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Intelligent Variable Structure Control for Speed and Levitation of a Train

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A B S T R A C T

In this paper, for the first time a general type-2 fuzzy system (Linguistic or Mamdani) is used to estimate the sliding surface of the sliding mode control (SMC) method for train speed and levitation control. One of the important issues in controlling the train is its speed control, taking into account the cost function and control signals. Because the train system in this article is nonlinear and contains uncertain terms, a nonlinear method should be used, so type-2 fuzzy systems perform well in this regard. Also, the controller is designed to withstand external disturbances and non-modeling dynamics. In addition to system stability, the vibration signal control also improves. A comparison between general type-2 fuzzy SMC and type-1 fuzzy SMC has been done in the simulation. The simulation results prove the efficiency and superiority of the proposed method.

1. Introduction

Today, fast trains are an effective public transport system and their use is growing rapidly in different countries. Electromagnetic suspension or electromagnetic levitation refers to the kind of technology in which the electric magnets in the train frame are absorbed into the magnetic rays (which are usually steel). By using electronic control systems that can maintain the distance between the train and the rail, they are prevented from communicating with each other. Since the magnetic field control may occasionally encounter small errors, there is the possibility of vibration in wagons. Magnetic field changes with regard to the train's load and possible roughness of rocks to keep this distance intact. It should be noted that this technology no longer needs wheel. Various methods have been proposed to control nonlinear systems with dynamics similar to the train system on sliding mode control [1-2], PID [3], fuzzy control [4-8] and artificial neural networks-based control [9-11].

On the other hand, one of the most significant issues in the transport industry is the design of system levitation-enabled systems. In active levitation systems, in order to improve the accuracy of control vibration of the vehicle, hydraulic operators, pneumatics, hydraulic pneumatics, etc., are placed in parallel with the springs, and then using data and information from the motion of the frame wagon as well as bogie is received, law control is applied correctly [12]. Sliding mode control is a convenient method for controlling the system in the presence of various uncertainties. Several studies on different methods of selecting a sliding surface for systems of levitation, such as optimal methods, follower model, robust model, integral fit, and different stable dynamics [17-19]. In this paper, an optimal strategy is presented. In some studies, for comparing the nonlinear estimation functions with the time available in the model system, they have been using comparative techniques [20-22]. Finding an appropriate comparative law to determine the adjustable control signal [22] and the boundary over the system uncertainty [23] is another benefit of

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comparative methods. Fuzzy logic type -1 is unable to solve the indefinite problem in the functions membership. This problem has been addressed using type-2 fuzzy logic and type-2 fuzzy systems. In other words, if in a fuzzy system in the form of a function membership, the condition and the result, as well as their parameters, were null and void, then the type-2 fuzzy logic should be used [24]. In various tasks, fuzzy systems have been used to control the train [25-28]. In [28], the system fuzzy type -1 tsk is used as the estimator in the system control train. In [28], vibration and response delay are well known and require the use of type-2 fuzzy systems. In [29], the linear train system model is controlled by a simple fuzzy system. Due to the nature of the nonlinear train and the complex dynamics, it does not seem that the model and method presented in [29] have the ability to implement physical and practical applications.

In this paper, a nonlinear model and a relatively complete train are first examined and the method of sliding mode control is used for this system train. The famous method of sliding mode control is the vibration (chattering) phenomenon that is greatly improved in the proposed method due to the flexible system type-2 fuzzy. Here, a law comparative, based on type-2 fuzzy systems for estimating the boundary above uncertainty system levitation is used. The following is followed by the complete train fast and then the system type-2 fuzzy and finally the proposed method and simulation are presented.

2. Model of the Fast Train

In general, the design of a control system to reduce the fluctuations coupé 1 and bogie 2 in a train is a good idea to reach the speeds and comfort of the passengers simultaneously, as well as to reduce costs. Here, we use control mode sliding to improve the fluctuations coupé and bogie in conjunction with lateral disturbances due to railways irregularities and coupe mass changes.

A quarter levitation train system is shown in fig. 1.

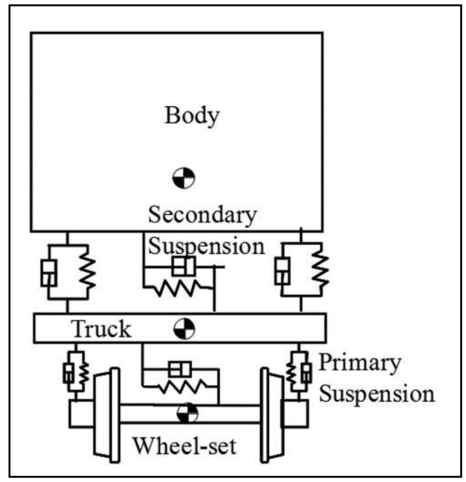

Figure 1. A fourth system levitation train model using newton's law:

$$m_c\ddot{y}_c = -k_s(y_c - y_b) - c_s(\ddot{y}_c - \ddot{y}_b) - f_s \quad (1)$$

$$m_b\ddot{y}_b = -k_s(y_c - y_b) + c_s(\ddot{y}_c - \ddot{y}_b) - k_p(y_b - w) + f_s$$

In the above relations, the mass is a quarter frame, y lateral frame displacement, k lateral frame coefficient, c lateral moderator, $f = u$ is the component that provides control and modulator power, m half the mass of bogie, y displacement lateral bogie, k lateral bogie hardness coefficient and w uncertain amount due to the shape of the railways line.

3. Sliding Mode Control for Fast train

Consider the dynamical equations governing the system levitation lateral train as follows: [30]

$$\ddot{y}_c = f_s(y) + g_s(y)u \quad (3)$$

$$\ddot{y}_b = f_s(y) + g_s(y)u \quad (4)$$

We define the sliding surfaces in terms of the degree of the system relative y_c to y_b and as a function of proportional-derivative of the matching error (output difference of model and system):

$$s_c = \grave{e}_c + \lambda e_c \quad (5)$$

$$s_b = \grave{e}_b + \lambda e_b \quad (6)$$

In this regard, we have:

$$e_c = [y_{cr} - y_c] \quad (7)$$

$$e_b = [y_{br} - y_b] \tag{8}$$

Taking into account the first level, we design the controller. The calculations for the other level will be similar.

$$s_c = \dot{e}_c + \lambda e_c \tag{9}$$

$$\dot{s}_c = \ddot{e}_c + \lambda\dot{e}_c = \ddot{y}_c + \lambda\dot{e}_c - f_s(y) - g_s(y)u + \lambda\dot{e}_c \tag{10}$$

So using [31]:

$$u_{cg} = \acute{g}_s(y)^{-1} - \acute{f}_s(y) + \ddot{y}_{cr} + \lambda\acute{e}_c) \tag{11}$$

In this regard

$$f_s(y) - \acute{f}_s(y)| \le F \tag{12}$$

$$0 \le g_{min} \le \acute{g}_s(y) = \sqrt{g_{min} g_{max} \le g_{max}} \tag{13}$$

The maximal term that moves the path to the sliding surface is:

$$u_p = -\acute{g}_s(y)^{-1} k\, sign(s_c) \tag{14}$$

The sliding condition is (15), and k can be calculated from (16) to satisfy this condition.

$$(1+x)^n = 1 + \frac{d}{dt}\left(\frac{1}{2}s_c^2\right) < -\eta|s_c| \tag{15}$$

$$k \ge a(F+\eta) + (a-1)| - \acute{g}_s(y)u_{cq} \tag{16}$$

In this regard:

$$a = \sqrt{\frac{g_{max}}{g_{min}}} \tag{17}$$

And as a result:

$$u_c = u_p + u_{cq} \tag{18}$$

By doing the same calculations, the bogie controller can also be designed. In order to create materials between the frame and bug movement, we use the combination of these two controllers. The parameter that specifies the percentage of use of each of the control signals is called the "decision parameter" and is displayed with m. In this way, the control signal for the control system will be (19) [31].

$$u = \mu u_c + (1-\mu)u_b \tag{19}$$

In this case, $1 \le \mu \le 0$, and as you can see, selecting $1 = \mu$, convert control to a single reference control model for the ideal coupé response and $0 = \mu$, transforming control into a single reference control model for the ideal bogie response. For values between zero and one decision parameter, control is a combination of high-level methods. In this way, the correct choice of μ will have an effective and decisive role in creating a compromise between designer control goals.

3.1. Setting the fuzzy parameter to the decision

To control the parameters of a control system, the use of fuzzy systems is highly utilized. The μ decision parameter is a value between zero and one that determines the contribution of each separate controller in the final control. According to the results of simulation, if $\mu \le \mathbf{0.4}$, the position of the coupé train, in the face of the ripples and irregularities of the railways, has high and unfavorable fluctuations, whereas for $\mu > \mathbf{0.1}$ bogie's state of affairs is very unfavorable, with great fluctuations. Therefore, it is very difficult to establish a compromise in order to optimize the coupé and bogie responses. Suggesting a reasonable and appropriate change to μ depending on the scope of coupé and bogie fluctuations can be a good solution for increasing the quality of responses together, in both coupé and bogie. Since it is not possible to simultaneously respond coupé and bogie to the ideal state, the relative desirability of responses will be important. That is, for a specific range of μ, the coupé and bogie matching are acceptable. The goal is to accept coupé's response and reduce the impact of bogie's fluctuations. Here, with the correct design of a fuzzy system, we have created this variable of interest. The inputs of this system are the size of the coupé and bogie displacement.

4. Type-2 Fuzzy System

In 1965, zade introduced a fuzzy type -1 logic. Ten years later, in 1975, introduced the type-2 fuzzy logic to solve some of the problems of fuzzy type-1 logic [32]. Membership in fuzzy type -1 is a non-fuzzy number, but in type-2 fuzzy, the degree membership is a fuzzy number. When the uncertainty of the data is high so that a number cannot be determined for the degree of membership, a fuzzy number must be selected for the membership degree, and the number obtained from the fuzzy operation twice is called a generic type-2 fuzzy [33]. Here the primary and secondary memberships are defined (figure 2).

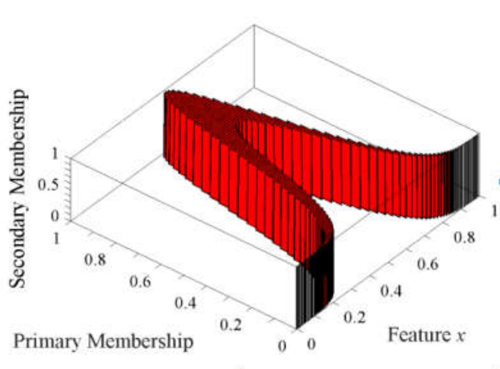

Figure 2. Primary and secondary membership functions in a general type-2 fuzzy number

For example, for μ1 = 0.45, x1 = 1. In this case, the secondary function membership center is 0.45.

In figure 3, a three-dimensional view of a general type -2 fuzzy system is shown.

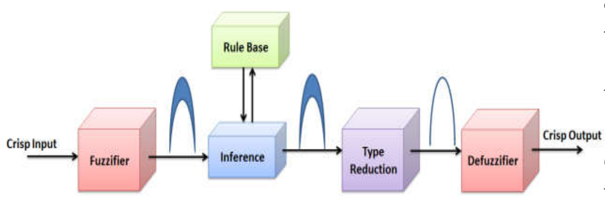

Figure 3. The structure of a general

type-2 fuzzy system.

$$\tilde{A} = \int_{x\in x} \mu_{\tilde{A}}(x)/x = \frac{\int_{x\in x} \left[\frac{\int_{x\in x\, jx} [J x \int \; \int_{\mu \in jx} \frac{f_x(\mu)}{\mu}}{\mu} \right]}{x} \quad (20)$$

In the relation (2-6), a set of type-2 fuzzy, (μ) is the initial membership function, J is the initial membership set of $x \in X$ and [0.1] ∈ (f) is a secondary function of the function.

5. Design Type-2 Fuzzy Sliding Mode Control for Fast Train

In this section, the control system levitation train is based on the sliding mode, coupled with a comparative approach. The reason behind the use of the sliding-resistant control is to deal with a variety of uncertainties due to external disturbances or any nonlinear behavior in the system. In this method, the sliding surface is extracted using an optimal strategy, resulting in a proportional-integral level. The reason for proposing the comparative algorithm is the uncertainty of the boundary above the uncertainties in the system. The results indicate that the effects of parametric uncertainty and external disturbances on the system performance are reduced, while the stability of the comparative-sliding control system based on the Lyapunov stability theory has been proved.

Consider the single-entry system described by equations (1) and (2) along with the uncertainty of the parameter and external perturbation. The state space equation is written in (21):

$$\dot{x} = (A + \Delta A)x + (B + \Delta B)u + (D + \Delta D)v + f(t) \quad (21)$$

D, δB, δAδ is the uncertainty of the parameter and (f) t a foreign turmoil indefinite or display a nonlinear non-linear behavior of the system.

Assumption 1:

All system uncertainties are in equation (21) in the input subclass of the input matrix, which means that:

$$\Delta A.\Delta B.\Delta D.f \in span\{B\} \quad (22)$$

In other words, unspecified matrix functions $E_1(t), E_2(t), E_3(t)$ and $E_4(t)$ have appropriate dimensions such that:

$$\Delta A = BE_1(t) \qquad \Delta B = BE_2(t) \qquad \Delta D = BE_3(t) \qquad f = BE_4(t) \quad (23)$$

Assuming the matching conditions, equation (21) can be rewritten as (24):

$$\dot{x} = Ax + Bu + Dv + \Delta Ax + \Delta Bu + \Delta Dv + f$$

$$= Ax + Bu + Dv + BE_1x + BE_2u + BE_3v + BE_4$$

$$= Ax + Bu + Dv + Bf_m \quad (24)$$

Which, f_m shows the uncertainty of the squeezed model and equals:

$$f_m = E_1x + E_2u + E_3v + E_4 \quad (25)$$

Assumption 2:

There is an unknown positive constant value such that:

$$|f_m| \leq \varphi \quad (26)$$

To select a sliding surface, the hypothesis $f_m = 0$ and $v = 0$ controller, which is obtained by minimizing the performance index (27), will be (28):

$$j = \frac{1}{2}\int_0^{\infty}(x^T Qx + u^T Ru)dt \quad (27)$$

$$u = -kx \quad (28)$$

In which

$$k = R^{-1}B^T P \quad (29)$$

is a symmetric response from the solution of the Riccati equation (30):

$$A^T P + PA + Q - PBR^{-1}B^T P = 0 \quad (30)$$

Using this control law, the dynamics of the system will be (31):

$$\dot{x} = (A - Bk)x \quad (31)$$

We can use this vector-matrix relationship to determine the sliding surface. Since the sliding variable is scalar, multiplying the vector of the row c and integrating from both sides, we get (32):

$$Cx = \int_0^t (CA - CBK)x\,dt \quad (32)$$

C is a design parameter.

Therefore, the proposed sliding surface is obtained as (33):

$$s = CX = \int_0^t (CA - CBK)x\,dt \quad (33)$$

5.1. Design adaptive sliding mode controller

The control signal to be applied to the levitation system is:

$$u = u_q + as - \beta sign(\gamma s) \quad (34)$$

That β, α and γ are extracted by selecting an appropriate lyapunov function and these parameters are updated by a general type-2 fuzzy system. To calculate u:

$$\dot{s} = C\dot{x} - CAx + CBkx$$
$$= C(Ax + Bu + Dv + Bf_m) - CAx + CBkx \quad (35)$$

Law control is equivalent to the form (36) $CB \neq 0$ and $\dot{s} = 0$ by putting

$$u_{eq} = -kx - \frac{CD}{CB}v \quad (36)$$

By replacing equations (34) and (36) in equation (35) we will have:

$$\dot{s} - C\{AX + B\left[-kx - \frac{CD}{CB}v + as - \beta sign(\gamma s)\right] + D v + Bf_m\} - CAX + CBKX = \alpha CBs - \beta CBsign(\gamma s) + CBf_m \quad (37)$$

We show the upper limit of model uncertainty with φ. If we set the estimation value of this parameter with φ and define it:

$$\tilde{\varphi} = \varphi - \bar{\varphi} \quad (38)$$

One choice for the function of lyapunov can be (39):

$$V = \frac{1}{2}s^2 + \frac{1}{2}\delta\tilde{\varphi}^2 \quad (39)$$

is a positive constant. We derive the equation (39) from time to time:

$$\begin{aligned}\dot{V} &= s\dot{s} + \delta\tilde{\varphi}\dot{\tilde{\varphi}} = s(\alpha CBs - \beta CBsign(\gamma s) + CBf_m) + \delta\tilde{\varphi}\dot{\tilde{\varphi}} \\ &= \alpha CBs^2 - \beta CBsign(\gamma s) + s\,CBf_m + \delta(\varphi - \bar{\varphi})(-\dot{\bar{\varphi}}) \\ &\leq \alpha CBs^2 - \beta CBsign(\gamma s) + |sCB||f_m| + \delta(\varphi - \bar{\varphi})(-\dot{\bar{\varphi}}) \\ &\leq \alpha CBs^2 - \beta CBsign(\gamma s) + |sCB|\varphi + \delta(\varphi - \bar{\varphi})(-\dot{\bar{\varphi}})\end{aligned} \quad (40)$$

We can use the first semester and choose α in this way that this term was negative and with zero placement of the total of 3 more semantics, a matching law was found for $\bar{\varphi}$. So if:

$$-\beta sCBsign(\gamma s) + |sCB|\varphi + \delta(\varphi - \bar{\varphi})(-\dot{\bar{\varphi}}) = 0 \quad (41)$$

we will have

$$\dot{V} \leq \alpha CBs^2 \quad (42)$$

And by choosing α as (43):

$$\alpha = \frac{-\varepsilon}{CB} \quad (43)$$

where $\varepsilon > 0$, we will have:

$$\dot{V} \leq -\varepsilon s^2 \quad (44)$$

Which indicates that the negative v is half-definite. But it is clear that if $0 \neq \dot{V} < 0$, s.

So, until the opposite s is zero, the function of the lyapunov function decreases continuously. Therefore, in accordance with equation (39) we will have:

$$\lim_{t\to\infty} s(t) = 0 \tag{45}$$

We need to find a comparative law for φ in such a way that it is independent of φ. The idea is that β and γ are chosen in such a way that the left side of equation (41) is equivalent to $(\varphi - \bar{\varphi})g$. This means that:

$$-\beta sCBsign(\gamma s) + |sCB|\varphi + \delta(\varphi - \bar{\varphi})(-\dot{\bar{\varphi}}) = (\varphi - \bar{\varphi})g \tag{46}$$

Where g is a function of $\bar{\varphi}$ and it is independent of φ. To achieve this, our suggestion is as $\beta = \bar{\varphi}$, and:

$$sCBsign(\gamma s) = |sCB| \tag{47}$$

An answer for the equation above is $\gamma = CB$ by replacing β and γ in equation (46):

$$-\beta sCBsign(\gamma s) + |sCB|\varphi + \delta(\varphi - \bar{\varphi})(-\dot{\bar{\varphi}}) = \left(|sCB| - \delta\dot{\bar{\varphi}}\right)(\varphi - \bar{\varphi}) \tag{48}$$

We now choose $\dot{\bar{\varphi}} = \frac{1}{\delta}|sCB|$, so

$$u = -kx - \frac{\varepsilon}{CB}s - \bar{\varphi}sign(sCB) \tag{49}$$

The structure of the proposed control system is shown in Fig. 4.

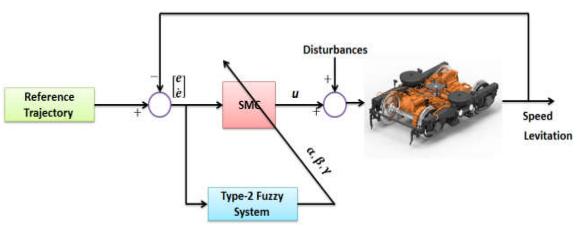

Figure 4: Structure of The Type-2 Fuzzy SMC

As is clear in Figure 4, the general type-2 fuzzy system calculates (online) the parameters of the sliding model control method. Therefore, any perturbation or uncertainty is immediately seen and the parameters are updated to minimize the effect of that perturbation or uncertainty on the system.

6. Simulation Results

According to the proposed control method, simulation was performed in MATLAB software environment. The model parameters are selected as follows [34]:

m_c = 15000 kg, m_b = 3000 kg

k_p = 2 MN/m, k_s = 200 kN/m

It is assumed that when $|u| = 2KN$ the operator is saturated. To test the consistency of the closed loop, the uncertainty is considered as follows:

$$f_m = 100sin(3t)$$

the initial design parameters are selected as follows:

$$C = [0 \quad 50 \quad 0 \quad 5]$$

$$Q = [10 \quad 0 \quad 0 \quad 0;0 \quad 1 \quad 0 \quad 0;0 \quad 0 \quad 1 \quad 0;0 \quad 0 \quad 0 \quad 1]$$

$$R = 10^{-6}$$

$$\varepsilon = 1 \;.\; \bar{\varphi}(0) = 10 \;.\; \delta = 6.66 \times 10^{-4}$$

Figure (4) shows the model of the run-off time. Comparison of coupé and bogie displacement before and after the controller is shown in figures 5 and 6, respectively. Figure 7 shows how the sliding variables change. The boundary error of high uncertainty is shown in fig. 8. Figure (9) shows the control output from (control signal) the operator.

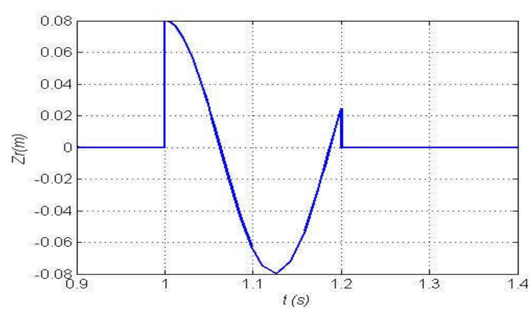

Figure 5. The railways deviation model

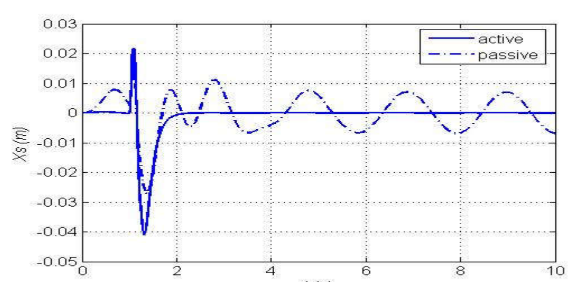

Figure 6. Coupé moving

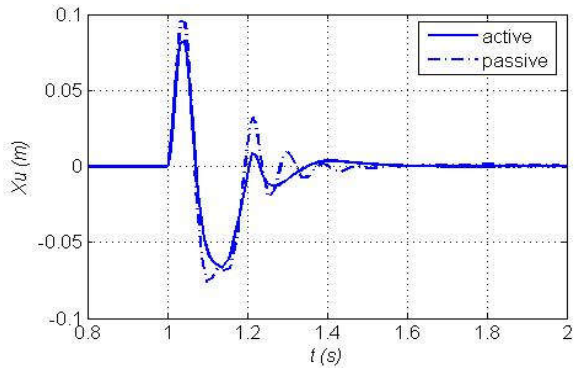

Figure 7. Bogie displacement

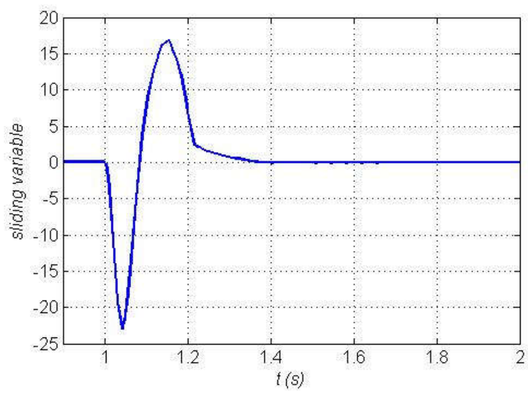

Figure 8. Sliding variable changes

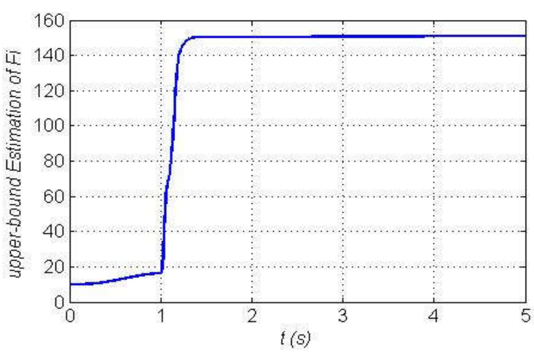

Figure 9. Estimation of the upper bound of the uncertainty

As shown in figures 5 to 10, the system-based sliding mode control based on type-2 fuzzy logic has been able to provide a decent performance with minimal cost and control signal. A comparison between our method and type-1 fuzzy sliding mode control for levitation of the train is shown in Fig. 10.

A comparison between our method and type-1 fuzzy sliding mode control for speed of the train is shown in Fig. 11.

From figures 11 and 12 can be seen that, the type-2 fuzzy sliding mode control perform better than type-1 fuzzy sliding mode control. Higher response speed and no slippage are the advantages of type-2 fuzzy system over type-1 fuzzy system.

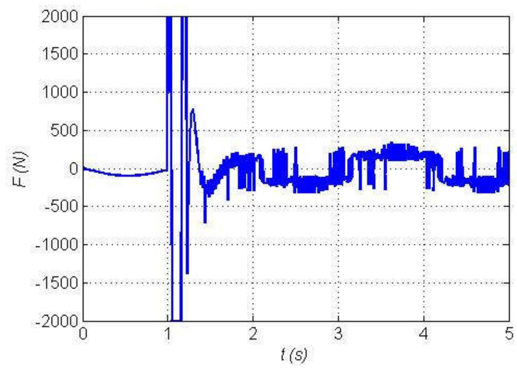

Figure 10. The operating force used by the manufacturer

7. Conclusions

In this paper, a novel method based on type-2 fuzzy sliding mode control was used for speed and levitation control of a fast train. First, a train model was introduced and in continues the proposed sliding mode control based on general (Linguistic or Mamdani) type-2 fuzzy logic was introduced. One of the challenges in sliding mode technique is determine the sliding surface where the general type-2 fuzzy systems was able to do this well. Our main goal in this paper was to have the lowest chattering and the lowest cost (control signal) that the proposed control system was able to achieve well. The new proposed method for train control was validated and it compared with type-1 fuzzy SMC. The results indicate the efficiency of the proposed method.

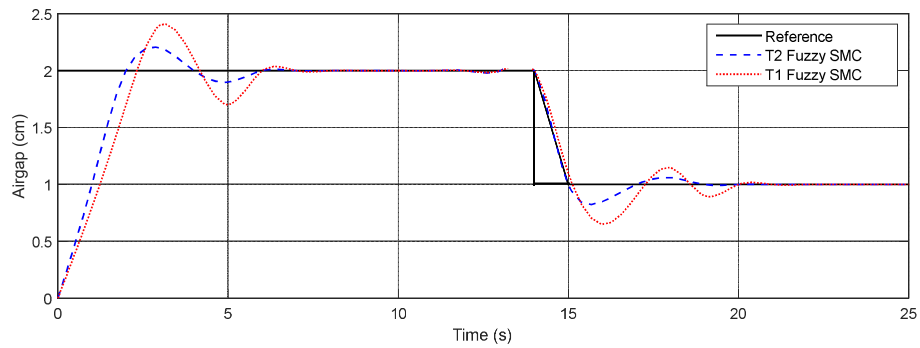

Figure 11. Levitation control

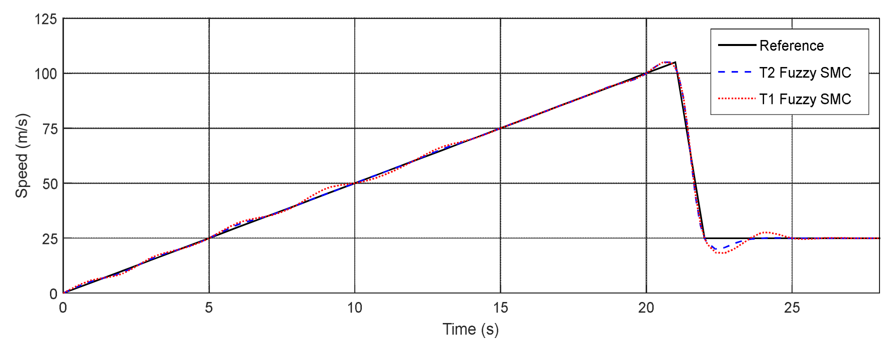

Figure 12. Speed control

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