PID Controller Tuning in Tram Pantograph Systems

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Abstract

A pantograph is an important component in electric trains and trams. This device is mounted on the roof of train or tram to collect electric current from overhead lines and transmit it to the vehicle. It is essential that the pantograph is always well-connected to the power line. However, the pantograph contact force is associated with uncertainties and disturbance, especially in high-speed, and therefore, its control is a challenging task. This paper introduces a control strategy to maintain a constant contact force between pantograph and catenary in existence of parametric uncertainties. A pantograph-catenary system with two degree-of-freedom is considered in this study. In the first step, a proportional–integral–derivative (PID) controller is designed for the system. In the second step, PID controller is tuned based on fuzzy logic. The fuzzy logic is utilized to optimize the controller's performance. Performance of the proposed controller is evaluated and analyzed on the system.
Keywords: Train/tram pantograph, Fuzzy logic, PID controller, PID tuning.

1 Introduction

In modern high-speed trains, electric current is collected and transmitted to the train through a pantograph mounted on the roof. The quality of the contact between pantograph and overhead power line is very essential in delivering electrical power to the train. Imbalances in the contact force may occur in high speed, which can lead to low-quality electrical power and train instability. Moreover, excessive contact force may cause excessive abrasion and contact wire uplift. Therefore, the contact force need to be maintained at a constant and continuous level [1, 2, 3, 4, 5]. Thus, this problem (control of contact force between pantograph and catenary) has attracted much attention in the study of pantograph-catenary system. Various control strategies are proposed in literature [6, 7, 8, 9, 10, 11, 12, 13, 14, 15] for control of pantograph-catenary system. The study in [7] proposes a proportional–integral (PI)-based control strategy for the train pantograph system. A camera is mounted on the roof of the train which collects images of pantograph-catenary interaction. The PI controller then defines the suitable distance in the system such that constant contact force is maintained. Authors in [8] investigated the design of a fuzzy controller for pantograph-catenary system. Their proposed controller is based on the Sugeno fuzzy inference system. The study in [9] introduces a state feedback controller for the pantograph system. Authors first linearized the system equation, and then, they designed the controller for the linearized system. Authors in literature [10, 12, 14] proposed a robust controller for pantograph system. Their approaches are designed based on $H\infty$ (i.e. "H-infinity") and H2 methods. The authors tuned the controller's coefficients through evolutionary algorithms.

Since pantograph-catenary systems are naturally associated with uncertainties, designing a state feedback or H controller is very problematic. The controller designed for a pantograph-catenary system should have three crucial attributes: (1) it is simple to implement and easy to tune, (2) it is adaptable to uncertainties and disturbances, and (3) it ensures the best performance. The state feedback or H controllers are proved to achieve satisfying control performance; however, they are not simple, and it is difficult to tune their parameters. Proportional–integral–derivative (PID) controllers are easy to implement; however, they are not robust to disturbances. For this purpose, we need to choose a suitable tuning approach. Therefore, in this paper, we designed a PID controller for a pantograph-catenary system with two degree-of-freedom, and we tuned its parameters through the fuzzy logic. The designed controller is simulated in MATLAB and its control performance is evaluated and analyzed. The rest of the paper is organized as follows. The pantograph-catenary system and its dynamical equations are explained in section 2. Section 3 provides the control strategy. The simulation results are shown in section 4, and section 5 presents the conclusions.

2 Pantograph-catenary system dynamics

Pantographs can be passive or active. Traditional pantographs were designed passive; they consists of viscous-elastic components with fixed parameters. Therefore, it is not possible to maintain a constant contact force in passive pantographs. The contact force can be monitored in active pantographs by an active actuator embedded in the system. Fig. 1 shows a pantograph-catenary system, and Fig. 2 shows the model diagram of an active pantograph with two degrees of freedom [16, 17, 18].

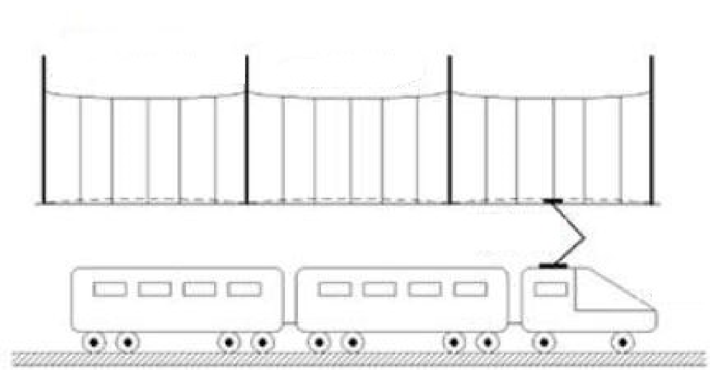

Figure 1: A pantograph-catenary system

The dynamics of a pantograph system is as follows.

$$\begin{aligned} &M_f\ddot{x_f} + b_{vh}(\dot{x_f} - \dot{x_h}) + k_h(x_f - x_h) = u_{up} - b_{vf}\dot{x_f} \\ &M_h\ddot{x_h} + b_{vh}(\dot{x_h} - \dot{x_f}) + k_h(x_h - x_f) + k_s(x_h - x_{cat}) = 0 \\ &-k_s x_h + (k_s + k(t))x_{cat} = 0 \end{aligned} \tag{1}$$

where b_{vf}, k_h, M_f, and u_{up} are damper constant, spring constant, and cylinder input signal, respectively. Considering $x_1 = x_h$, $x_2 = \dot{x_h}$, $x_3 = x_f$, and $x_4 = \dot{x_f}$, the state space equation (2) is attained.

$$\begin{bmatrix} \dot{x_1} \\ \dot{x_2} \\ \dot{x_3} \\ \dot{x_4} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ \frac{1}{M_h}\left(\frac{{k_s}^2}{k_s+k_{ave}} - (k_h + k_s)\right) & -\frac{b_{vh}}{M_h} & \frac{k_h}{M_h} & \frac{b_{vh}}{M_h} \\ 0 & 0 & 0 & 1 \\ \frac{k_h}{M_f} & \frac{b_{vh}}{M_f} & -\frac{k_h}{M_f} & -\frac{(b_{vh}+b_{vf})}{M_f} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{1}{M_f} \end{bmatrix} \tag{2}$$

where k_{ave} is the average value of spring constant. The parameter valuse are shown in Table 1. The proposed control approach is presented in the next section.

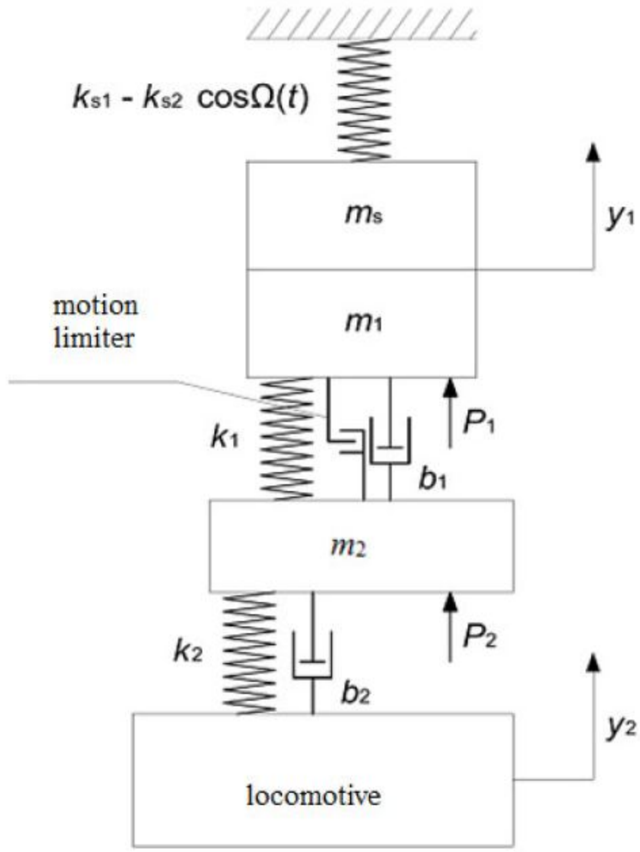

Figure 2: Model of an active pantograph with two degrees of freedom

Table 1: Electric vehicle and energy storage system parameters

Parameter	Value	Unit
M_h	9.1	kg
k_s	82300	N/m
M_f	17.2	kg
v	0.5	-
V	170	km/h
L	65	m
k_h	7000	N/m
b_{vh}	130	N.s/m
k_{ave}	3600	N/m
b_{vf}	30	N.s/m

3 Proposed methodology

A PID controller is designed for the pantograph system. The controller limits the pantograph contact force in a reasonable range. Fuzzy logic is utilized to tune the parameters of PID controller. In a PID controller, an error value (difference between the desired and measured variables) is computed in time step, and a correction based on proportional, integral, and derivative terms (known as P, I, and D) is applied to the closed-loop feedback system, such that the error value is minimized. The proportional term (P) is used to maintain system stability. The integral term (I) is for decreasing the steady-state error. The derivative term (D) is used to diminish system disturbances [19, 20]. The differential equation of a PID controller is as follows.

$$\begin{aligned}
u(t) &= k_p(e(t) + \frac{1}{T_i}\int_0^t e(t)dt + T_d\frac{de(t)}{dt}) \\
G_c(t) &= \frac{k_d s^2 + k_p s + k_i}{s} \\
k_i &= \frac{k_p}{T_i} \\
k_d &= k_p T_d
\end{aligned} \tag{3}$$

where k_p, k_i, k_d are the proportional, integral, and derivative terms, respectively. $e(t)$ is the error, and $u(t)$ is the control input. We used the Ziegler–Nichols tuning method to tune PID parameters [21, 22]. A Mamdani fuzzy system is used along with the tuning method (tuning on the PID terms) to decrease the error value and its derivative value [23, 24, 25]. The diagram of fuzzy controller is presented in Fig. 3. In the above diagram,

Figure 3: Fuzzy controller diagram

fuzzy components are defined as (4).

$$\begin{aligned}
k_p &= \frac{k_p - {k_p}^{min}}{{k_p}^{max} - {k_p}^{min}} \\
k_d &= \frac{k_d - {k_d}^{min}}{{k_d}^{max} - {k_d}^{min}} \\
\alpha &= \frac{{k_p}^2}{k_i k_d}
\end{aligned} \tag{4}$$

The minimum and maximum values of k_p and k_d are as follows:

$$\begin{aligned}
&{k_p}^{min} = 0.5 \ {k_p}^{max} = 1.3 \\
&{k_d}^{min} = 0.065 \ {k_d}^{max} = 0.17
\end{aligned} \tag{5}$$

The simulation results are shown in the next section.

4 Simulation results

The membership functions in fuzzy approach are chosen as Figs. 4, 5, and 6. According to the system response figures, the PID-fuzzy controller performance is satisfying. Fig. 7 shows the system response to step input, using conventional PID and proposed PID (fuzzy-based PID). Fig. 8 shows the inputs of PID controller. The trajectories show that the controller performs optimally in existence of disturbances and noises.

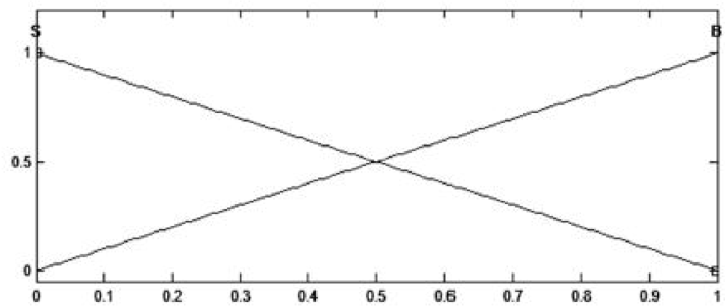

Figure 4: Membership functions for e and $\dot{e}$

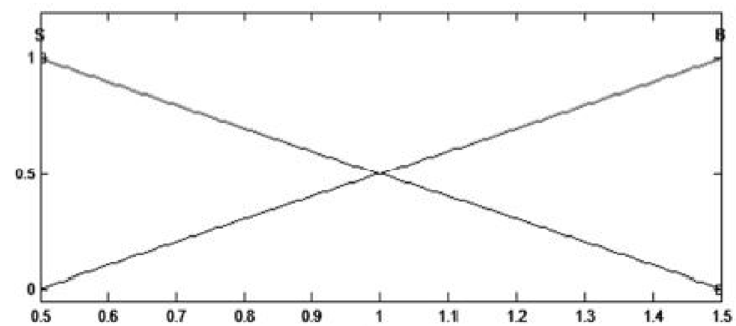

Figure 5: Membership functions for k_p and k_d

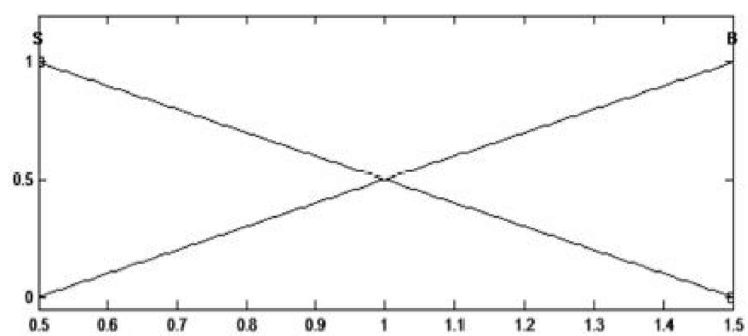

Figure 6: Membership functions for α

5 Conclusion

In this paper a PID controller is designed based on fuzzy logic. A antograph-catenary system with two degree-of-freedom is regulated through the proposed control approach. The simulations are performed in the existence of disturbance. Simulation results proved the effectiveness of PID-fuzzy controller.

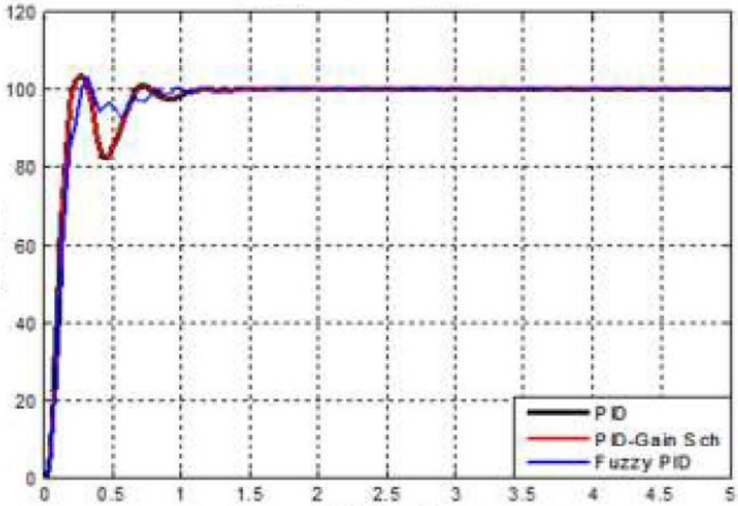

Figure 7: Pantograph response to step input

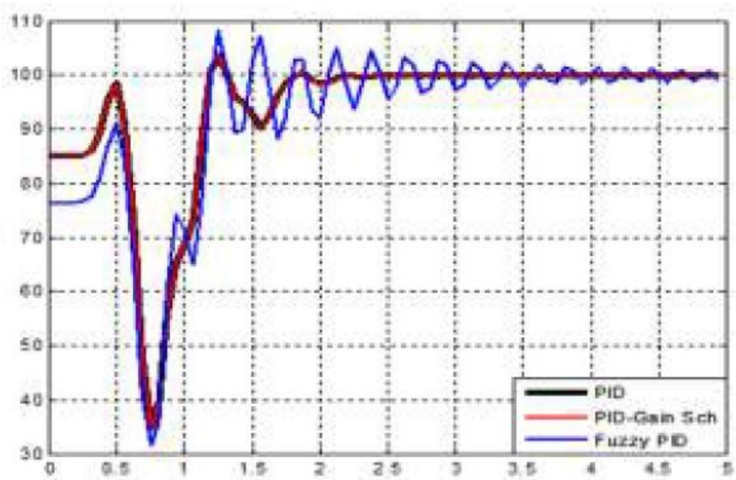

Figure 8: Input signals of pantograph

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