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Modelling and Controller Design for a Cruise Control System

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***Abstract-* This paper presents the performance of different control approaches that consist of conventional, modern and intelligent controller that employed in a cruise control system. The cruise control system is one of the most enduringly popular and important laboratory models for teaching control system engineering. The system is widely used because it is very simple to understand and yet the control techniques cover many important classical and modern design methods. In this paper, the mathematical modelling for linear and nonlinear dynamic model of the cruise control system is obtained. PID, state space and artificial intelligence controller (fuzzy logic) are designed for linear model. Meanwhile, PID with feedforward controller is proposed for nonlinear model with disturbance effect. Feedforward-type PD controller is proposed in this study in order to eliminate the gravitational and wind disturbance effect. Simulation will be carried out using. Finally, a comparative assessment of the impact of each controller on the basis of results acquired.**

I. INTRODUCTION

Automobile cruise control system is functional as an automatic speed control for a car. Thus, it maintains the speed of the car throughout a journey. The output of the system which is speed is controlled by the controller in order to provide the desired speed at which the car is to be maintained. Normally, the drivers have to press step the acceleration pedal consistently, to maintain the car's speed. The controller provides comfortability and easiness to drivers when driving the car. Comfortability means driving without having to control the pedals frequently and less tiring. Easiness means controlling the speed of the car by pressing buttons instead of pedals.

The problem of cruise control system is to maintain the output speed of the system as set by input signal. The example, if driver desires to cruise or maintain the car speed at 110 meter per second, then the system should be able to produce the desired output. This can be achieved by various methods of controller such as using proportional-integral-derivatives (PID) controller, state-space controller, fuzzy logic controller and many more. The cruise control system also experienced problem when there are disturbances from external system such as gravitational force and wind gust speed. However these short-falls can be overcome by adding cascade controller and feedforward controller to cruise control system.

Modelling is a task that requires creatively and problem-solving skills. A complex model of a car with dampers, springs and masses can be reduced to much simpler form of model such as moving cart. By the reduction, the system seems much simpler and great amount of complex and tedious calculations has been avoided. For example, calculations that involve the masses, springs, dampers and other related products. In modelling a system cruise control, it is important that the model should represent the most general situation or case so that the model will take into accounts all of the important parameters, including those that are due to disturbances which directly or indirectly affect the overall performance of the system.

After modelling the cruise control system, the design of the controller such as PID control can be applied and the stability analysis based on linear state-space model or transfer function is analyzed. Furthermore, some modern controller such as state space controller [1] and intelligent controllers for cruise control such as fuzzy control [2], neural control [3], can also be found. Although a simple and quick simulation of the feedback system may be handy for a quick check of the design, a more accurate simulation should be done by applying the controller to the original nonlinear model.

This paper present several controllers design such as PID controller, state space controller and artificial intelligence controller (fuzzy logic) for linear model. Meanwhile, the nonlinear model focuses on PID with feedforward controller. Feedforward-type PD controller is proposed in this study in order to eliminate the gravitational and wind disturbance effect. Finally, a comparative assessment of the impact of each controller on the system performance is presented and discussed.

II. MODELLING THE CRUISE CONTROL SYSTEM

The purpose of the cruise control system is regulating the vehicle speed so that it follows the driver's command and maintains the speed at the commanded level. Base on the command signal v_R from the driver and the feedback signal from the speed sensor, the cruise controller regulates vehicle speed v by adjusting the engine throttle angle u to increase or decrease the engine drive force F_d. The longitudinal dynamics of the vehicle as governed by Newton's low (or d'Alembert's principle) is

$$F_d = M\frac{d}{dt}v + F_a + F_g \tag{1}$$

where $M(dv/dt)$ is the inertia force, F_a is the aerodynamic drag and F_g is the climbing resistance or downgrade force. The forces F_d, F_a, and F_g are produced as shown in the model of Fig. 1 [4], where v_w is the wind gust speed, M is the mass of the vehicle and passenger(s), θ is the road grade, and C_a is the aerodynamic drag coefficient. The throttle actuator and vehicle propulsion system are modeled as a time delay in cascade with a first order lag and a force saturation characteristic. The following parameter values are adopted from [5]. However, some values need to be modified so that the block diagram could represent the same model with slightly different values just to provide computing and calculation challenges rather than reusing the identical values: C_1=743, T=1s, τ=0.2s, M=1500kg, C_a=1.19N/(m/s)^2, F_{dmax}=3500N, F_{dmin}=-3500N, and gravity constant g=9.8m/s^2.

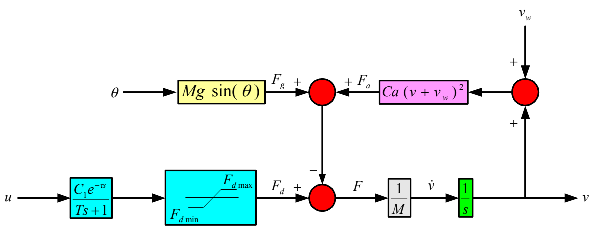

Fig. 1. Vehicle longitudinal by dynamic model

The controller design for this system begins by simplifying the model. Consider to sell all the initial conditions to zero. The same applies to the disturbance parameters. Hence, it is assumed is no wind gust and no grading exists during the movement of the car. Applying this zero initial condition to the block diagram, the model is left with the forward path and the unity feedback loop of the output speed. Since the state-variables have been chosen to be the output speed and the drive force, the corresponding state and output equations are found to be:

$$\dot{v} = \frac{1}{M}(F_d - C_a v^2) \tag{2}$$

$$\dot{F}_d = \frac{1}{T}\left(C_1 u(t-T) - F_d\right) \tag{3}$$

$$y = v \tag{4}$$

However, a problem of non linearity arises. There is a squared term in the equation (2). One way to overcome this problem is to linearize all of the state-equations by differentiating both left and right hand sides of the equations with M, C_a, C_1, T and v remain constant. After differentiating, the state-equations become

$$\frac{d}{dt}\dot{v} = \frac{1}{M}(-2C_a v\delta v + \delta F_d) \tag{5}$$

$$\frac{d}{dt}\dot{F}_d = \frac{1}{T}\left(C_1 \delta u(t-T) - F_d\right) \tag{6}$$

and the output equation becomes

$$y = \delta v \tag{7}$$

In the equation, δv means that the output is discrete and δF_d also means that drive force is discrete. The symbol v means the desired and $\delta u(t\text{-}\tau)$ is the time delay of the engine. Up to this point, both the state and output equations are written in time domain. The linearized model provides a transfer function can be obtained by solving the state-equations for the ratio of $\Delta V(s)/\Delta U(s)$.

$$\frac{\Delta V(s)}{\Delta U(s)} = \frac{\frac{C_1 e^{-\tau s}}{MT}}{\left(s + \frac{2C_a v}{M}\right)\left(s + \frac{1}{T}\right)} \tag{8}$$

Using the power series expansion approximation for the time delays, the time delay of the transfer function of the system is approximated to be

$$e^{-\tau s} \approx \frac{1}{1+\tau s} = \frac{\frac{1}{\tau}}{s + \frac{1}{\tau}} \tag{9}$$

Substitute this expression into the plant transfer function of

$$G_p(s) = \frac{\Delta V(s)}{\Delta U(s)} = \frac{\frac{C_1}{MT}}{\left(s + \frac{2C_a v}{M}\right)\left(s + \frac{1}{T}\right)\left(s + \frac{1}{\tau}\right)} \tag{10}$$

It is obvious that the system described by this transfer function is third order system, as a result of the time delay approximation. Despite of that, the transfer function has been successfully linearized. The upcoming calculation shall be as difficult as if the linearization has not been done. At least the complexity of the calculations should be reduced.

Hence, after substituting the values of the constants into equation (10), the final form of the linearized transfer function derived from the block diagram through state equation is shown below.

$$G_p(s) = \frac{\Delta V(s)}{\Delta U(s)} = \frac{2.4767}{(s+0.0476)(s+1)(s+5)} \tag{11}$$

The linearized system equations can also be represented in state-space form. This can be done by Linear Ordinary Difference Equation [7]. The state-space representation is shown in equation (12-13). The mathematical model in state space form is used to design the pole placement controller in the next section.

$$\begin{bmatrix} \dot{v}_1 \\ \dot{v}_2 \\ \dot{v}_3 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -6.0476 & -5.2856 & -0.238 \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 2.4767 \end{bmatrix} [\Delta u(t)] \tag{12}$$

$$y(t) = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix} \tag{13}$$

III. CONTROLLER DESIGN

The problem of cruise control system is to maintain the output speed v of the system as set by input signal base on the command signal v_R from the driver. Cruise controller design is applied assuming a single-loop system configuration with a linear model and nonlinear model, as shown in Fig. 2. The controller function $G_c(s)$ is designed to augment or modify the open-loop function in a manner that produces the desired closed-loop performance characteristics. The plant functions Gp(s) represent the actuators and the controller part of the system, and the plant parameters are determined primarily by functional aspects of the control task. Before make any decision of controller design, a few of design specification have been set. In this design, we take two considerations to be met which are settling time T_s less than 5s and percentage of overshot *%OS* is less than 10%. Controller designs are dividing into two sections such as design for linear model and design for nonlinear model. Linear model controllers are focused to three controller such as proportional-integral-derivatives (PID) controller, state-space controller and fuzzy logic controller. For nonlinear model, proportional-integral-derivatives (PID) with feedforward and feedforward-type PD controller are proposed.

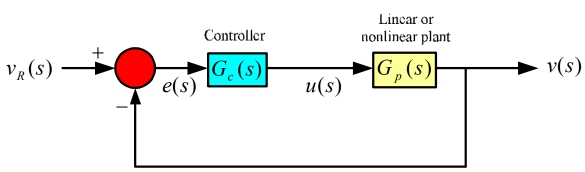

Fig. 2. The cruise control system configuration

Nonlinear model using PID controller is design of the controller has been based on use of the linearized model. Although a simple and quick check of the design, a more accurate simulation should be done by applying the controller to the original nonlinear model as shown in Fig. 3.

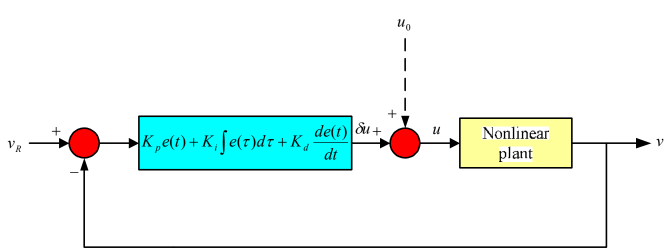

Fig. 3. PID control applied to the nonlinear plant

The practical issues need to be considered where controller is described by

$$\delta u(t) = K_p e(t) + K_i \int e(\tau)d\tau + K_d \frac{de(t)}{dt} \qquad (14)$$

which is design for a linearized small-signal model. When it is used to control the original plant, the nominal input u_0 must be reinserted to introduce the nominal throttle angle and velocity. With controller as described, the injection of u_0 can be accomplished by setting u_0 as the initial condition of the integrator when cruised control is initiated. In practice, the required nominal values are determined by the state of the vehicle at the moment when the cruise control is activated.

The basic concept of feedforward (FF) control is to measure important disturbance variables and take corrective action before they upset the process to improve the performance result. A feedforward control system is shown in Fig. 4, where disturbances are measured and compensating control actions are taken through the feedforward controller. Deviations in the controlled variables can be calculated as

$$\Delta v = G_p G_{ff} \Delta D + G_d \Delta D \qquad (15)$$

where G_p is the process transfer function model, G_d is the disturbance model, G_{ff} is the feedforward controller, u is a vector of the manipulated variables, and D is a vector of disturbances where D_1 and D_2 are disturbances from external system such as gravitational force and wind gust speed.

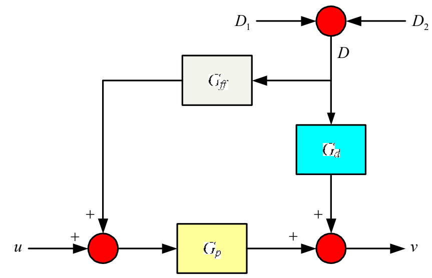

Fig. 4. A feedforward control system

In order to make Δv zero, a feedforward controller of the following form is designed. Supposed that,

$$G_d = \left(\frac{k_d}{\tau_d s + 1} \right) \qquad (16)$$

$$G_p = \left(\frac{k_p}{(\tau_{p1} s + 1)(\tau_{p2} s + 1)(\tau_{p3} s + 1)} \right) \qquad (17)$$

Then from equation (16-17), the ideal feedforward controller,

$$G_{ff} = -G_p^{-1} G_d = k_{ff} \left(\frac{(\tau_{p1} s + 1)(\tau_{p2} s + 1)(\tau_{p3} s + 1)}{(\tau_d s + 1)} \right) \qquad (18)$$

where feedforward controller gain is $k_{ff} = -k_d / k_p$. In process plant applications, G_{ff} is typically chosen to be of static form, and it is this approach that will be adopted in this project. The solutions of G_p refer process reaction curve method [4] and solutions of G_d refer equation (11). After simulate, if the performance of the system is not really good, the values of k_{ff}

will be tuned manually to get the best response where the value of feedforward controllers gain k_{ff1} and k_{ff2} are 0.5 and 1.

Add Feedforward-type PD Control (FFPD) control is a new technique to improve feedforward control is to measure important disturbance variables and take corrective action before they upset the process. Based on the model, the FFPD controller combined a feedforward path with the proportional-derivative (PD) control inside feedforward controller G_{ff}. To cooperate with the feedforward action, a PD mode was applied for small error conditions to eliminate the steady state offset. To design the FFPD, the process and to get the value of k_{ff} in FF are applied to K_{P1} and K_{P2}. The values of K_D will be tuned manually to get the best response where the both K_{D1} and K_{D2} are 1.

IV. Result and Analysis

A. Comparison Results for Linear Model

To perform comparison between controller design for linear model cruise control system, one of the first things that must be done during controller design is deciding upon a criterion for measuring how good a response is. However, in dynamic systems where the transient behaviour is also important, it becomes important to introduce several other criterions. Fig. 5 shows the overall step responses of the velocity (m/s) versus the time (s) are compared. The most common are compare the percent overshoot *%OS*, peak time T_P, settling time T_S, rise time T_R and the percent steady state error ($\%e_{ss}$) to know the stability of the system. All the specifications values of the responses are summarized in Table 1. By comparing the characteristics of proportional-integral-derivatives (PID) controller, state space controller and fuzzy logic controller, fuzzy logic controller is more stable than proportional-integral-derivatives (PID) controller and state-space controller.

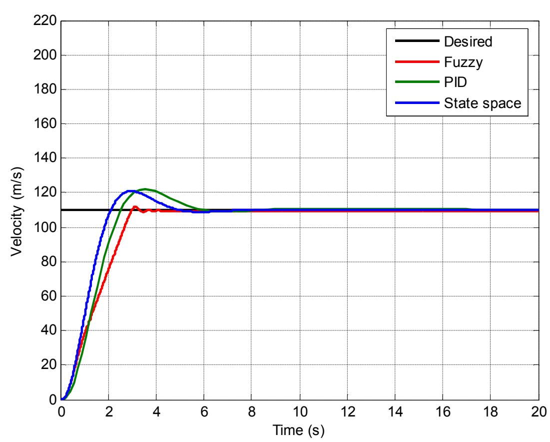

Fig. 5. Comparison of the overall controller responses

TABLE 1

Specifications	Controller		
	PID	State Space	Fuzzy Logic
Percent Overshoot (*%OS*)	10.2%	10%	1.91%
Peak Time (T_P)	3.54s	2.97s	3.16s
Settling Time (T_S)	5.5s	5s	3.37s
Rise Time (T_R)	1.7s	1.38s	2.21s
Percent Steady State error ($\%e_{ss}$)	0.01	0.01	0.01

B. Comparison Results for Nonlinear Model

The original non-linear model provided the realistic scenario. By comparing the results presented in Fig. 6 and Table 2 where compare the percent overshoot *%OS*, peak time T_P and settling time T_S to know the stability of the system. It is noted that the performances to original nonlinear model (PID), modified by adding the feedforward (FF) and adding the feedforward-type PD (FFPD) respect to any possible disturbance occurred. Without adding feedforward, the percentage overshoot for jerking are big and settling time also increase compared adding the feedforward controls. Clearly, the advantages of feedforward-type PD are it can decrease the jerking and provide better result in terms of performance.

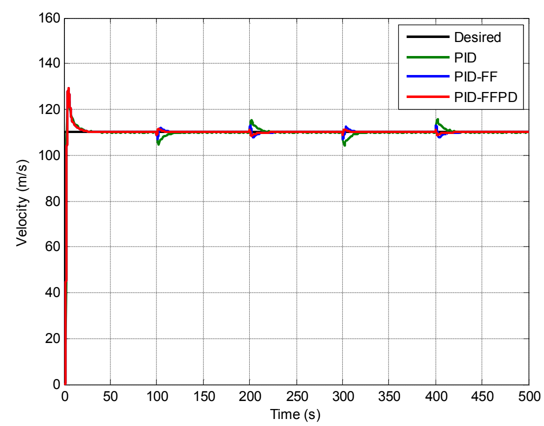

Fig. 6. Comparison of without feedforward controller and adding feedforward controllers responses

V. Conclusion

The mathematical model for cruise control system has been derived successfully. The plant is consists of two plant which are linear model and nonlinear model. Several controller of conventional, modern and intelligent scheme have been successfully designed to control the cruise control system. However, the analysis results had shown that to achieve better simulation result, a controller has to be applied to the nonlinear model. This method will lead to real performance of the system in actual condition. On the other hand, if just compared on the controllers design only it will not give a good result and valid because each controller have their own tuning method. And there is a possibility where by using only one suitable controller, we can achieve the desired output and response. That why, the analysis is focused on a nonlinear system with one PID controller. The feedforward (FF) and feedforward-type PD (FFPD) also included for further study and to compare the operation of the system when disturbance occurred.

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Table 2

Specifications		Disturbance			
		Wind gust speed		Gravitational force	
		Increase	Decrease	Increase	Decrease
PID	Percent Overshoot (*%OS*)	-5%	4.55%	-5.64%	5.64%
	Peak Time (T_P)	102.20s	202s	301.90s	402.10s
	Settling Time (T_S)	132.50s	232s	336.50s	436.40s
PID-FF	Percent Overshoot (*%OS*)	-2.27%	2.64%	-2.73%	2.82%
	Peak Time (T_P)	100.80s	201s	300.80s	401.10s
	Settling Time (T_S)	125.60s	224.60s	331.70s	432.30s
PID-FFPD	Percent Overshoot (*%OS*)	-1%	1.09%	-1.18%	1.18%
	Peak Time (T_P)	100.30s	201.20s	301.90s	402.40s
	Settling Time (T_S)	121.90s	222.40s	325s	425.10s