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Semi-active Vibration Control of Lateral and Rolling Motions for a Straddle Type Monorail Vehicle

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Abstract: This paper is concerned with the vibration elimination of a monorail vehicle under a lateral wind load and a vertical disturbance. A nonlinear adaptive control is designed for vibration attenuation of the vehicle model by using a set of MR dampers both in the lateral and vertical directions. There are limited amount of data in literature discussing dynamic instability of the monorail vehicle under the effect of model uncertainties. The proposed adaptive controller achieves good performance in road holding and ride comfort despite uncertainties in model parameters.

Keywords: Adaptive control, MR damper, semi-active suspension, monorail vehicle.

1. INTRODUCTION

The straddle type monorail vehicles have certain differences from traditional rail vehicles. They stride over the guideway and run above it. Monorail vehicles have three types of tires such as running, guide and stabilization tires. While running tires provide the longitudinal movement, guide tires lead the truck along the guideway. Moreover, stabilization tires prevent excessive rolling motion of the vehicle.

Monorail transit systems have some advantages such as; low manufacturing cost comparing subway systems, low running noise and good climbing ability. They can also be operated on the small radius of curve tracks (Masamichi et al., Goda et al 2002). In monorail vehicles, running on rubber tires cause abrasion. Existing uncertainties in a monorail vehicle have an effect on the performance of suspension systems. The reference (Goda et al. 1999) considers track irregularities in monorail vehicles. Semi-active dampers with adaptive control are promising devices to improve performance and stability of an uncertain system (Yildiz et al. 2014).

There are many studies on controlling suspension systems by using active and semi-active devices. To develop a control algorithm that take maximum advantage of the unique features of the MR damper, a model must be developed that can adequately characterize the damper's nonlinear and hysteretic behaviour (Yildiz et al. 2014, Watanabe 2007). Controlling the rolling and vertical motions of the monorail vehicle with semi-active devices is a new research area. In this study, a lateral wind effect and a vertical load are considered as disturbance effects in the model of the monorail vehicle. The proposed adaptive controller is remarkable because of dealing with external disturbances and uncertainties in the model parameters.

2. MODELING OF THE MONORAIL VEHICLE

Straddle type monorail vehicles run on rubber tires that straddle a single guideway beam. Hitachi's monorail car shown in (Fig.1) has three types of tires. The running tires support the vertical load of the car and transmit the driving and breaking forces to the guideway. The guide tires located at the four corners of the bogie frame lead the truck along the guideway.

Fig. 1. The straddle type monorail of Hitachi (Hitachi Pres., 2013).

In this study, Hitachi's straddle type vehicle structure is used for modelling (Goda et al 2000). In the modelling structure (Fig.2), the lateral and roll dynamics of the monorail vehicle is considered and the longitudinal dynamics is neglected. It is assumed that the monorail car body and bogie are rigid and the center of the masses have the coordinate systems $O_c y_c z_c$ and $O_b y_b z_b$, respectively. The lateral displacement of the car body is denoted by y_c and the roll movement of the car body is defined by ϕ_c. Similarly, the lateral and angular displacements of the bogie is denoted as y_b and ϕ_b, respectively. Air suspensions installed between the car body and the bogie for ride comfort of the monorail car are modeled as vertical and lateral springs and dampers. The bogie frame of the monorail vehicle is connected to the guideway with the running, guide and stabilizing tires. The tires are modeled as stiffness and

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damping elements. To apply a semi-active control for suppressing lateral and rolling movement, a set of MR damper is placed between the car body and the bogie. Parameters of the monorail vehicle are given in Table 1 and Table 2.

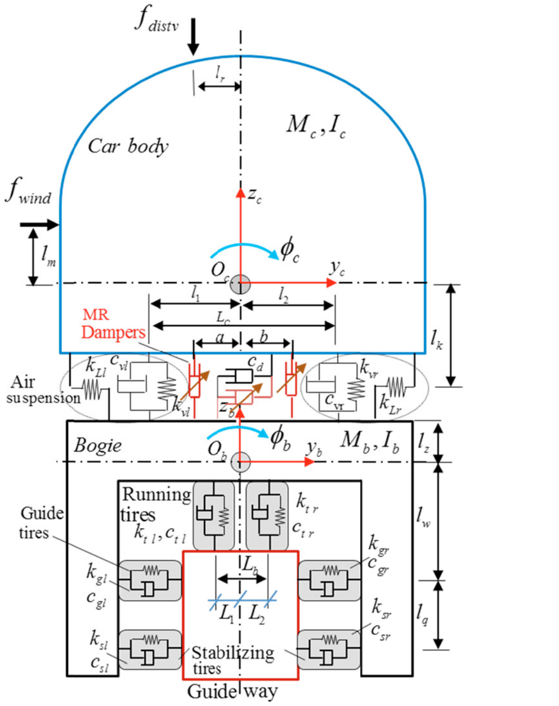

Fig. 2. Structure of the straddle type monorail vehicle for modelling.

Table 1. Monorail vehicle mass related parameters

Definitions	Symbol	Unit	Value
Mass of the car body	M_c	kg	9500
Mass of the bogie	M_b	kg	4700
Roll inertia of the car body	I_c	kgm^2	20000
Roll inertia of the bogie	I_b	kgm^2	1500

The total kinetic energy equation is written as follows:

$$\sum T = T_{c\_ver} + T_{c\_lat} + T_{c\_roll} + T_{b\_ver} + T_{b\_lat} + T_{b\_roll}$$
$$= \frac{1}{2}M_c\dot{z}_c^2 + \frac{1}{2}M_c\dot{y}_c^2 + \frac{1}{2}I_c\dot{\phi}_c^2 + \frac{1}{2}M_b\dot{z}_b^2 + \frac{1}{2}M_b\dot{y}_b^2 + \frac{1}{2}I_b\dot{\phi}_b^2 \quad (1)$$

The potential energy resulted from springs elements is obtained as

$$U = \frac{1}{2}k_{vl}(z_c + l_1\phi_c - (z_b + l_1\phi_b))^2 + \frac{1}{2}k_{vr}(z_c - l_2\phi_c - (z_b - l_2\phi_b))^2 +$$
$$\frac{1}{2}k_{Ll}(y_c - l_k\phi_c - (y_b + l_z\phi_b))^2 + \frac{1}{2}k_{Lr}(y_c - l_k\phi_c - (y_b + l_z\phi_b))^2 + \quad (2)$$
$$\frac{1}{2}k_{t\,l}(z_b + L_1\phi_b)^2 + \frac{1}{2}k_{t\,r}(z_b - L_2\phi_b)^2 + \frac{1}{2}k_{gl}(y_b - l_w\phi_b)^2 +$$
$$\frac{1}{2}k_{gr}(y_b - l_w\phi_b)^2 + \frac{1}{2}k_{sl}(y_b - (l_w + l_q)\phi_b)^2 + \frac{1}{2}k_{sr}(y_b - (l_w + l_q)\phi_b)^2$$

The damping potential is defined as

$$D = \frac{1}{2}c_{vl}(\dot{z}_c + l_1\dot{\phi}_c - (\dot{z}_b - l_2\dot{\phi}_b))^2 + \frac{1}{2}c_{vr}(\dot{z}_c - l_2\dot{\phi}_c - (\dot{z}_b - l_2\dot{\phi}_b))^2$$
$$+\frac{1}{2}c_{t\,l}(\dot{z}_b + L_1\dot{\phi}_b)^2 + \frac{1}{2}c_{t\,r}(\dot{z}_b - L_2\dot{\phi}_b)^2 + \frac{1}{2}c_{gl}(\dot{y}_b - l_w\dot{\phi}_b)^2 \quad (3)$$
$$+\frac{1}{2}c_{gr}(\dot{y}_b - l_w\dot{\phi}_b)^2 + \frac{1}{2}c_{sl}(\dot{y}_b - (l_w + l_q)\dot{\phi}_b)^2 + \frac{1}{2}c_{sr}(\dot{y}_b - (l_w + l_q)\dot{\phi}_b)^2$$

The equations of motion are derived using the Lagrange equation

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \frac{\partial L}{\partial q_i} + \frac{\partial D}{\partial \dot{q}_i} = Q_i \quad (4)$$

where q_i is the generalized coordinate variables and $L = T - U$ is Lagragian equation. Also, Q_i shows the generalized forces and moments.

Table 2. Monorail vehicle parameters

Definitions	Symbol	Unit	Value
Stiffness of the air suspension in radial direction	k_{vl}, k_{vr}	N/m	2.0×10^5
Stiffness of the air suspension in lateral direction	k_{Ll}, k_{Lr}	N/m	1.0×10^5
Stiffness of the tires in radial direction	k_{gl}, k_{gr}, k_{sl}, k_{sr}, k_{tl}, k_{tr}	N/m	1.0×10^6
Damping coefficient of the tires in radial direction	c_{tl}, c_{tr}	$N\cdot s/m$	3.8×10^3
Damping coefficient of the air suspension in radial direction	c_{vl}, c_{vr}	$N\cdot s/m$	1.5×10^4
Damping coefficient of the MR damper	c_d	$N\cdot s/m$	1.2×10^5
Width between right air suspension and left air suspension	L_c	m	1.6
Width between right running tire and left running tire	L_b	m	0.37

The equation of motion of the straddle type monorail vehicle is written in matrix form as follows

$$M\ddot{x}_s = C\dot{x}_s + Kx_s + Hf + LF_{dist} \quad (5)$$

where M, C and K matrices represent the mass, damping and stiffness properties of the system, respectively. H is a matrix that points the location of the MR dampers. The external disturbances are applied to the system by L vector. The state vector of the system given in equation (5) is the form of $x_s = [z_c \quad y_c \quad \phi_c \quad z_b \quad y_b \quad \phi_b]^T$.

Each forces of the MR damper in f vector and the transformed form of equation (5) are given as

$$f = \left[F_{mr_l} \quad F_{mr_m} \quad F_{mr_r}\right]^T \quad (6)$$

$$\ddot{x}_s = M^{-1}C\dot{x}_s + M^{-1}Kx_s + M^{-1}Hf + M^{-1}LF_{dist} \quad (7)$$

When the state vector is selected as $x = [x_s \quad \dot{x}_s]^T$, then Eq. (7) can be written as a state space equation as follows

$$\dot{x} = Ax + Bu + WF_{dist}$$
$$= \begin{bmatrix} 0_{6x6} & I_{6x6} \\ M^{-1}K & M^{-1}C \end{bmatrix} x + \begin{bmatrix} 0_{6x3} \\ M^{-1}H \end{bmatrix} f + \begin{bmatrix} 0_{6x2} \\ M^{-1}L \end{bmatrix} F_{dist} \quad (8)$$