليل مناسب للنماذج الرياضية، فإن عزل اهتزازات المحرك يمكن تحسينها في السيارات الحديثة باستخدام مواد ذكية. ومن هذه المواد الذكية (المطاط الحساس للمغنطة (Magnetorheological Elastomer (MRE)). عادة، الاستجابات الديناميكية لمواد المطاط اللزج تلاحظ من خلال اختبارات الظواهر التي تتضمن الزحف وإرخاء الإجهاد والنماذج الريولوجية. محاكاة هذه النماذج الديناميكية ووصف مثبتات المحرك باستخدام (MRE) تم تناوله بشكل محدود في الدراسات السابقة. وهذا ساهم بشكل كبير في غياب مثبتات (MRE) في النطاق التجاري، برغم مميزاتها وأدائها في المجال النظري. الهدف هو تطوير معادلة المميزات لـ (MRE) ومحاكاة سلوكها كمثبتات (MRE). في هذا البحث، تظهر المقارنة بين نموذجي (Standard Linear Solid (SLS)) و (MRE) الخصائص الميكانيكية لـ (MREs). هذه الخصائص الميكانيكية استخدمت في محاكاة السلوكيات الديناميكية لمثبتات (MRE). بعدها تم استخدام تحليل الحساسية لتحديد أهمية المعاملات التي تساهم في أداء مثبتات (MRE). تحليل الحساسية يظهر أن الحقل المغناطيسي كمُدخل أهم من صلابة مكونات (MREs). من هذه المعلومة فإن مثبت (MRE) يمكن التحكم به لتقليل اهتزاز في مجال التردد المنخفض والتردد العالي في نموذج نصف السيارة. يظهر من استخدام معايير مختلفة لقياس الاهتزاز أن هناك تخفيضاً كبيراً للاهتزاز باستخدام مثبت (MRE). أظهرت النتائج التي تم الحصول عليها عندما تم استبدال المطاط العادي بـ (MRE) أن تخفيض الاهتزاز بنسبة 27% في مجال التردد المنخفض و 25% في مجال التردد العالي. كما أظهرت النتائج أن أداء (MRE) في النماذج غير الخطية ليس واعداً كثيراً وهناك حاجة إلى دراسات إضافية في هذا المجال. القيم المعرّفة في هذه الدراسة يمكن أن تكون مفيدة في التصميم اللاحق لأنظمة تثبيت المحرك (MRE).

APPROVAL PAGE

The thesis of Ismail Ladele Ladipo has been approved by the following:

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DECLARATION

I hereby declare that this thesis is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institution.

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Dedicated to Allah (SWT)

"And [remember, O Muhammad], when those who disbelieved plotted against you to restrain you or kill you or evict you [from Makkah]. But they plan, and Allah plans. And Allah is the best of planners"

- Quran (8:30)

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LIST OF ABBREVIATIONS

6-DOF	6-Degree of freedom
dB	decibel
CS	Characteristic stiffness
ER	Electrorheology
ERF	Electrorheological Fluids
FRF	Frequency Response Function
GSLS	General Standard Linear Solid
KSLS	Kelvin Standard Linear Solid
MR	Magnetorheology
MF	Magnetic field
MS	Magneto Sensitive
MRE	Magnetorheological Elastomer
MREs	Magnetorheological Elastomers
MRF	Magnetorheological Fluid
MRFs	Magnetorheological Fluids
MRFE	Magnetorheological Fluid Elastomer
MRVE	Magnetorheological Visco Elastomer
NVH	Noise, Vibration and Harshness
Rd	Relative displacement
RPM	Revolution per minute
SA	Sensitivity Analysis
SI	Sensitivity Index

LIST OF SYMBOLS

$\ddot{\theta}_b$	Chassis angular acceleration
θ_b	Chassis angular displacement
m_c	Chassis mass
x_c	Chassis displacement
η	Coefficient of viscosity
K	Constant for the dimensions of length for mount
l	Connecting rod length
ω_c	Crankshaft angular velocity
J	Creep compliance function
ζ	Damping ratio
T_d	Displacement transmissibility
G_o	Dynamic stiffness at resonance
α	Dynamic stiffness ratio at low and high frequency
$G_{(\varepsilon,\omega)E}$	Elastomer model storage modulus
α_E	Elastomer model storage modulus ratio at low and high frequency
η_E	Elastomer model coefficient of viscosity
$\omega_{t(E)}$	Elastomer model transition frequency
$\delta_{G(\varepsilon,\omega)E}$	Elastomer model loss factor
$\ddot{\theta}_E$	Engine angular acceleration
θ_E	Engine angular displacement
F_T	Engine force

m_e	Engine mass
c_E	Engine mount damping coefficient
ω	Frequency (rad/s)
Ω	Frequency ratio
T_f	Force transmissibility
F_o	Force transmitted by engine to chassis
C_{sf}	Front suspension damping
k_{sf}	Front suspension stiffness
Hz	Hertz
σ_o	Initial stress
ε_o	Initial strain
B_l	Input matrix at low frequency
B_h	Input matrix at high frequency
β	Magnetic field intensity
m	Mass
α_M	MRE model storage modulus ratio at low and high frequency
$G_{(\varepsilon,\omega)M}$	MRE model storage modulus
η_M	MRE model coefficient of viscosity
$\delta_{(G(\varepsilon,\omega)M)}$	MRE model loss factor
$(\omega_t)_M$	MRE model transition frequency
ω_o	Natural frequency
$F_{s(1..2)}$	Nonlinear front and rear suspension spring force
$F_{d(1..2)}$	Nonlinear front and rear suspension damper force

C	Output state space matrix
$G^*_{(\varepsilon,\omega)P}$	Passive rubber mounts complex shear modulus
$G_{(\varepsilon,\omega)P}$	Passive rubber mounts storage modulus
$\delta_{(G(\varepsilon,\omega)P)}$	Passive rubber mounts loss factor
φ	Phase angle
r	Ratio of harmonic force frequency over undamped natural frequency
k_{sr}	Rear suspension stiffness
R_d	Relative displacement
ω_o	Resonance frequency
X_o	Road profile initial displacement
r_c	Rotational radius of crank arm
σ	Stress
σ_s	Stress in spring element
σ_d	Stress in damping element
σ_M	Stress in Maxwell model
σ_E	Stress in spring element
ε	Strain
ε_s	Strain in spring element
ε_d	Strain in damper element
k_s	Suspension total stiffness
c_s	Suspension damping
T	Tesla
θ	Temperature

CHAPTER ONE

INTRODUCTION

1.1 OVERVIEW

Rubber is the conventional material for mounts used in passive isolation of engine vibration. Semi–active and active methods have also been suggested and used in different research. Hydraulic, Electrorheological (ER) and Magnetorheological (MR) fluids are used in semi-active and active mounts.

Different research on fluids with nonlinear characteristics in adaptive hydraulic engine mount systems have been reported (Geisberger, Khajepour, & Golnaraghi, 2002; Gołdasz & Sapiński, 2011; Kim, Choi, Hong, & Han, 2004). While active mounts have been used as a replacement for semi-active mounts. Active mounts are however complex, less reliable and expensive (Kim et al., 2004).

Recently in the automobile industry, efforts have been directed towards using lighter materials for construction of engines. However, the power requirement of new vehicle engines is on the increase. The construction materials and power requirements of engines affects the selection of appropriate engine mounts in modern vehicles.

It is evident that conventional mounts have for the past three decades reached their performance limits due to evolving vehicle designs and can no longer meet the requirements by current practices in automotive engineering (Harrison, 2004). The associated noise, vibration and harshness (NVH) issues with modern automobiles vehicles are cause for concern.

Apart from the trends in automobile industry, operation behaviors of engine mounts require that mounts have variable loss factor and storage modulus properties.

Thus, the need to find alternative materials that are suited for the requirements. The identification of engineering materials which have variable dynamic stiffness and damping modulus represents immense potentials in reducing engine vibration.

MR or Magneto-sensitive (MS) materials to which Magnetorheological Elastomers (MREs) belongs, are a class of smart materials whose dynamic stiffness and damping modulus can be varied by applying magnetic field (Li, Zhang, & Du, 2013). MR materials in liquid and foam forms are called Magnetorheological Fluids (MRFs). MREs are solid analogue of MRFs (Li, Li, Li, & Du, 2014). Unlike MRFs, MREs are non-contaminable. The research into the engineering applications of MREs is relatively new when compared to MRFs.

The composition of MREs is a complex polymeric system which consists of elastomeric medium (highly viscoelastic medium) serving as the dispersed medium for different solids and liquids. The particle chains in MREs are intended to always operate in pre-yield regions while in MRFs, the particle operate in post yield continuous shear or flow regimes. With continuously variable rheological properties, MREs could be used for numerous applications.

Various magneto-mechanical properties have been reported to be exhibited by MREs (Ginder, Clark, Schlotter, & Nichols, 2002; Guan, Dong, & Ou, 2008). Some of the important differences between MREs and MRFs are that, MRFs have field dependent yield stress but MREs have controllable shear modulus that is dependent on magnetic field. Also, MREs do not require containers to hold the MR materials and the solid matrix particles do not coagulate with time. Unfortunately, little is known in publication on the commercial uses of MREs (Brigadnov & Dorfmann, 2003).

The engine mount system comprises of vehicle chassis (the foundation), the engine and the road (source of vibration) and engine mounts (isolator). The application of MREs as engine mount is relatively new. Almost all commercially available semi-active mounts are made of rubber, hydraulic fluid, Electrorheological Fluids (ERFs) or MRFs.

The ability to manipulate the storage modulus and loss factor of MREs in engine mount systems is of interest in this research. Of the two properties, that is most difficult to model but easier to control is damping modulus (Kallio, 2005). The needs for solid state mechatronics device such as MREs are a growing field. Like other smart materials, hysteresis behavior of magnetorheological composites is nonlinear and thus mathematical models that can be used to study MREs behaviors must also be able to predict the phenomenological behaviors of MREs.

This research aims to study an alternative rubberlike material whose variable dynamic properties can be used in solving the problems in engine mount systems. The mechanical properties of MREs is investigated from the mathematical equations developed from the MRE model. The simulation behaviors of MREs is then compared to existing model. Magnetorheological Elastomer (MRE) model is used to replace MRE mount and used in simulation studies for comparison of the performance of Passive rubber mounts and MREs mounts in engine mount systems.

One of the motivations of this work is the unavailability of dynamic analysis developed from the mechanical model which can be used to simulate the magneto-rheological response of MREs.

The results of this research can thus be adapted to simulate MREs in other applications where semi-active vibration isolation using MREs are required.

1.2 PROBLEM STATEMENT AND ITS SIGNIFICANCE

The connection of more powerful engines to lighter vehicle frames has indeed resulted in vibration problems that passive elastomeric and hydraulic mounts cannot adequately address (Marzbani, Jazar, & Fard, 2013). The following are some problems in existing engine mount systems:

(a) Passive rubber mounts are designed with a trade-off when selecting frequencies of vibration which the mount will isolate. It is either low frequency or high frequency vibration that is reduced. The vibrations in both frequencies are difficult to be isolated due to the static properties of rubber mount. Passive rubber mount therefore perform poorly for transient response of shock excitations (Adiguna, Tiwari, Singh, Tseng, & Hrovat, 2003).

(b) Semi-active and active mounts are expensive, complex and their performance is nonlinear (Shangguan, 2009). Semi-active mounts with fluids causes contamination to the environment due to spilling (Elahinia, Ciocanel, Nguyen, & Wang, 2013). Thus, existing engine mount systems needs modifications in their design or improvement in properties of materials that are currently used as mounts (Yu, Naganathan, & Dukkipati, 2001).

(c) MREs applications to solve engineering problems still need to be understood properly before it is implemented in real applications (Li, Zhou, & Tian, 2010). Despite the success of using smart material such as Magnetorheological Fluid (MRF) in engineering applications like structural vibration isolation, engine mounts and suspension system, it has constraints namely being a liquid are non-environmentally friendly unlike MRE (Kciuk & Turczyn, 2006).

(d) The application of MREs to engineering problems is also limited due to the unavailability of analytical models to describe the rheological and phenomenological behavior of MREs**.** The lack of a standard for the constituents' components of MREs during fabrication also hindered the development of a mathematical model which can be used to simulate the behaviors of MREs (Hu et al., 2005).

The implementation of MRE as an engine mount is influenced by simulation results with parameters to predict accurately the behavior of MRE mount. Due to the limited research on the use of MREs, such simulation parameters are unavailable in literature.

The MRE has the potentials to replace existing passive engine mounts in vehicles Therefore, there is need to develop a mathematical model which can be used for MRE and simulate behaviors of engine mount systems that uses MREs isolators.

1.3 RESEARCH PHILOSOPHY

The powertrain of automobiles is the largest concentration of mass in a vehicle. This implies that the engine design and its components vibration is a factor to be considered in the design of automobiles (Darsivan, Martono, & Faris, 2009). The situation is critical now that lighter engine designs are emerging. The traditional passive isolators are becoming deficient in performance and there is the need to improve their capabilities.

Based on the engineering applications of MREs which is a rapidly growing field of knowledge, it is proposed that further studies on the mechanical properties of this smart material will increase the understanding and potentials of MREs.

The ability to describe the behavior of MRE using analytical model in simulation before implementation in real vehicles is important (Dorfmann & Ogden, 2003). The development of models which can be used in the design studies of the prototype MRE mount enables the characterization of MREs in general and its behavior as engine mounts in particular. These mathematical models are used to simulate the mechanical behaviors of MREs when used in different engineering applications. The mechanical behaviors include shear stress and strain properties (which determines the damping modulus), hysteresis (energy lost during working cycles), temperature and magnetic field input effect.

MREs have dynamic characteristics which can be utilized in the design of engine mounts to reduce the vibration of engine mount system in all frequency. The performance evaluation of MRE (which have promising performance) to rubber (that are currently been used) as passive engine mount is thus important.

The use of MRE mounts could lead to increase attenuation of vibrations in engines and other applications where mounts are required. Thus, further investigation of existing mathematical models for rubberlike materials is necessary. This is partly due to the peculiar nature of MREs which is different from other visco-elastic materials.

This could lead to the establishment of the advantages of using MRE as mounts in engine mount systems.