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Autonomous Vehicle Control, Part III: Train Velocity Control with Passenger Comfort Index using PD-PI, PI-PD and 2DOF-2 Controllers Compared with a PID Controller

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Abstract:

This paper is the third in a series of research papers presenting the control of autonomous vehicles. It handles the train velocity control with constraints on its acceleration and jerk as a passenger comfort index using PD-PI, PI-PD and 2DOF-2 controllers from the second generation of PID controllers compared with a PID controller from the first generation of PID controllers. The MATLAB optimization toolbox is used to tune the three proposed controllers using an ITAE performance index with passenger comfort index constraint. The step time response of the control system using the four analyzed controllers is presented and compared and the time-based characteristics are compared. The comparison reveals the best controller among the four controllers depending on a quantitative comparison study for both reference and disturbance inputs.

Keywords — Autonomous control, train velocity control, Passenger comfort index, PD-PI controller, PI-PD controller, 2DOF-2 controller, PID controller, controllers tuning.
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I. INTRODUCTION

This is the third research paper in a research series about autonomous vehicle control. It deals with the control of automatic high velocity train for velocity control considering passenger comfort as a constraint on the train velocity. We start by taking an idea about some historical literature about the control of autonomous train velocity since 2005:

Tallfors (2005) addressed different aspects of identification and control of resonant elastic systems such as trains. He developed a method to find the mechanical parameters through a series of experiments for the simulation of a train with single motor torque as input and motor speed as output. He treated also control problem with tandem coupled motors with and without extra sensor for the shaft torque [1]. Yang, Zhang, Chen and Zhang (2011) established the ¼ vehicle mathematical model using semi-active suspension system for high speed trains. They carried out the simulation of the high speed train under the condition of passive suspension and semi-active suspension using fuzzy adaptive PID control. They concluded that the stability and comfort can be improved effectively using their proposed control approach [2]. Durmus, Urak and Soylemez (2013) introduced the moving block railway to increase the transport capacity and reduce the headway transmissibility. They explained the concept of moving block system and the use of an adaptive PD control for train speed control. They presented step time response for the train velocity showing smooth time response without overshoot and with acceleration less than 0.7 m/s^2 [3]. Utomo, Sumardi and Widianto (2015) investigated the use of fuzzy logic controller to control train speed through modeling, design, testing and analysis. Their analysis covered the rise time, fall time, settling time and steady-state error. Their fuzzy logic controller achieved a step time response of 2.925 settling time and steady-state error of 2 % at train speed change of 0.5 m/s [4].

Hou, Guo and Niu (2019) derived a multi-point train dynamics model to improve the accuracy of high speed train control and solve the problem of speed jump when the train runs through curvature. They designed a predictive fuzzy adaptive controller and showed through simulation that the multi-point model of the high speed train could solve the speed jump problem of the train with fast response and high accuracy [5]. Yin et al. (2020) recorded train operation data in Beijing Metro within 3 years and developed 3 data driven approaches: linear regression model, nonlinear regression model and neural network model. They observed that the neural network model enhanced the prediction accuracy for the train control model. They concluded that the data driven approaches were successfully applied to Beijing Metro for the design of train control algorithms [6]. Can, Wang and Zhao (2021) proposed a new model for the PID controller based on practical train operation stages and considered different response time delay. They used an improved fruit fly optimization algorithm to tune the PID controller. They compared through simulation with other tuning techniques [7]. Cavacece (2022) proposed a MIMO model based on data driven approach to assess passenger vibration comfort on rail vehicles. He considered the acceleration measurement in trains (tramway and underground) and developed acceleration analysis in the time domain and transmissibility of the acceleration in the frequency domain [8].

Li and Wang (2023) designed a train operation target curve aiming at the comfort of automatic train operation system to meet a ‘comfort index’ for the train. They established two simulation models to compare with experimental work. One model was based on PID control and the second model was based on fuzzy PID. They used train maximum acceleration in the in the longitudinal direction and the jerk (acceleration rate) as indices for passenger comfort with limits of 1.52 m/s^2 and 0.4 m/s^3 for stages other than starting and stopping. They concluded that the conventional PID controller was not good as the fuzzy PID regarding passenger comfort [9]. Liu, Feng, Xiao and Li (2024) proposed an offline reinforcement learning strategy for automatic tracking of autonomous trains with tracking controller based on improved offline conservative Q-learning algorithm. They designed a multi-objective reward function to distinguish the tracking process of trains in different sections. Simulation results showed that the used automatic control algorithm was superior in terms of safety and comfort [10].

II. THE CONTROLLED TRAIN VELOCITY AS A PROCESS

Li and Wang used au undelayed second-order model for a train velocity of an urban rail train and tuned a PID controller for this purpose [9]. Their transfer function model for the train velocity as a process, $G_p(s)$ is given by [9]:

$$G_p(s) = 0.07128\ 1\ (s^2 + 0.4356s + 0.0324) \quad (1)$$

To investigate the dynamics of the train velocity, a unit step time response is generated using the ‘step’ command of MATLAB [11] which is shown in Fig.1.

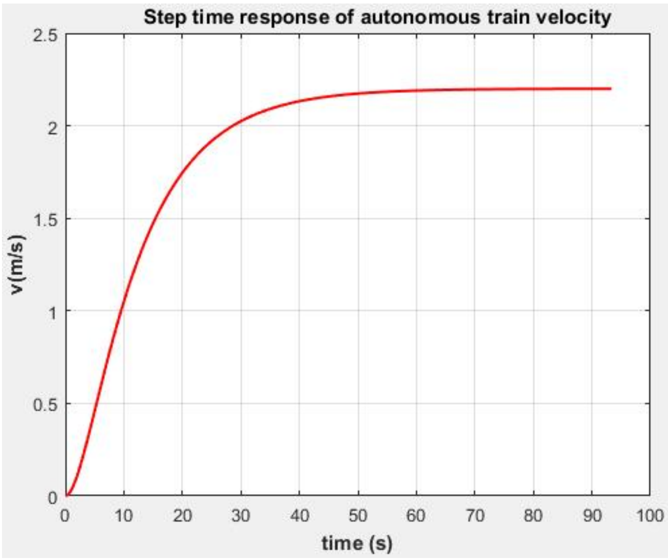

Fig.1 Autonomous train velocity step time response.

COMMENTS:

- Natural frequency: 0.18 rad/s
- Damping ratio: 1.21
- Maximum overshoot: zero
- Settling time: 44.45 s

- Steady-state error: -1.1996 m/s
- This process dynamically has bad dynamics because of its high settling time and steady-state error.

III. CONTROLLING THE TRAIN VELOCITY USING A PD-PI CONTROLLER

The PD-PI controller was introduced by the author in 2014 as one of the good controllers of the second generation of the PID controllers. The author tested the performance of the PD-PI controller through its use in controlling first-order delayed processes [12], highly oscillating second-order process [13], integrating plus time-delay process [14], delayed double integrating process [15], third-order process [16], boost-glide rocket engine [17], rocket pitch angle [18], LNG tank pressure [19], boiler temperature [20] boiler-drum water level [21], greenhouse internal humidity [22], coupled dual liquid tanks [23], BLDC motor [24], furnace temperature [25], electro-hydraulic drive [26], barrel temperature [27], mold packing pressure [28], IMM ram velocity [29], full-electric IMM [30], Al-Jazari hydraulic turbine [31], Banu Musa axial turbine power control [32], wind turbine speed [33], steam turbine speed [34] and autonomous car steering angle [35].

The block diagram of the control system incorporating a PD-PI controller comprises a PD-control and PI-control modes in series after the error detector feeding its output directly to the controlled process.

The PD-PI controller has a transfer function, $G_{PDPI}(s)$ given by [22]:

$$G_{PDPI}(s) = [K_dK_{pc2}s^2+(K_dK_i+K_{pc1}K_{pc2})s+K_{pc1}K_i]/s \quad (2)$$

Where:

K_{pc1} = proportional gain of the PD-control mode.

K_d = derivative gain of the PD-control mode

K_{pc2} = proportional gain of the PI-control mode.

K_i = derivative gain of the PI-control mode

The PD-PI controller has four gain parameters to be tuned to optimal performance for the control system.

- The transfer function of the control system comprising the PD-PI controller and the controlled process is derived using the block diagram of the control system and Eqs.1 and 2.
- Two new functional constraints are imposed on the train acceleration and jerk (acceleration rate) for purpose of passenger comfort with upper limit:
  - Upper limit of train acceleration [9,36]: 1.52 m/s^2.
  - Upper limit of train jerk [9,37]: 0.40 m/s^3.
- The performance index to me minimized by the optimization technique was selected as the ITAE [38].
- The MATLAB optimization toolbox [39] is selected to perform the minimization of the ITAE and provide the optimal gain parameters of the PD-PI controller.
- The tuned parameters of the PD-PI controller are as follows:

K_{pc1} = 15.176440 , K_d = 44.323237

K_{pc2} = 0.201336 , K_i = 0.029955 (3)

- Using the closed-loop transfer function of the closed-loop control system and the PD-PI controller gains in Eq.3 with reference input and zero disturbance input and the transfer function of the closed-loop control system with disturbance input and zero reference input, the unit step response is generated using the MATLAB command '*step*' [11]. The train acceleration is obtained by differentiating the train velocity numerically using the MATLAB command '*diff*' [40]. The train jerk is obtained by the numerical differentiation of the train acceleration using the same command '*diff*'. The results are presented in Fig.2 for train velocity and Fig.3 for train acceleration and jerk.

COMMENTS:

- Control system characteristics for reference input tracking:

- Maximum percentage overshoot: 3.556 %
- Settling time: 13.0 s
- Maximum acceleration: 0.636 m/s^2
- Maximum jerk: 0.364 m/s^3

- Control system characteristics for disturbance rejection (with second-order high pass filter):
  - Maximum time response: 1.112×10^{-14} m/s
  - Minimum time response: -0.207×10^{-14} m/s
  - Approximate settling time to zero: 10 s

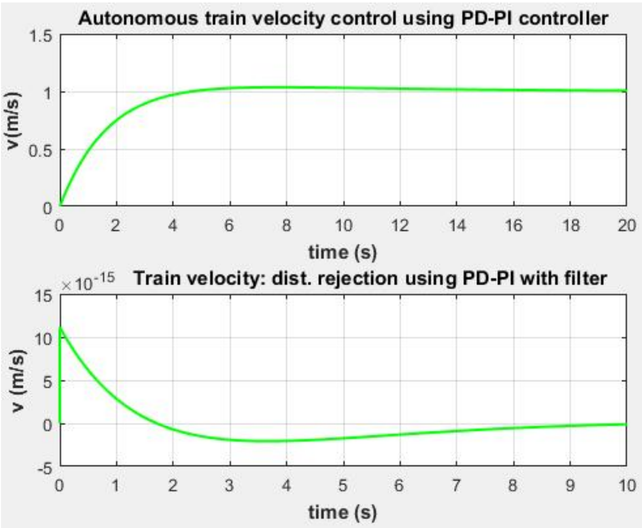

Fig.2 Train speed control using a PD-PI controller.

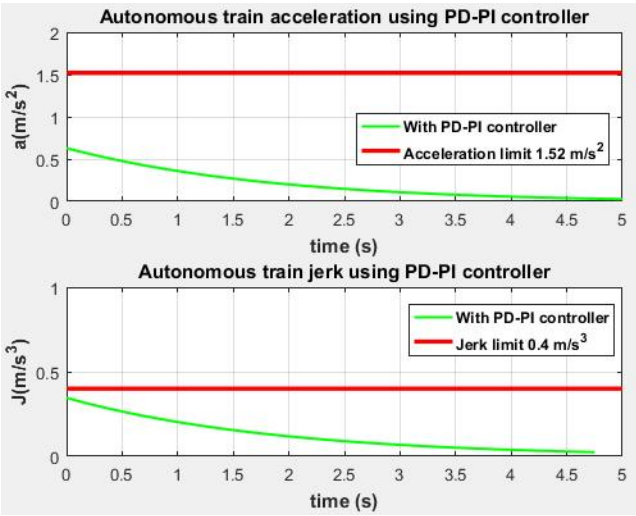

Fig.3 Train acceleration and jerk using a PD-PI controller for a unit step input.

IV. CONTROLLING THE TRAIN VELOCITY USING A PI-PD CONTROLLER

The PI-PD controller was introduced by the author in 2014 as one of the controllers of the second generation of the PID controllers. The author tested the performance of the PI-PD controller through its use in controlling a highly oscillating second-order process [41], second-order processes [42], delayed double integrating process [43], third-order process [43], boost-glide rocket engine [17], LNG tank pressure [19], boiler-drum water level [21], greenhouse internal humidity [22], coupled dual liquid tanks [23], BLDC motor [24], IMM electro-hydraulic drive [30], IMM barrel temperature [27], IMM mold packing pressure [28], IMM ram velocity [29], full-electric IMM [30], Al-Jazary hydraulic turbine [31], Banu-Musa axial turbine power [32], Wind turbine speed [33] and car steering angle [35].

The block diagram of the control system incorporated the PI-PD controller is shown in Fig.4 [45]. It is composed of a forward element which is a PI control mode and a feedback element in an internal loop about the process which is a PD control mode.

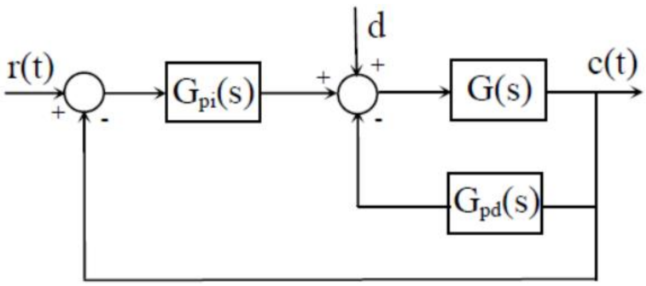

Fig.4 Structure of the PI-PD controller [45].

The PI-PD controller elements have the transfer functions:

$$G_{PI}(s) = K_{pc1} + (K_i/s)$$
$$G_{PD}(s) = K_{pc2} + K_d s \quad (4)$$

Where:

K_{pc1} = proportional gain of the PI-control mode.

K_i = integral gain of the PI-control mode

K_{pc2} = proportional gain of the PD-control mode.

K_d = derivative gain of the PD-control mode

The PI-PD controller has four gain parameters to be tuned to provide the optimal performance of the control system. The tuning technique is the same as that used in the PD-PI controller in the previous section considering constraints for passenger comfort.

- The tuned parameters of the PI-PD controller are as follows:

K_{pc1} = 0.974616 , K_i = 0.114594

K_{pc2} = 0.201083 , K_d = 0.001854 (5)

- Using the closed-loop transfer function of the closed-loop control system and the PI-PD controller (using the block diagram in Fig.3 with zero disturbance signal) and the controller gains in Eq.5 with reference input and the transfer function of the closed-loop control system with disturbance input and zero reference input, the unit step response of the control system incorporating the PI-PD controller is shown in Figs.5 for train velocity and 6 for train acceleration and jerk due to a unit step input.

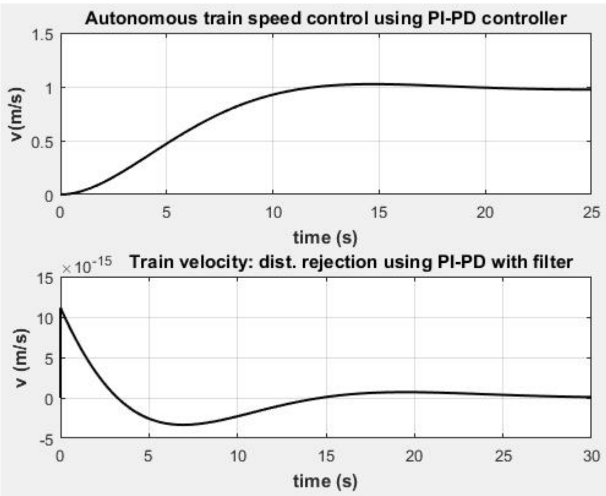

Fig.5 Wind turbine speed control using a PI-PD controller.

COMMENTS:

- Control system characteristics for reference input tracking:
  - ➢ Maximum percentage overshoot: 2.419 %
  - ➢ Settling time: 29.25 s
  - ➢ Maximum acceleration: 0.127 m/s^2
  - ➢ Maximum jerk: 0.069 m/s^3

- Control system characteristics for disturbance rejection (with second-order high pass filter):
  - ➢ Maximum time response: 1.113×10^{-14} m/s
  - ➢ Minimum time response: -0.334×10^{-14} m/s
  - ➢ Approximate settling time to zero: 20 s

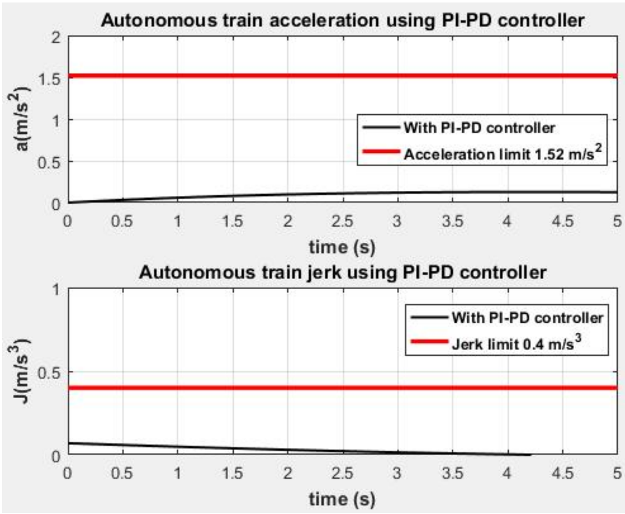

Fig.6 Train acceleration and jerk using a PI-PD controller for a unit step input.

V. CONTROLLING THE TRAIN VELOCITY USING A 2DOF-2 CONTROLLER

The 2DOF controller is one of the second generation controllers introduced by the author starting from 2014 to replace the first generation PID controllers. The author used different structures of 2DOF control to control a variety of industrial processes having bad dynamics such as: liquefied natural tank level [47], liquefied natural gas pressure [19], boost-glide rocket engine [17], BLDC motor [24], delayed double integrating process [43], boiler drum water level [21], furnace temperature [25], boiler temperature [20], an electro-hydraulic drive [26], cavity gate pressure [48], IMM barrel temperature [27], IMM mold packing pressure [28], IMM ram velocity [29], full-electrical IMM [30], Al-Jazary turbine [31], Banu Musa axial turbine power [32] and second-order like processes [46], wind turbine speed [33] and car steering angle [35].

The block diagram of a control system incorporating a 2DOF, structure 2 and the controlled process is shown in Fig.7 [29].

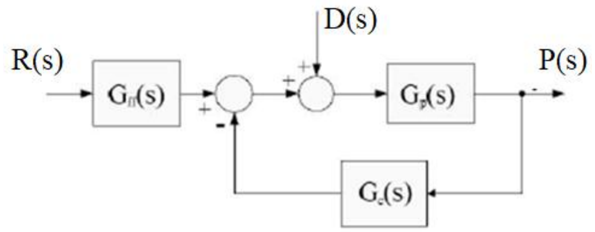

Fig.7 Train velocity control system using 2DOF-3 controller [29].

- The 2DOF-2 controller is composed of two elements: PI-control-mode of $G_{ff}(s)$ transfer function in a forward path receiving the reference input and another PID-control mode of $G_c(s)$ transfer function in the feedback path of the control system loop.
- The 2DOF-2 controller elements have the transfer functions:

$$G_{ff}(s) = K_{pc1} + (K_i/s)$$

And $$G_c(s) = K_{pc2} + (K_i/s) + K_d s \quad (6)$$

- The 2DOF-2 controller has four gain parameters K_{pc1}, K_i, K_{pc2} and K_d to be tuned to adjust the performance of the closed-loop control system and fulfil the requirements of passenger comfort.
- The transfer functions of the closed-loop control system in Fig.7 are derived from the block diagram using Eqs.1 for the process and 6 for the 2DOF-2 controller for both inputs R(s) and D(s).
- The unit step time response of the control system, v(t) for a reference input is obtained using the closed loop transfer function derived from the block diagram of the control system with zero disturbance and the '*step*' command of MATLAB [11].
- The same procedure for tuning the PD-PI and PI-PD controllers is applied for the 2DOF-2 controller.
- Minimizing the error function ITAE subjected to constraints for passenger comfort reveals the following optimal gain parameters of the 2DOF-2 controller:

$$K_{pc1} = 0.508093 \;\; ; K_i = 0.029209$$

$$K_{pc2} = 0.334362 \;\; ; K_d = -0.00086 \quad (7)$$

- The closed-loop transfer functions are used to plot the unit step input step time response of the control system as shown in Fig.8 for train velocity and Fig.9 for train acceleration and jerk.

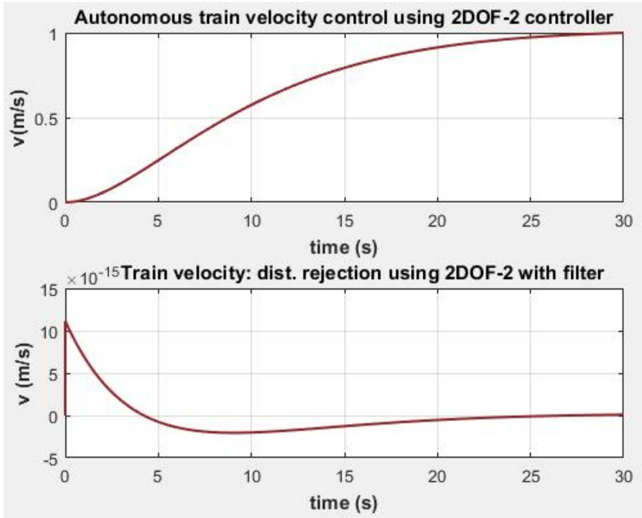

Fig.8 Train velocity control using a 2DOF-2 controller.

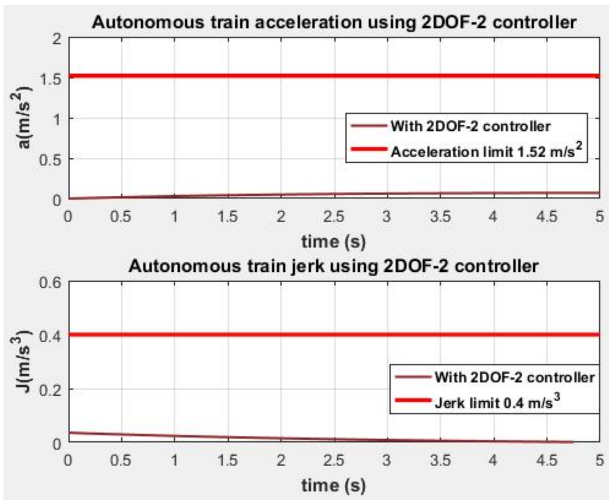

Fig.9 Train acceleration and jerk using a 2DOF-2 controller for a unit step input.

COMMENTS:

- Control system characteristics for reference input tracking:
  - ➢ Maximum percentage overshoot: zero
  - ➢ Settling time: 25.90 s
  - ➢ Maximum acceleration: 0.0707 m/s^2
  - ➢ Maximum jerk: 0.0360 m/s^3

- Control system characteristics for disturbance rejection (with second-order high pass filter):
  - ➢ Maximum time response: 1.113×10^{-14} m/s
  - ➢ Minimum time response: -0.204×10^{-14} m/s
  - ➢ Approximate settling time to zero: 25 s

VI. CONTROLLING THE TRAIN VELOCITY USING A PID CONTROLLER

PID controller is one of the first generation of PID controllers. The PID controller is still in use in many automatic control applications [2, 9, 49, 50 and 51].

- The PID controller is set in the forward path of a single-loop control system incorporating a classical controller and the controlled process. It receives its input from the error detector and feeds its output to the process.
- It has the transfer function, $G_{PID}(s)$:

$$G_{PID}(s) = K_{pc} + (K_i/s) + K_d s \qquad (8)$$

Where K_{pc} is its proportional gain, K_i is its integral gain and K_d is its derivative gain.

- The transfer functions of the closed-loop control system are derived from the block diagram using the train speed transfer function in Eq.1 and the PID controller transfer function in Eq.8 for reference and disturbance inputs.
- The PID controller is tuned by the authors of reference [9] who provided the following gain parameters for the PID controller:

$$K_{pc} = 16 \;\; ; \;\; K_i = 10 \;\; ; \;\; K_d = 38 \qquad (9)$$

- The closed-loop transfer functions are used to plot the unit step input step time response of the control system using the '*step*' command of MATLAB [11] as shown in Fig.10 for the train velocity and Fig.11 for the train acceleration and jerk due to the unit step reference input.

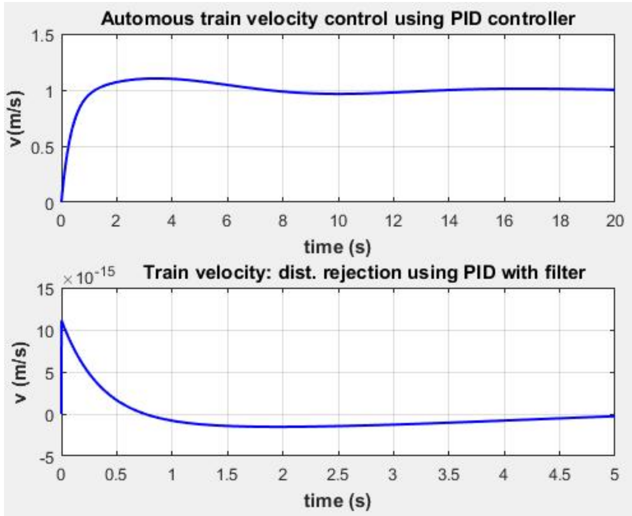

Fig.10 Train velocity control using a PID controller.

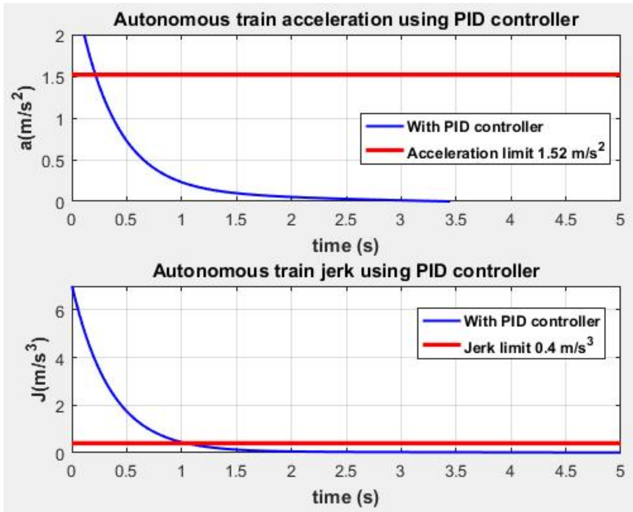

Fig.11 Train acceleration and jerk using a PID controller for a unit step input.

COMMENTS:

- Control system characteristics for reference input tracking:
  - ➢ Maximum percentage overshoot: 10.268 %
  - ➢ Settling time: 12.187 s
  - ➢ Maximum acceleration: 2.708 m/s^2
  - ➢ Maximum jerk: 7.047 m/s^3
- Control system characteristics for disturbance rejection (with second-order high pass filter):
  - ➢ Maximum time response: 1.110×10^{-14} m/s

- Minimum time response: -0.153×10^{-14} m/s
- Approximate settling time to zero: 5 s

VII. COMPARISON ANALYSIS

- To evaluate the effectiveness of using the proposed controllers, the step time response for reference input is compared with that using a PID controller tuned in reference [9] considering the acceleration and jerk comfort index of the train passengers.
- A quantitative comparison for the time-based characteristics of the control systems proposed to control the train velocity is given in Table 1 for a reference step input and disturbance rejection.

TABLE 1
TIME-BASED CHARACTERISTICS OF THE TRAIN VELOCITY CONTROL SYSTEM FOR REFERENCE INPUT TRACKING AND DISTURBANCE REJECTION

Controller	PD-PI	PI-PD	2DOF-2	PID
OS_{max} (%)	3.556	2.419	0	10.268
T_s (s)	13	29.25	25.90	12.187
a_{max} (m/s^2)	0.636	0.127	0.0707	2.708
J_{max} (m/s^3)	0.364	0.069	0.036	7.047
$10^{14}v_{Dmax}$ (m/s)	1.112	1.113	1.113	1.110
$10^{14}v_{Dmin}$ (m/s)	-0.207	-0.334	-0.204	-0.153
T_{s0} (s)	10	20	25	5

OS_{max} = maximum percentage overshoot
T_s = settling time to 2 % tolerance.
a_{max} = maximum acceleration during reference input tracking.
a_{min} = minimum acceleration during reference input tracking.
T_{s0} = approximate settling time to zero during disturbance input tracking.

VIII. CONCLUSIONS

- This research paper investigated the use of PD-PI, PI-PD and 2DOF-3 controllers from the second generation of PID controllers to control the train velocity.
- The process under control (train velocity) is an example of processes with bad dynamics because of its large steady-state error and settling time.
- The performance of the proposed controllers was compared with that of a PID controller from the first generation of PID controllers.
- This was the first time in these series of research papers conducted by the author to consider a comfort index for the train passengers as a constraint during the controller tuning process.
- Imposing a functional constraint during the tuning process of the proposed controllers has affected the time characteristics of the control system during reference input tracking (mainly maximum percentage overshoot and settling time).
- The maximum overshoot of the control system was 3.556, 2.419, 0 and 10.268 % for PD-PI, PI-PD, 2DOF-2 and PID controllers for reference input tracking.
- The settling time of the step input tracking was 13, 29.25, 25.90 and 12.187 s for PD-PI, PI-PD, 2DOF-2 and PID controllers. The relatively small settling time of the time response using a PID controller was due to the violation of the limits of the comfort index which was not the case with the other controllers.
- The maximum acceleration of the train during the reference step input was 0.636, 0.127, 0.0707 and 2.708 m/s^2 for PD-PI, PI-PD, 2DOF-2 and PID controllers with only the PID controller violating the index limit of 1.52 m/s^2.
- The maximum jerk of the train during the reference step input was 00.364, 0.069, 0.036 and 7.047 m/s^3 for PD-PI, PI-PD, 2DOF-2 and PID controllers with only the PID controller violating the index limit of 0.4 m/s^3.
- If the selection criterion for the best controller is the settling time and passenger comfort index, then the 2DOF-2 controller will be the best one to control the train velocity.
- Regarding the disturbance rejection, the four proposed controllers provided very low maximum time response, minimum time response. The settling time to zero with using a proper second-order high-pass filter

with the disturbance input was in the range 5 to 25 s. response and minimum settling time.

- In general, the analysis supports the effectiveness of the proposed controllers are a replacement for the controllers from the first generation of PID controllers.

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DEDICATION

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- The company started production of freight wagons.
- In 1969: started producing passenger cars.
- In 1978: started producing tram cars.
- In 1988: started producing metro cars.
- How great you are SEMAF. This is why I dedicate this research work to SEMAF.

BIOGRAPHY

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- Now with the Faculty of Engineering, Cairo University, EGYPT.
- Research on Automatic Control, Mechanical Vibrations, Mechanism Synthesis and History of Mechanical Engineering.
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