UNIVERSITY OF TECHNOLOGY SYDNEY
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MODELING AND CONTROL OF SMART STRUCTURES EMBEDDED WITH MAGNETORHEOLOGICAL DEVICES

by

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Certificate of Authorship/Originality

I, Sayed Royel declare that this thesis, is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Electrical and Data Engineering at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise reference or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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ABSTRACT

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Dr. Ricardo P. Aguilera

Engineering structures are the essence of supporting the development of society. However, quite often do they suffer from hostile dynamic loadings or external disturbances that may affect structural health or function. Modeling and control techniques can be applied to resiliently preserve structural health and function with a low energy cost, which is the main theme of the thesis. Smart structures embedded with semi-active control devices offer a promising solution to the problem, such as the magnetorheological (MR) damper (MRD), pin joint (MRP), and elastomer base isolator (MRE). This study first aims at exploring the solutions to the present problem in system modeling and controller design of MR based systems to effectively damp out unwanted vibrations as well as control the embodied energy level. Multi-variable hysteresis models for these structural members are developed, capable of effectively working in a wide scale of loading amplitude and frequency. The modeling objective is to illustrate the intrinsic nonlinearity with traceable relationships between model parameters and control signals in order to realize the field-controlled method for MR structure systems. Experimental data are obtained from a long-stroke MRD, a recent prototype of MRP and an MRE under different loading conditions for model identification and performance assessment. To achieve robustness, a second-order sliding mode controller is designed and applied to the MRE to provide a real-time feedback control of structures. The performance of the proposed technique is evaluated in the simulation of a seismically excited three-

storey benchmark building model. To exploit the frequency domain advantage, this study also focuses on the cyclic dissipation of vibration-induced energy in the smart devices under a controlled magnetic field to analyze the energy relationships of the smart devices in the structures. A frequency-shaped second-order sliding mode controller (FS2SMC) is designed along with a low-pass filter to implement the desired dynamic sliding surface. The proposed controller can shape the frequency characteristics of the equivalent dynamics for the MR structure against induced vibrations, and hence, dissipate the mechanical energy flow within the devices to prevent structural damage. The energy spectra of a 10-floor building subject to four benchmark earthquakes are analyzed in terms of kinetic, damping, strain, and input energies to illustrate the capability of an energy-efficient embedded structure. The merits of FS2SMC in engineering structures can also be verified in a half-car model for reducing the roll angle while adjusting the spectrum to prevent natural modes of the structure under external excitations.

Dedication

To my parents associate professor *Sayed Jahangir Alam* and *Hafiza Khatun*, wife *Farjana Hoq*, and son *Sayed Shoayb Ibraheem*.

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List of Publications

Journal Papers

J-1. Q. P. Ha, **S. Royel**, and C. Balaguer (2018), "Low-energy Structures Embedded With Smart Dampers," *Energy and Buildings*, vol. 177, pp. 375 - 384, doi: 10.1016/j.enbuild.2018.08.016.

J-2. Q. P. Ha, **S. Royel**, J. Li and Y. Li (2016), "Hysteresis Modeling of Smart Structure MR Devices using Describing Functions," *IEEE/ASME Transactions on Mechatronics*, vol. 21, no. 1, pp. 44 - 50, doi: 10.1109/TMECH.2015.2506539.

J-3. Y. Yu, **S. Royel**, J. Li, Y. Li and Q. P. Ha (2016), "Magnetorheological Elastomer Base Isolator for Earthquake Response Mitigation on Building Structures: Modeling and Second-Order Sliding Mode Control," *Earthquakes and Structures*, vol. 11, no. 6, pp. 943-966, doi: 10.12989/eas.2016.11.6.943.

J-4. Y. Yu, Y. Li, J. Li, X. Gu, and **S. Royel** (2018), "Nonlinear Characterisation of the MRE Isolator Using Binary-coded Discrete CSO and ELM," *International Journal of Structural Stability and Dynamics*, vol 18, no 8, doi: 10.1142/S0219455418400072.

Conference Papers

C-1. **S. Royel**, Q. Ha. and R. P. Aguilera (2018), "Frequency-Shaped Second-Order Sliding Mode Control for Smart Suspension Systems," *Proc. IEEE International Conference on Control, Automation, Robotics and Vision*, pp. 907-912, Singapore, Nov. 18 - 21, doi: 10.1109/ICARCV.2018.8581139.

C-2. **S. Royel** and Q. Ha (2017), "Frequency Shaped Sliding Mode Control of Magnetorheological Smart Structure Systems," *Proc. IEEE International Confer-*

ence on Mechatronics, pp. 117–122, Gippsland, Australia, Feb. 13-15, doi: 10.1109/ICMECH.2017.7921090.

C-3. **S. Royel**, Y. Yu, Y. Li, J. Li and Q. P. Ha (2015), "A Hysteresis Model and Parameter Identification for MR Pin Joints using Immune Particle Swarm Optimization," *Proc. IEEE International Conference on Automation Science and Engineering*, pp. 1319-1324, Gothenburg, Sweden, Aug. 24 - 28, doi: 10.1109/CoASE.2015.7294281.

C-4. **S. Royel**, Z. Movassaghi, N. M. Kwok and Q. P. Ha (2012), "Smart Structures Using MR dampers with Second Order Sliding Mode Control," *Proc. IEEE International Conference on Control, Automation and Information Science*, pp. 170-175, Ho Chi Minh, Vietnam, Nov. 26 - 29, 2012, doi: 10.1109/ICCAIS.2012.6466580.

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Notation

$\mathbb{N}, \mathbb{Z}, \mathbb{R}, \mathbb{C}$	the field of natural, integers, real and complex numbers
$\mathbb{R}^+$	the set of strictly positive real numbers
$\mathbb{C}^-$	the open left half of the complex plane, i.e. $\{z \in \mathbb{C} : \mathrm{Re}[z] < 0\}$
$\mathrm{Re}[z](\mathrm{Im}[z])$	the real (imaginary) part of a complex variable z
$\mathbb{R}^n$	the n-dimensional Euclidean space
$\mathbb{R}^{n\times m}$	the set of real matrices with n rows and m columns
$\mathbf{I}^{n\times n}(\mathbf{0}^{n\times n})$	the $n \times n$ identity (zero) matrix
$A^{\mathrm{T}}(x^{\mathrm{T}})$	the transpose of a matrix A (a vector x)
A^{-1}	the inverse of a nonsingular square matrix A
$\lambda(A)$	the spectrum of the non-defective matrix A, i.e. the set of eigenvalues
$\mathrm{diag}(a_1, \ldots, a_n)$	a diagonal matrix with diagonal elements a_1 to a_n
$\mathrm{dist}(p, M)$	the distance from a point $p \in \mathbb{R}^n$ to a set $M \subseteq \mathbb{R}^n$
B_p	the closed ball of radius p with center at the origin is defined by $\{x \in \mathbb{R}^n \mid \|x\| \leq p\}$; p is a nonnegative real number
$f : S_1 \to S_2$	the function f mapping a set S_1 into a set S_2
$f^{-1}(\cdot)$	the inverse of a function $f(\cdot)$
$f'(\cdot)$	the first derivative of a real-valued function $f(\cdot)$
$\mathrm{sgn}(\cdot)$	the signum function
$\mathrm{sat}(\cdot)$	the saturation function
$\tanh(\cdot)$	the hyperbolic tangent function

$\dot{x}$	the first derivative of x with respect to time
$\ddot{x}(\dddot{x})$	the second (third) derivative of x with respect to time
$x^{(r)}$	the rth derivative of x with respect to time
$j = \sqrt{-1}$	the imaginary unit
$\|p\|$	the absolute value of a scalar p
p_{m}	the minimal value of a positive scalar p
p_{M}	the maximal value of a positive scalar p
$\\|x\\|$	the Euclidean norm (or 2-norm) of a vector x
$\\|\cdot\\|_1$	the 1-norm
max (min)	maximum (minimum)
sup	supremum, the least upper bound
inf	infimum, the greatest lower bound
$\forall$	for all
$\in$	belongs to
$\exists$	there exists
$\subset$	subset of
$\rightarrow$	tends to
$\Rightarrow$	implies that
$\equiv$	identically equal
$\approx$	approximately equal
$\Leftrightarrow$	equivalent to, if and only if
$:=$	equal to by definition
(xx)	equation number xx in the thesis
[xx]	reference number xx in the bibliography

Abbreviation

1(2) SMC	First (Second)-order sliding mode control
1(3)D	One (Three) dimensional
DF	Describing function
CE	Control energy
DE	Damping energy
DFG	Describing function gain
DFP	Describing function phase
dof	Degree-of-freedom
DI	Differential inclusion
FDF	Fractional-order describing function
FFOA	Fruit fly optimization algorithm
FRF	Frequency response function
FSSMC	Frequency-shaped (FS) sliding mode control
FS2SMC	Frequency-shaped second-order sliding mode control
FTSMC	Fast terminal sliding mode control
GSMC	Global sliding mode control
HCM	Half car model
HE	Hysteretic energy
HIS	Hydraulically interconnected system
HOSMC	Higher-order sliding mode control
IE	Input energy

IMPM	Inverse mode participation matrix
IMTM	Inverse modal transformation matrix
IPSO	Immune particle swarm optimization
KE	Kinetic energy
LC	Lyapunov-based control
LPF	Low-pass filter
LQR	Linear quadratic regulator
LUT	Look up table
MR	Magnetorheological
MRF	Magnetorheological fluid
MRD	Magnetorheological damper
MRP	Magnetorheological pin joint
MRE	Magnetorheological elastomer base isolator
RMSE	Root means square error
NTSMC	Nonsingular terminal sliding mode control
SAC	Semi-active (SA) control
SE	Strain energy
SISO	Single input single output
SMC	Sliding mode control
TF	Transfer function
TSMC	Terminal sliding mode control
UC	Uncontrolled case