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Application of Self Tuning Fuzzy Logic Control to Full Railway Vehicle Model

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Abstract

This paper presents the dynamic modeling and intelligent control of the full railway vehicle against the railway irregularities. In order to safe and comfortable transportation of passengers, vibration analysis and control studies are investigated by using Matlab–Simulink software. The 54 degrees of freedom railway vehicle model is used for analysis. The controllers are placed between the car body and bogies. For reducing the car body vibrations caused by a lateral and two vertical sinusoidal track irregularities, fuzzy logic and self-tuning fuzzy logic control schemes are applied to railway vehicle. The fuzzy logic based algorithms herein are used for realizing the active control of car body vibrations. The simulations of vibration analysis are obtained in time and frequency domains and compared with uncontrolled case. A good vibration reduction performance is achieved by using applied control algorithms.

Keywords: self tuning fuzzy logic; railway vehicle dynamics; active control; numerical simulation,

1. Introduction

Rail transportation is a preferred transport option, due to offering safe, speed and comfortable travelling. The applications of new technologies to railway transportation systems pave the way for increment of cruising speed. In the case of high cruising speeds, the effects of vibrations caused by rail disturbances on a vehicle car body and passengers have a great importance. Hence, safe and comfortable transportation of passengers, especially under high speeds, has become an important engineering problem to solve.

During the last few decades, many studies have been performed on the rail vehicle modeling and control. The studies generally focus on dynamic modeling of rail systems such as rail-sleeper-ballast models and bridge-rail-vehicle interactions. Various dynamic models have been presented in the literature [1-4]. Furthermore, different types of controllers are applied to control of railway vehicles [5-7].

In this study, dynamic modeling of the railway vehicle, a mainline locomotive operating in Turkish railways is performed firstly. Whereas quarter or semi vehicle models are used generally for railway vehicle dynamic modeling and control studies in literature, full vehicle model is set up to enrich this study. Lagrange's equation is used to obtain the differential equations of motion for 54 degrees of freedom system. Full vehicle model is established to investigate the effects of vertical and lateral rail disturbances on the car body vibrations, including the pitch, roll and

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yaw angular displacements and accelerations. The active vibration controllers are designed to minimize the disruptive effects of track disturbances on the car body. The secondary suspensions between the car body and bogies also act as the actuators of the controller system. The lateral and vertical controllers are specifically designed to suppress the car body vibrations for a safer and more comfortable transport. Fuzzy Logic (FLC) and Self-Tuning Fuzzy Control (STFLC) algorithms are used in the active controller design because of their simplicity, satisfactory performance and robustness.

2. Mathematical modeling of railway vehicle

The railway vehicle, used in this study, is similar to a mainline locomotive operating in Turkish. The 54 DOF railway vehicle consists of one car body, three bogies and totally six wheelsets, two wheelsets per bogie, as seen in Fig. 1. The wheelsets are connected to bogies by the use of primary suspensions. The bogies are connected to the car body with secondary suspensions. The physical parameters of mass, inertias, coefficients of springs and dampers are closely provided by Turkish State Railways. The car body has six degrees of freedom and each bogie has six degrees of freedom. By assuming the constant cruising speed, the rolling motion of the wheelset is neglected so each wheelset has five degrees of freedom. A detailed explanation and definition for the railway vehicle model can be found in the previous work [6]. The equations of motion of the railway vehicle system, derived by means of Lagrange's equation, are given in matrix form as below:

$$[M]\underline{\ddot{x}}+[C]\underline{\dot{x}}+[K]\underline{x}=[F_r]+[F_u] \tag{1}$$

where M, C, and K are the mass, damping and stiffness matrices, respectively. The displacement vector is,

$$\begin{aligned}\underline{x}=[&X_c,Y_c,Z_c,\theta_c,\phi_c,\psi_c,X_{t1},Y_{t1},Z_{t1},\theta_{t1},\phi_{t1},\psi_{t1},X_{t2},Y_{t2},Z_{t2},\theta_{t2},\phi_{t2},\psi_{t2},X_{t3},Y_{t3},Z_{t3},\theta_{t3},\phi_{t3},\psi_{t3},\\&X_{w1},Y_{w1},Z_{w1},\theta_{w1},\psi_{w1},X_{w2},Y_{w2},Z_{w2},\theta_{w2},\psi_{w2},X_{w3},Y_{w3},Z_{w3},\theta_{w3},\psi_{w3},X_{w4},Y_{w4},Z_{w4},\theta_{w4},\psi_{w4},\\&X_{w5},Y_{w5},Z_{w5},\theta_{w5},\psi_{w5},X_{w6},Y_{w6},Z_{w6},\theta_{w6},\psi_{w6}]^T\end{aligned} \tag{2}$$

where, *X*, *Y* and *Z*, are the longitudinal, lateral and vertical displacements, respectively. The subscripts *c*, *ti* (i=1,2,3) and *wj* (i=1,2,…,6) denote the car body, bogies and wheelsets, respectively. θ, ϕ and ψ represent the roll, pitch and yaw motions. The rail disruptive force vector is defined in the following form,

$$\begin{aligned}[F_r]=\big\lfloor &zeros(1,25)\left(k_{hy}Y_{r1}\right)\left(k_{hz}\left(Z_{r1}+Z_{r2}\right)\right)\left(k_{hy}R_1Y_{r1}+k_{hz}a\left(Z_{r2}-Z_{r1}\right)\right)00\\&\left(k_{hy}Y_{r2}\right)\left(k_{hz}\left(Z_{r3}+Z_{r4}\right)\right)\left(k_{hy}R_1Y_{r2}+k_{hz}a\left(Z_{r4}-Z_{r3}\right)\right)00\left(k_{hy}Y_{r3}\right)\left(k_{hz}\left(Z_{r5}+Z_{r6}\right)\right)\left(k_{hy}R_1Y_{r3}+k_{hz}a\left(Z_{r6}-Z_{r5}\right)\right)\\&00\left(k_{hy}Y_{r4}\right)\left(k_{hz}\left(Z_{r7}+Z_{r8}\right)\right)\left(k_{hy}R_1Y_{r4}+k_{hz}a\left(Z_{r8}-Z_{r7}\right)\right)00\left(k_{hy}Y_{r5}\right)\left(k_{hz}\left(Z_{r9}+Z_{r10}\right)\right)\left(k_{hy}R_1Y_{r5}+k_{hz}a\left(Z_{r10}-Z_{r9}\right)\right)\\&00\left(k_{hy}Y_{r6}\right)\left(k_{hz}\left(Z_{r11}+Z_{r12}\right)\right)\left(k_{hy}R_1Y_{r6}+k_{hz}a\left(Z_{r12}-Z_{r11}\right)\right)0\big\rceil^T\end{aligned} \tag{3}$$

and control force vector can be expressed as,

$$\begin{aligned}[F_u]=[&0\left(U_{y1}+U_{y2}+U_{y3}\right)\left(U_{z1}+U_{z2}+U_{z3}+U_{z4}+U_{z5}+U_{z6}\right)\\&\left(h_3\left(U_{y1}+U_{y2}+U_{y3}\right)+b_2\left(\left(U_{z2}+U_{z4}+U_{z6}\right)-\left(U_{z1}+U_{z3}+U_{z5}\right)\right)\right)\\&\left(L_b\left(\left(U_{z5}+U_{z6}\right)-\left(U_{z1}+U_{z2}\right)\right)\right)\left(L_b\left(U_{y1}-U_{y3}\right)\right)0\left(-U_{y1}\right)\left(-\left(U_{z1}+U_{z2}\right)\right)\left(h_2U_{y1}-b_2\left(U_{z2}-U_{z1}\right)\right)\\&000\left(-U_{y2}\right)\left(-\left(U_{z3}+U_{z4}\right)\right)\left(h_2U_{y2}-b_2\left(U_{z4}-U_{z3}\right)\right)000\left(-U_{y3}\right)\left(-\left(U_{z5}+U_{z6}\right)\right)\\&\left(h_2U_{y3}-b_2\left(U_{z6}-U_{z5}\right)\right)zeros(1,32)\big]^T\end{aligned} \tag{4}$$

3. Controller design

The field of fuzzy sets was first introduced by Lotfi Zadeh (1965), and fuzzy control was first investigated by Kickert, and Mamdani, (1978). Many academic studies are carried out and application projects are held in electronics, mechatronics subjects in which controller design is needed. In this study, active vibration controllers are designed by means of FLC and STFLC algorithms to minimize vibrations detrimental effects. One of the aims of this study is to compare different fuzzy logic based control algorithms on a full railway vehicle for comfort.

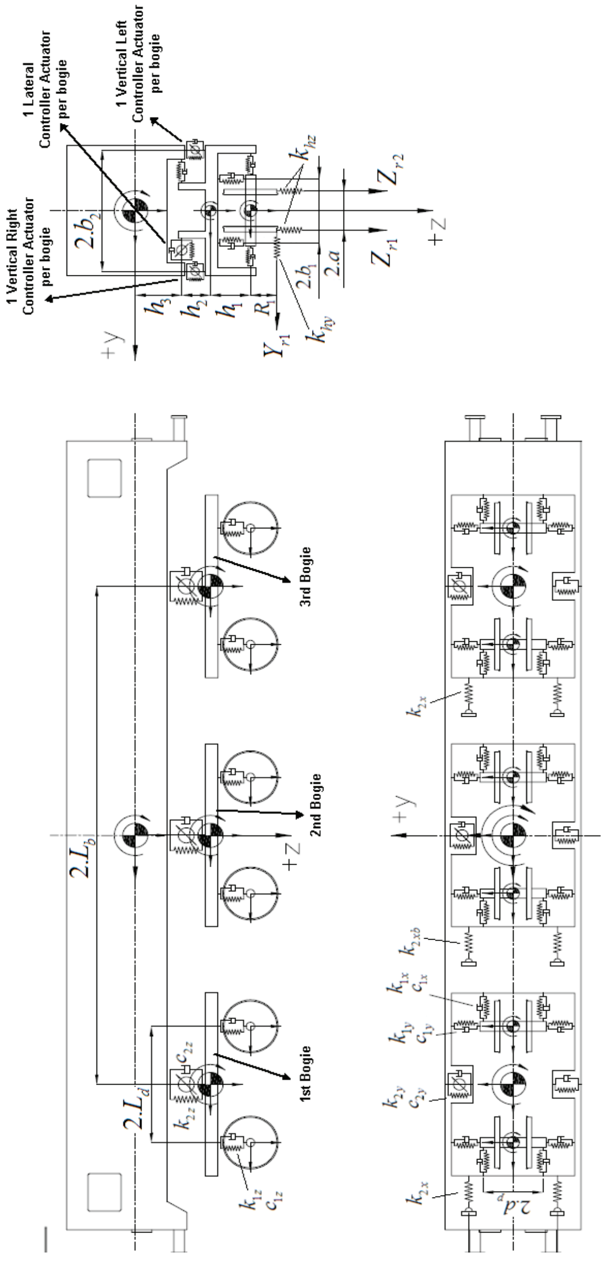

Figure 1. The 54 DOF railway vehicle.

To minimize the car body vibrations using FLC and STFLC, three lateral and six vertical actuators are designed. There are one lateral, one vertical right and one vertical left controller actuator per bogie in vehicle, also shown in Fig. 1. Lateral controllers are designed to suppress car body lateral and yaw angular vibrations whereas the vertical controllers are designed to suppress car body vertical and pitch, roll angular vibrations caused by lateral and vertical rail disturbances. Design and control applications are held in Matlab-Simulink software with Fuzzy Logic Toolbox.

Consider the lateral controllers. When the car body goes forward in the positive lateral direction and rotates about center of mass by a yaw angle, three different lateral errors occur at the pivot points of bogies. These lateral errors are the displacement differences from the zero position where is aimed to keep the car body in equilibrium. The lateral displacement errors of car body at the pivot points of each bogie are defined as,

$$e_{y1} = ref_{Y_c} - \left(Y_c - L_b\psi_c\right), \quad e_{y2} = ref_{Y_c} - \left(Y_c\right), \quad e_{y3} = ref_{Y_c} - \left(Y_c + L_b\psi_c\right) \tag{10}$$

The lateral rail disturbance functions are considered as sine functions that excite the car body lateral vibrations so the reference values for lateral errors $\left(ref_{Y_c}\right)$ and the reference values for lateral error derivatives $\left(ref_{\dot{Y}_c}\right)$ are considered as zero. The lateral displacement errors (e_{y1} , e_{y2} and e_{y3}) and the derivatives of the lateral displacement errors are the inputs of the controllers. Additionally, U_{y1} , U_{y2} and U_{y3} are the outputs of the controllers. The block diagram of lateral FLC and STFLC for 1st bogie pivot point are seen in Fig. 2. The other lateral controllers' block diagrams have also the same algorithm.

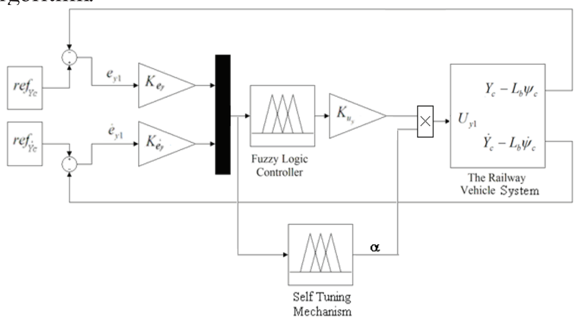

Figure 2. Block diagram of lateral controller (STFLC).

The linguistic variables defining the rule base for the FLC is given in Table 1. N, Z, P, S, M, B and V represent "Negative", "Zero", "Positive", "Small", "Medium", "Big" and "Very" respectively. As an example, the first and last rules are given as follows: *IF* e *is* NB *and* de/dt *is* N *THEN* u *is* NB. Sezer and Atalay (2011) explained these variables in detail.

The displacement error, the derivative of displacement error and the controller output membership functions are defined common normalized domain [-1,1] for FLC, whereas the controller output membership function is defined normalized domain [0,16] for STFLC. The scaling factors of inputs K_{e_y} , $K_{\dot{e}_y}$ and output K_{u_y} are tuned to keep the car body stable around zero position. The proposed FLC is modified by dynamically adjusting the output scaling factor K_{u_y} by a gain updating factor α, with the aid of self tuning mechanism shown in Fig. 2. The value of α is determined by fuzzy rules, given in Table 2. Mudi and Pal (2000) also proposed similar algorithm in their study [8]. Mamdani and Centroid methods are used for fuzzy based control algorithms.

Table 1. Rule base for the FLC.

	(de/dt)		
Error (e)	***N***	***Z***	***P***
NB	NB	NM	NS
NS	NM	NS	Z
Z	NS	Z	PS
PS	Z	PS	PM
PB	PS	PM	PB

Table 2. Rule base of α for the STFLC

	(de/dt)		
Error (e)	***N***	***Z***	***P***
NB	VB	SB	Z
NS	B	MB	B
Z	B	S	B
PS	MB	MB	VB
PB	S	VS	VS

Consider the vertical controllers. The vertical controllers have the same membership functions and rule bases, with the lateral controllers, both for FLC and STFLC. When the car body goes down in the positive vertical direction and rotates about the center of mass by a roll and pitch angles, six different vertical errors occur at the right and left pivot points of bogies. The vertical displacement errors of the car body and the derivatives of the vertical displacement errors at the pivot points of each bogie are defined as,

$$e_{z1} = ref_{Z_c} - \left(Z_c - b_2\theta_c - L_b\phi_c\right), \quad e_{z2} = ref_{Z_c} - \left(Z_c + b_2\theta_c - L_b\phi_c\right), \quad e_{z3} = ref_{Z_c} - \left(Z_c - b_2\theta_c\right),$$

$$e_{z4} = ref_{Z_c} - \left(Z_c + b_2\theta_c\right), \quad e_{z5} = ref_{Z_c} - \left(Z_c - b_2\theta_c + L_b\phi_c\right), \quad e_{z6} = ref_{Z_c} - \left(Z_c + b_2\theta_c + L_b\phi_c\right) \tag{12}$$

4. Simulation results

The physical effects such as thermal expansion, collapses or deformations cause random irregularities on railways in the course of time. These irregularities are generally known as alignment, gauge and cross-level. In this study, the lateral and vertical rail disturbances are inputs of the vehicle model and considered as pure sinusoidal functions to simulate the random rail geometry. The cruising speed is assumed as V=120 *km/h*.

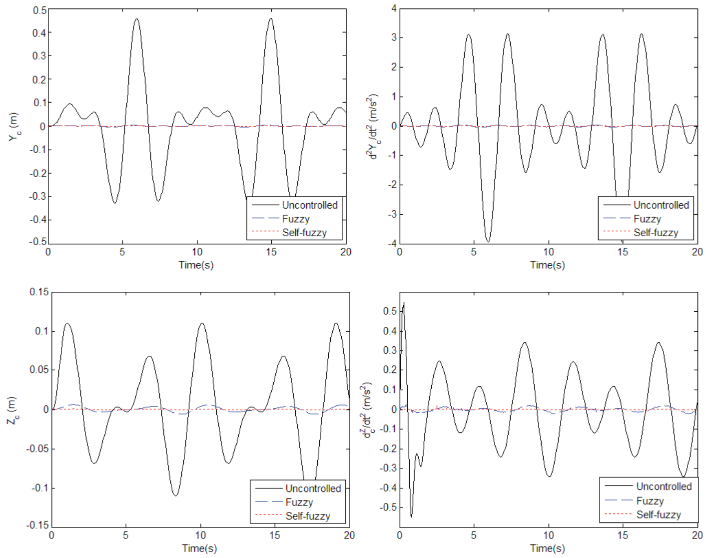

Figure 3. Controlled and uncontrolled time responses of the car body for lateral and vertical motions

The lateral and vertical rail irregularity functions defined above are the system inputs that excite railway vehicle vibrations. The system responses to these inputs are achieved by means of 54 differential equations given in [6]. Minimizing the car body vibrations is crucial for safety and comfort of passengers and goods. The uncontrolled displacements and accelerations may cause instability and discomfort due to rail irregularities. For these reasons the fuzzy logic control based active controls are performed on the car body. The car body vibrations arisen from sinusoidal disturbance are controlled by three lateral and six vertical actuators explained in previous section. To review the performance of the designed controllers, the controlled and uncontrolled results are given in time and frequency domains. The controlled and uncontrolled time responses of the car body's translational displacements and accelerations are seen in Figs. 3 and 4, respectively. The translational displacements and accelerations of the car body were suppressed perfectly by applying fuzzy logic controllers.

To investigate the robustness of the designed FLC and STFLC, mass of the car body is altered about ±%20 and observed results are presented in the frequency domain (Figure 5). Although altering the mass of the car body, frequency responses of the lateral and vertical translational displacements stayed robust in both situations.

5. Conclusions

This paper presents a dynamic modeling and active vibration control of the interested railway vehicle under sinusoidal railway irregularities. The full railway vehicle model allows us to observe the effects of bogies and wheelsets vibrations on the car body. Active vibration controllers, driving three lateral and six vertical actuators placed at secondary suspensions, are designed by using the FLC and STFLC algorithms because of its simplicity, satisfactory performance and robustness. Despite the complexity of the system, the car body vibrations are suppressed successfully by operating the lateral and vertical controllers synchronously, both in time and frequency domains. The robustness of the designed fuzzy logic based controllers is also verified by simulations in frequency domain. Consequently, in order to enhance the ride comfort and safety, especially STFLC algorithm can be used effectively to suppress car body vibrations of a railway vehicle system.

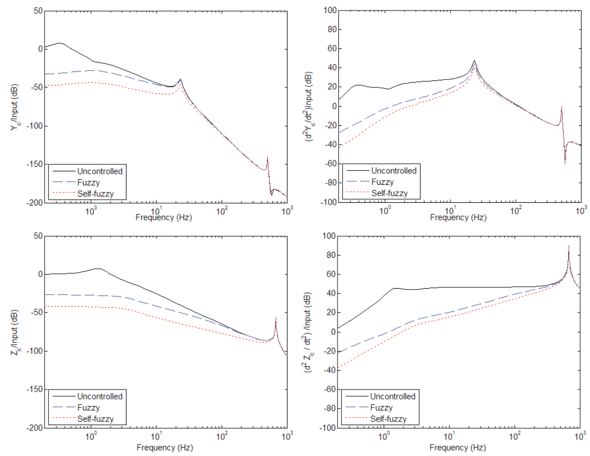

Figure 19. Controlled and uncontrolled frequency responses of the car body for lateral and vertical motions.

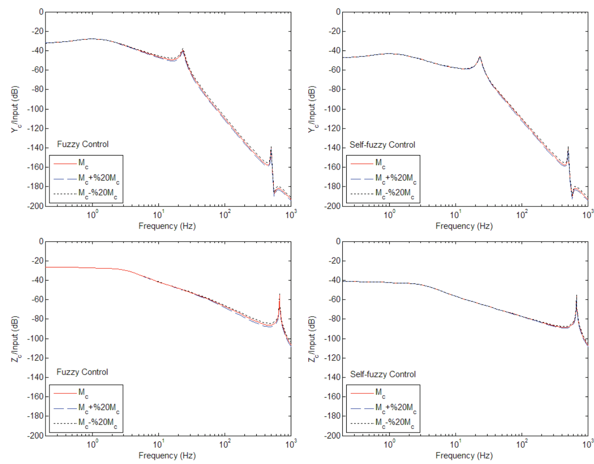

Figure 5. The robustness of the FLC and STFLC.

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