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Semi-active magnetorheological dampers for reducing response of high-speed railway bridges

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ABSTRACT

To reduce the resonant response of high-speed railway bridges, semi-active magnetorheological dampers are proposed in this study. The elements are connected to the structure in a double beam configuration. An H_∞ control algorithm to drive magnetorheological damping forces of MR dampers is derived. Feasible solutions for an uncertain time-delay model are obtained by using standard linear matrix inequality techniques. Weight functions as a loop shaping procedure are also introduced in the feedback controllers to improve the tracking ability of magnetorheological damping forces. To this end, the effectiveness of magnetorheological dampers controlled by the proposed scheme, along with the effects of the uncertain and the time-delay parameters on the models, are evaluated and compared with the performance of fluid viscous dampers in similar applications reported in previous research through numerical simulations.

1. Introduction

One of the common characteristics of civil structures is that the inherent structural damping that reduces vibrations is very small and, as a result, disturbances applied to these structures may induce long lasting and sometimes severe structural vibrations. Therefore, many kinds of passive, semi-active and active energy dissipation systems such as tuned mass dampers (TMD), active tuned mass dampers (ATMD), fluid viscous dampers (FVD), and piezo actuators have been investigated and developed. In particular, semi-active magnetorheological dampers (MR) have attracted researchers' attention recently. However, the effectiveness of MR dampers applied to railway bridges has not been investigated significantly in previous works, and based on the authors' experience, this type of devices could be an interesting solution to mitigate the excessive transverse vibrations that these structures may experiment under high-speed traffic.

Jiang and Christenson (2010) proposed the use of MR dampers to reduce the dynamic response of existing highway bridges. Initial experimental tests to validate some simulations were performed. The results showed that the effectiveness of MR dampers was limited and the displacement response of the bridge was only reduced about 17%. This is due to the fact that the MR dampers were installed far from the antinodes of the controlled mode shapes and the control algorithm to drive the MR dampers was not robust enough in this study. To overcome these problems, a combination of a double-beam system and MR dampers is proposed in this work that permits installing the dampers closer to, and even at the exact location of the main beam antinodes. Moreover, due to the periodic character of the railway excitation, the H_∞ control algorithm approach constitutes a promising solution in order to reduce the resonant vibration of railway bridges under high-speed trains.

Additionally, a combined system of tuned mass and magnetorheological dampers called semi-active MR-TMD, was studied in Liu, Yuan, and Zhang (2011). The optimal TMD parameters were determined based on the criteria proposed by Den Hartog (1947) and Luu, Zabel, and Koenke (2012) and the active forces provided by the linear-quadratic regulator (LQR). However, to perform a practical implementation of this study, many issues need to be clarified further, such as how to determine control signals applied to MR dampers, the evaluation of the tracking ability of MR dampers, the optimal location of MR dampers along the beam length, designing observers to reduce the number of sensors as well as to overcome difficulties in measuring the required variables, etc. These issues will also be evaluated in next sections.

Another important issue in structural control problems is the existence of uncertainties of different nature and levels associated to the estimation of structural properties, modeling errors and time-variant material inertial properties. Besides, the presence of delays in the actuators' response due to the electrical and electromagnetic characteristics of MR dampers and in the transmission of the

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Nomenclature

Symbol	**Description**
a_k	distance from the kth wheel–axle set to the first wheel–axle set
A	MR model parameter to be identified
c_0	viscous damping constant of MR damper
c_{0a}	MR model parameter to be identified
c_{0b}	MR model parameter to be identified
c_B, c_b	viscous damping coefficients of the main and auxiliary beams
C_D	equivalent damping coefficient of FVDs
d	rated distance between the two bogies of a coach
d_j	distance from the left end of the beams to the jth MR damper
D	full length of each coach
EI_B, EI_b	bending stiffness of the main and auxiliary beams
F_0	gravity force of the wheel–axle set
$F_1(t), F_d(t)$	real time-varying parameters with Lebesgue measurable elements
F_{cB}	damper force of MR damper
F_{cBi}, F_{cBi}	modal damper forces of the main and auxiliary beams
$F_{MR}(x,t)$	total force generated by the MR dampers
$F_v(x,t)$	vertical force of the train acting on the main beam
F_{FVD}	fluid viscous damper force
$J_{\gamma i}$	H_∞ performance index
k_0	stiffness coefficient of MR damper
L	length of each span
$\overline{m}_B$, $\overline{m}_b$	mass per unit length of the main and auxiliary beams
n	MR model parameter to be identified
N	total number of intermediate coaches
N_B, N_b	number of modes to be considered for the main and auxiliary beams
N_D	total number of MR dampers
N_s	total number of sensors
N_v	total number of train axles
q_B, q_b	generalized coordinates of the main and auxiliary beams
t	continuous time variable
t_k	the time when the kth wheel–axle reaches the bridge
$V_i(x,t)$	Lyapunov function
u	input voltage
u_i	modal control force
$u_{\max}$	largest modal control force
v	speed of the train
$\dot{x}$	damper velocity
x	coordinate of beam
x	damper displacement (only used in Section 3)
x_0	initial displacement of MR damper
z	evolutionary variable
Z_B, Z_b	vertical displacements of the main and auxiliary beams
$\mathbf{A}_{0i}$, $\mathbf{B}_{0i}$, $\mathbf{C}_{0i}$	modal state-space matrices
$\mathbf{A}_{ci}$, $\mathbf{B}_{ci}$, $\mathbf{C}_{ci}$, $\mathbf{D}_{ci}$	state matrices of LPF
$\mathbf{A}_i$, $\mathbf{B}_{di}$, $\mathbf{B}_{wi}$	state matrices of the system considering LPF
$\mathbf{C}_i$, $\mathbf{H}_{di}$, $\mathbf{D}_{wi}$	state matrices of the controlled output considering LPF
$\mathbf{D}_B$, $\mathbf{D}_b$	modal matrices corresponding to the sensors positions $x_1, x_2,\ldots$
$\mathbf{E}_{1i}$, $\mathbf{D}_i$, $\mathbf{E}_{2r}$	modal state matrices of controlled output
$\mathbf{f}_c$	control force vector in physical space
$\mathbf{G}_i$	control gain
$\mathbf{J}_1, \mathbf{J}_2, \mathbf{J}_3$	submatrices in LMIs
$\mathbf{K}_i$	control gain considering LPF
$\mathbf{L}_B$, $\mathbf{L}_b$	modal matrices of the main and auxiliary beams
$\mathbf{L}_1$, $\mathbf{L}_d$, $\mathbf{E}_1$	real constant matrices representing the structure of uncertainties
$\mathbf{M}_c$, $\mathbf{G}_c$, $\mathbf{U}_c$, $\mathbf{N}_c$	submatrices in LMIs
$\mathbf{q}_B$, $\mathbf{q}_b$	generalized coordinate vectors of the main and auxiliary beams
$\mathbf{R}_1$, $\mathbf{R}_2$, $\mathbf{R}_3$, $\mathbf{R}_4$	linear matrix inequalities
$\mathbf{T}_i(s)$	modal transfer function
$\mathbf{U}_w$, $\mathbf{J}_w$, $\mathbf{U}_{c2}$	submatrices in LMIs
$\mathbf{v}_i$	modal state vector
$\mathbf{x}_{ci}$	state variable vector of LPF
$\mathbf{x}_i$	state variable of the system considering LPF
$\mathbf{X}$, $\mathbf{P}_1$, $\mathbf{P}_2$, $\mathbf{P}_3$, $\mathbf{Q}$	symmetric positive definite submatrices in LMIs
$\mathbf{z}_{0i}$	controlled output
$\mathbf{z}_i$	controlled output vector of the system considering LPF
$\mathbf{Z}_{Bs}$, $\mathbf{Z}_{bs}$	structural response vectors corresponding to sensors positions $x_1, x_2\ldots$
α	scaling factor
α_a	MR model parameter to be identified
α_b	MR model parameter to be identified
β	MR model parameters to be identified
γ	MR model parameters to be identified
γ_i	upper bound of H_∞ control performance
ΔA_i, ΔB_{di}	matrix representing time-varying parameter uncertainties
ε_i	scalar in LMIs
μ	frequency ratio between the auxiliary and main beams
ζ_B, ζ_b	modal structural damping of the main and auxiliary beams
η	mass ratio between the auxiliary and main beams
ρ_0	factor to control the largest control force in LMIs
$\overline{\sigma}$	the maximum eigenvalue
$\underline{\sigma}$	the minimum eigenvalue
τ	time-delay of the system
$\overline{\tau}$	largest time-delay of the system
ϕ_B, ϕ_b	mode shapes of the main and auxiliary beams
$\mathbf{\Phi}_B$, $\mathbf{\Phi}_b$	mode shape vectors of the main and auxiliary beams
ω_B, ω_b	natural frequencies of the main and auxiliary beams
ω_c	cut-off frequency

measurement information, is often a source of instability and poor performance in controlled structures. For this reason, an uncertain time-delay model is also derived to improve the performance of the control system with MR dampers.

In this paper, a semi-active MR damper system implemented in a double beam system is investigated. The application of double-beam systems to reduce the resonant response of railway bridges has recently been investigated by Museros and Martinez-Rodrigo (2007), Martinez-Rodrigo and Museros (2011) and Martinez-Rodrigo, Lavado, and Museros (2010). The authors proposed the connection of the bridge deck with a set of auxiliary beams through FVDs. For semi-active damping devices, it is well-known that their effectiveness is highly dependent on the designing control law of the active control forces considered as a primary part of the controllers because the designing control law produces the desired control signal (the active control force) based on the measured structural response variables to control the MR damper. Therefore, in order to make MR dampers more effective and