Dissertation

MODELING AND SEMI-ACTIVE VIBRATION CONTROL OF STRUCTURES USING MAGNETORHEOLOGICAL ELASTOMERS

磁気粘弾性エラストマを用いた構造物のセミアクティブ制振とモデル化に関する研究

Kanazawa University
Graduate School of Natural Science and Technology
Division of Mechanical Science and Engineering

(Abstract)

Student Number 1524032017
Name: Nguyen Xuan Bao
Chief advisor: Prof. Toshihiko Komatsuzaki

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Abstract

Magnetorheological elastomer (MRE) is a class of smart materials that mainly generate a magnetic field dependent variable stiffness. MREs have attracted significant interest for application in the field of intelligent devices, such as vibration absorbers and isolators. In this research, a novel variable stiffness vibration isolator that uses MREs accompanied with semiactive vibration controller was developed. Firstly, the dynamic viscoelastic characteristics of MRE was clarified. The MRE properties are strongly nonlinear functions of magnetic flux density, displacement amplitude, and the excitation frequency. The dynamic viscoelastic model of the MRE-based isolator was presented, and a procedure to determine the six model parameters was introduced. Secondly, a fuzzy semi-active control algorithm was used to enhance performance of the MRE-based isolator in a structure under seismic excitation. Both numerical simulation and experimental results showed that the fuzzy semi-active controller overcame the drawbacks of traditional semi-active controller. Furthermore, a robust adaptive controller was proposed for the semi-active isolator to suppress structural responses with uncertain parameters. The proposed controller requires lesser control force than the standard adaptive controller, avoids the singularity problem, and provides robust stability. The controller worked remarkably better than the fuzzy controller in protecting a two-story shear building during seismic events.
Chapter 1&2 Background of Magnetorheological elastomer

Magnetorheological elastomer (MRE) is a class of smart materials that mainly generate a magnetic field dependent variable stiffness. MREs are the solid analogues [1] to MRFs composed of iron particles embedded in a low permeability carrier matrix (usually rubber). Because of variable stiffness, MRE devices can efficiently alter natural frequencies. Consequently, researchers have given interest to the application of MREs to intelligent devices in vibration control system design, such as vibration absorbers and isolators [2, 3]. MR elastomer (MRE) was first proposed by Jolly et al. in 1996 [4]. In recent years, several researches have been reported regarding improvement and investigation of the mechanical properties of MRE [6-11]. In order to improve the properties of the MRE, many researches have focused on component materials, fabrication processes and optimal magnetic systems. The properties of MRE are clarified in [11-14, 19]. The properties are nonlinear and dependent on frequency of excitation, amplitude excitation, and magnetic field.

Vibration isolation is to prevent vibration energy transmission from one part to another by installing vibration isolator between them. MRE-based isolator has been intensively studied and several designs have been reported. An MRE-based isolator is a smart device that has the ability to govern the transmissibility by adjusting its properties such as stiffness and damping [15-18]. In order to design MRE-based isolator systems for various technical applications, a numerical model is necessary to represent dynamic behaviors of MRE. Because of the nonlinear properties, modeling of the MRE properties is a substantial challenge, particularly in vibration control technology. Recently, MRE modeling has been considered in two approaches: micro model and macro model. In the microscopic modeling, the change of chains of iron particles under the change of magnetic field strength were considered [20, 21]. The macroscopic modeling is based on stress–strain (or force–displacement) relationship of MREs in different levels of amplitudes, frequencies, and magnetic fields. There are many models of MRE such as four-parameter viscoelastic model [22], the Maxwell model combined with Ramber-Osgood model [23], the Bouc-Wen model [24], and modified Kelvin–Voigt model [25].

The MRE-based isolator is one of the semi-active devices that require an efficient controller. Because of nonlinearity in the model, not many control algorithms exist that could effectively operate MRE devices. The following semi-active control algorithms are usually used in recent years. The on-off skyhook algorithm [26, 27] has been extensively used in MRE devices. The Lyapunov control algorithm [17] determines the control voltage to minimize the derivative of the Lyapunov function. The Bang–Bang controller [29] is introduced to dissipate energy in the structure. The semi-active fuzzy control algorithm [19, 30, 31] can generate a continuous control output. These controllers may exhibit unsatisfactory isolation performance, and even cause instability. To overcome these drawbacks, the design of a robust controller for the nonlinear dynamic system is necessary.
Chapter 3 Properties and Modelling of MRE-based isolator

In this chapter, the viscoelastic characteristics of MREs in shear mode are first clarified systematically in order to achieve a mathematical basis for the model development. Then, a numerical model that expresses viscoelastic behaviors of the MRE is proposed. The model consists of the following components: viscoelasticity of host MRE, magnetic field-induced property, nominal viscosity in conjunction with high stiffness property in low excitation frequency that are modeled in analogy with a standard linear solid model (Zener model), a stiffness variable spring, and a smooth Coulomb friction, respectively.

![Measurement system](image)

![MRE components model](image)

![Procedure to determine model parameters](image)

Table 3.1 Parameter for the proposed MRE model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stiffness (K_1)</td>
<td>13 Nmm(^{-1})</td>
</tr>
<tr>
<td>Stiffness (K_2)</td>
<td>10 Nmm(^{-1})</td>
</tr>
<tr>
<td>Viscous damping (C)</td>
<td>0.035 Nsm(^{-1})</td>
</tr>
<tr>
<td>Friction displacement (x_2)</td>
<td>0.09 mm</td>
</tr>
<tr>
<td>Maximum friction force (F_{f\text{max}})</td>
<td>(-0.24I^2 + 2.75I + 2.4)</td>
</tr>
<tr>
<td>Variable stiffness (K_m)</td>
<td>(-0.38I^2 + 4.25I)</td>
</tr>
<tr>
<td>Applied current (I)</td>
<td>(I \in [0,6]) Ampere</td>
</tr>
</tbody>
</table>
The measurement setup is shown in Figure 3.1. The parameters are determined according to the following procedure, from step 1 to step 3, as shown in Figure 3.3. The model parameter values and the approximation formulae were identified as listed in Table 3.1. The effectiveness of the proposed model is shown in Figures 3.4-3.6.

![Figure 3.4 Stiffness and loss factor versus excitation frequency $x_0 = 0.75$ mm](image1)

![Figure 3.5 Stiffness and loss factor versus excitation amplitude $f = 15$ Hz](image2)

![Figure 3.6 Stiffness and loss factor versus applied current with $x_0 = 0.75$ mm](image3)

The proposed model predicts with high accuracy the dynamic viscoelastic characteristics of MRE in a wide range of frequencies (3–30 Hz) and shear strain (4%–16%).
Chapter 4: Semi-active fuzzy control of 1-DOF system using magnetorheological elastomers

The MRE-based isolator is one of the semi-active devices that require an efficient controller. Because of nonlinearity in the model, not many control algorithms exist that could effectively operate MRE devices. The on-off algorithms are widely used include sky-hook on-off algorithm, clipped-optimal algorithm, Lyapunov algorithm, a sub-optimal H-\infty strategy [26-30]. In these algorithms, the command applied current has only two options: either zero or the maximum value. Consequently, fast switching produces periodical acceleration and jerk peaks that result in negative effects on the quality of structures.

![Figure 4.1 Base-excited 1-DOF system](image1)

![Figure 4.2 Block diagram of fuzzy logic controller](image2)

![Figure 4.3 Fuzzy logic membership functions](image3)

As shown in Figure 4.2, the controller consists of three basic parts: fuzzification, fuzzy inference, and de-fuzzification. Relative displacement ($x_r$) and velocity ($\dot{x}$) were defined as the controller inputs and were divided into two intervals of linguistic variables: negative (Neg) and positive (Pos). As the control output, tunable stiffness ($k^*$) was divided into high stiffness (High) and low stiffness (Low). The membership functions is depicted in Figure 4.3. Fuzzy rules play an important role in a fuzzy control system and they are listed in Table 4.1.

System responses using passive, on-off semi-active, and fuzzy semi-active control schemes were calculated in order to evaluate the performance of the proposed controller. The model parameters are listed in Table 4.1. Fig. 4.4, 4.5 show that the semi-active fuzzy control provided better performance than its
counterparts. By using fuzzy controller, the reduction rates were 31% and 34% for the RMS and maximum displacement values, respectively. The acceleration RMS and maximum acceleration values also decreased in the case of the fuzzy semi-active control by 21% and 37%, respectively.

Table 4.1 Fuzzy logic rules.

<table>
<thead>
<tr>
<th>Relative displacement/Velocity</th>
<th>Neg</th>
<th>Pos</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neg</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Pos</td>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>

Fuzzy inference | Mamdani type  
De-fuzzification  | Center of gravity

Table 4.2 Parameters used in simulation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damping coefficient</td>
<td>1 Ns^{-1}</td>
</tr>
<tr>
<td>Mass</td>
<td>1.138 kg</td>
</tr>
<tr>
<td>Spring constant (minimum, $k_0$)</td>
<td>974.5 Nm^{-1}</td>
</tr>
<tr>
<td>Spring constant (maximum, $k_{max}$)</td>
<td>1948.9 Nm^{-1}</td>
</tr>
<tr>
<td>Base excitation amplitude</td>
<td>2 mm</td>
</tr>
</tbody>
</table>

Figure 4.4 Frequency response for 1-DOF system (simulation).

Figure 4.5 Displacement response by random excitation: (a) the passive ($k^* = k_0$), (b) the passive ($k^* = k_{max}$), (c) the on-off semi-active control, and (d) the fuzzy semi-active control.
Chapter 5 Semi-active fuzzy control of multi-degree-of-freedom structure using MREs

A semi-active fuzzy controller was designed to enhance the performance of the isolator in suppressing multi-degree-of-freedom structural vibrations (Fig. 5.1). The control strategy was built to determine the command applied current. The efficiency of the MRE-based isolator was evaluated by the responses of the scaled building under seismic excitation (Fig. 5.2). Experimental results show that the isolator accompanied with a fuzzy controller remarkably reduces the relative displacement and absolute acceleration of the scaled building compared to passive-off and passive-on cases. The maximum relative displacement between third mass and fundament plate also decreases by 30%, absolute acceleration are reduced by 15% and 24% (Fig. 5.3).

Figure 5.1 Schematic of the two-story building with a fundament plate is rigidly connected by an MRE-based isolator.

Figure 5.2 Experimental setup

Figure 5.3 Transmissibility of the scaled building: (a) displacement transmissibility and (b) acceleration transmissibility.
Chapter 6 Robust adaptive controller for semi-active control of uncertain structures using an MRE-based isolator

In this chapter, the design of the new semi-active controller for an MRE-based isolator is investigated to overcome the drawbacks of traditional controllers from two perspectives. Firstly, an inverse model is designed for the isolator so that it can be used to predict an appropriate electric current supplied to the electromagnet based on the desired control force. Secondly, a robust adaptive controller is proposed for a nonlinear system with unknown dynamic parameters. The control scheme consists of three parts: a standard adaptive linearizing controller, an adaptive sliding mode controller, and a single robust controller. The proposed method guarantees zero convergence of the displacement response and provides robust stability. In addition, the singularity problem that usually appears in standard adaptive control is eliminated.

The inverse model is necessary to describe the relationship between the desired force and the corresponding applied current/voltage [33, 34]. In this study, the inverse dynamics model for the MRE-based isolator is diagramed as shown in Figure 6.1.

![Fig. 6.1 The inverse model. The MRE force is expected to track the desired force, $F_{MRE}(t) = F_{Desired}(t)$.](image-url)

The objective of the controller design is to develop a control algorithm for the isolator having structural uncertainties in mass, damping, and stiffness, under the unknown earthquake excitation, such that the
relative displacements are stabilized at zero. The closed-loop system is described in Fig. 6.2. The system consists of an isolated building and a control system. The inputs to the isolated building are the ground motion acceleration, \( \ddot{x}_g \), and the applied current to the isolator. Floor displacement responses, \([x, \dot{x}]\), are the outputs of the isolated building. This responses are the inputs of control system. In the control system, the dynamic parameters are assumed unknown. The robust adaptive controller is then proposed for uncertain dynamic to alleviate the drawbacks of standard adaptive control. The adaptive algorithm update the uncertain parameters to gain the actual parameters. The control scheme consists of three parts: a standard adaptive nonlinear controller \( F_a \), an adaptive sliding mode controller \( F_s \), and a single robust controller \( F_r \). By using the switching algorithm between the standard adaptive controller and the sliding mode controller, the proposed controller gains better stability with lesser control force compared to the case where single controllers are used independently. The control force is limited within the controllable range of the isolator. The inverse model is then employed to obtain the applied current. Finally, the MRE-based isolator exerts an actual force on the two-story building. The proposed controller works remarkably better than the fuzzy controller as shown in Fig. 6.3.

A robust adaptive controller was then proposed for the semi-active isolator to reduce seismic vibration. The robust adaptive controller suppressed significantly structural responses with uncertain parameters. The proposed controller overcomes the drawbacks of the conventional semi-active controller, avoids the singularity problem, and provides robust stability.

![Relative displacement and acceleration of the second floor under the El Centro earthquake.](image)

Figure 6.3 The relative displacement and acceleration of the second floor under the El Centro earthquake.
Chapter 7. Conclusion

This research was aimed at investigating a MRE-based isolator in the field of modeling and vibration control by a proposed dynamic model and innovative semi-active controllers. The major achievements of this study are summarized as follows:

- The dynamic viscoelastic characteristic of MRE-based isolator was presented. The MRE properties are strongly nonlinear functions of magnetic flux density, displacement amplitude, and the excitation frequency.
- The dynamic viscoelastic model of the MRE-based isolator was presented, and a procedure to determine the six model parameters was introduced. The force-displacement relationship obtained by the numerical model is nearly consistent with the measurement results. Moreover, the proposed model predicts with high accuracy the dynamic viscoelastic characteristics of MRE in a wide range of frequencies (3–30 Hz) and shear strain (4%–16%).
- A fuzzy control algorithm was used to enhance performance of the MRE-based isolator in a structure under seismic excitation. Both numerical simulation and experimental results show that the “fuzzy semi-active control” provides better performance than the rest of the passive cases, “fixed base,” “passive off,” and “passive on.” The peaks of the third mass displacement and absolute acceleration are reduced by 15% and 24%, respectively. The maximum relative displacement between third mass and fundament plate also decreases by 30%. The MRE-based isolator used in conjunction with the fuzzy controller is efficient for mitigating vibrations in a two story building.
- The results showed that the fuzzy semi-active controller overcomes the drawback of traditional semi-active control in reducing chattering.
- The inverse model of an MRE-based isolator was derived. A good agreement is obtained between the predicted and measured electric currents to be supplied to a magnetic coil. This result proves that the inverse model works effectively.
- A robust adaptive controller was proposed for the semi-active isolator to reduce seismic vibration. The controller suppressed significantly structural responses with uncertain parameters. Furthermore, the proposed controller requires lesser control force than the standard adaptive controller. The proposed controller overcomes the drawbacks of the conventional semi-active controller, avoids the singularity problem, and provides robust stability.
References


学位論文審査報告書（甲）

1. 学位論文題目（外国語の場合は和訳を付けること）。

Modelling and semi-active vibration control of structures using magnetorheological elastomers
（邦訳）磁気粘弾性エラストマを用いた構造物のセミアクティブ制振とモデル化に関する研究）

2. 論文提出者 （1）所 属 機械科学専攻
（2）氏 名 Nguyen Xuan Bao

3. 審査結果の要旨（600～650字）

当該学位論文に関し、平成30年7月31日に第1回学位論文審査委員会を開催し、提出された学位論文及び関連資料について詳細に検討した。さらに、同年8月1日の口頭発表後、第2回学位論文審査委員会を開催し、慎重に協議した結果、以下の通り判定した。

本論文は、外部磁場により粘弾性の変化する磁気粘弾性エラストマを機械構造物の防振へ適用するにあたり、当該構造物のモデル化及びそれを踏まえた効果的な振動制御手段の検討に関するものである。まず、周波数帯域、制御精度、及び制御に依存する当該物性を高精度に表現可能な数学モデルを提案した。続いて、当該材料を構造物の免震支承層に適用し、模型を地震に対する構造物の応答を低減する手段として、ファジー推論に基づく正則制御を構築し、従来の制御におけるチャリングや電力消費の問題を著しく改善できることを実験及び数値計算により示した。さらに、不確定なパラメータを含む系に対して特異性を回避しつつ制御効果を最大化するロバスト適応型コントローラの実装が可能であることを、理論的検討及び数値計算により示した。

以上のように、本研究は主に数理的な側面から磁気粘弾性エラストマの精密なモデル化に基づく、正則制御の高機能化手段を提案するものであり、関連分野への技術的貢献及び学術的価値は高いと考える。よって、本論文は博士（学術）に準ずると判定する。

4. 審査結果 （1）判定（いずれかに○印） 合 格
（2）授与学位 博 士 （ 学術 ）