Modeling and Control of an Electronic-Vacuum Booster for Vehicle Cruise Control

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A mathematical model and control laws for an Electronic-Vacuum Booster (EVB) for application to vehicle cruise control will be presented. Also this paper includes performance test result of EVB and vehicle cruise control experiments. The pressure difference between the vacuum chamber and the apply chamber is controlled by a PWM-solenoid-valve. Since the pressure at the vacuum chamber is identical to that of the engine intake manifold, the output of the electronic-vacuum booster is sensitive to engine speed. The performance characteristics of the electronic-vacuum booster have been investigated via computer simulations and vehicle tests. The mathematical model of the electronic-vacuum booster developed in this study and a two-state dynamic engine model have been used in the simulations. It has been shown by simulations and vehicle tests that the EVB-cruise control system can provide a vehicle with good distance control performance in both high speed and low speed stop and go driving situations.

Key Words : Cruise Control, Electronic-Vacuum Booster, Distance Control, Stop and Go

1. Introduction

Driver assistant systems currently under development by most automotive manufacturers and recently commercialized by several companies are Intelligent Cruise Control (ICC) systems and Stop and Go (S&G) Systems. Because the increasing traffic density rarely makes it possible to drive at a pre-selected speed, cruise control systems for passenger cars are becoming less and less meaningful. The ICC and S&G systems control both speed and distance to preceding vehicles and can both improve the driving comfort and reduce the danger of rear-end collision. Although ICC systems are already commercially available, the bandwidth of such systems is very low and the headway distance (the safe vehicle-to-vehicle distance to avoid collisions) is large. Therefore, these systems are almost useless on the busy urban traffic highway, and it is concluded that the bandwidth of the longitudinal vehicle control system should be increased significantly to reduce the headway distance and to be meaningful in the busy urban traffic highway. So vehicle cruise control systems with S&G systems extend the ICC systems. Vehicles with S&G can follow other cars in dense traffic while keeping a safe distance at low velocities.

There have been many attempts to apply PID-type control laws (Fujioka et al, 1995 ; Germann et al, 1995) in the development of ICC. Gain scheduling and adaptive control schemes have been used in ICC development to meet the various situations encountered by the controlled vehicle (Gortan et al, 1995 ; Hedrick et al, 1991). Linear Quadratic (LQ) and Linear Quadratic Gaussian (LQG) optimal control theories have been used to develop a car following algorithm

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(Hedrick, 1993; Kanellakopoulos et al, 1996; Kyongsu et al, 2000). Sliding control has been used for vehicle longitudinal control to deal with nonlinearities in vehicle dynamics (Hedrick et al, 1991). A neural net has been used to compute the desired vehicle acceleration for ICC (Muller et al, 1992). Fuzzy logic has been used in ICC development by Fiat and Dimler-Benz AG as part of the PROMETHEUS program (Kett et al, 1995). It was indicated that a linear PID-controller could not provide satisfactory performance because the controller was not able to handle the noisy sensor data, resulting in a jerky driving behavior (Germann et al, 1995).

This paper describes modeling and control of a solenoid-valve-controlled electronic vacuum booster (EVB). A nonlinear computer model for the electronic vacuum booster has been developed and the model has been validated by vehicle tests. Simulations were performed using a complete nonlinear vehicle model and experimental studies have been done using a test vehicle.

2. Modeling of an Electronic-Vacuum Booster (EVB)

Brake system models are essential in controller development and simulation for vehicle cruise control. Figure 1 shows a schematic diagram of a brake system with the EVB. The vacuum booster uses the negative pressure generated in the engine intake manifold to amplify the force produced at the brake pedal. This is achieved by the use of two air chambers separated by a diaphragm. One of the chambers (vacuum chamber) is connected to the intake manifold and the other chamber (apply chamber) can be connected to the atmosphere or the vacuum chamber. The pressure difference between the two chambers applied over the surface of the diaphragm provides the amplified brake force (Yi, et al, 2000). The EVB consists of the ordinary vacuum booster and a PWM solenoid-operated pneumatic valve. The pneumatic valve controls airflow passage.

Figure 2 shows schematic diagrams of the pneumatic valve. In Fig. 2, P, F, M, K, z indicate pressure, friction force, mass, spring stiffness and displacement, respectively. The subscripts, "a", "A", and "v", indicate the atmosphere, the apply chamber, and the vacuum chamber, respectively. Also Fig. 2 shows four stages of the EVB control valve. Under normal operation, the vacuum booster is in the "release" stage. In this stage the two chambers are connected and thus the booster applies no force to the master cylinder. As the

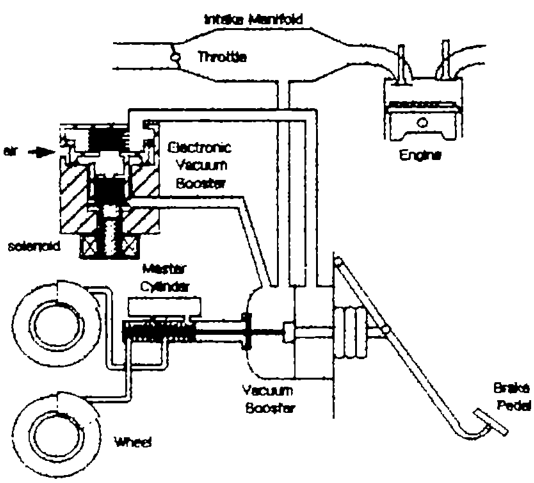


Fig. 1 Schematic diagram of an EVB controlled brake system

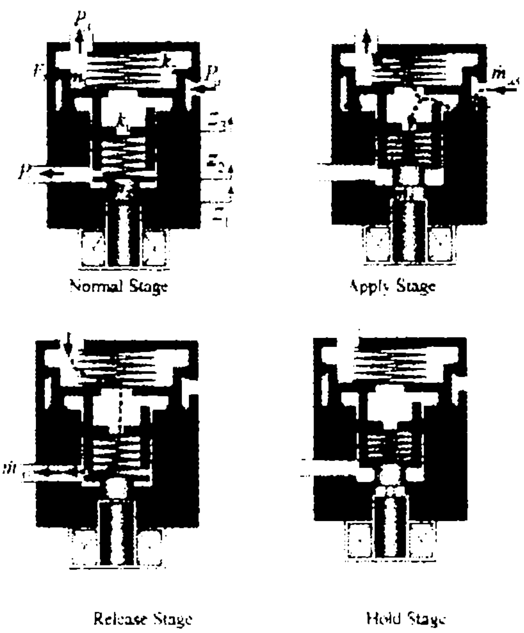


Fig. 2 Operational stages of the EVB control valve

PWM control input is applied to the solenoid, the pneumatic valve seals the flow passage between the two chambers and opens the apply chamber to atmospheric pressure ("Apply stage"). As the air flows in to the apply chamber, the apply chamber pressure increases and the flow passage between the apply chamber and the atmosphere is closed due to the pressure difference created across the masses m_2 and m_3 ("Hold" stage). The hold stage implies that the force created by the solenoid and the force created by the pressure difference across the masses m_2 and m_3 are in equilibrium. Therefore, the force created by the vacuum booster is proportional to the duty input to the PWM solenoid.

Since the EVB uses the negative pressure generated in the engine intake manifold, the differential pressure in the EVB may have different values for the control input depending on the engine intake manifold pressure. Two state engine model has been used to simulate the EVB controlled brake system. Figure 3 shows a schematic of two-state engine model. Two states are the intake manifold pressure (P_m) and the engine angular velocity (ω_e).

Intake manifold pressure is caused by air mass flow from throttle and vacuum chamber of EVB. Pressure change rate can be written as follows.

$$\dot{P}_m=\frac{RT_m}{M_{air}V_m}(\dot{m}_{ai}+\dot{m}_{vm}-\dot{m}_{ao}) \quad (1)$$

where $\dot{m}_{ai}=MAX\cdot TC\cdot PRI$ (2)

MAX = The maximum air mass flow rate into manifold

$$TC=\begin{cases}1-\cos(1.14459\alpha-1.0600) & (\alpha<79.46^\circ)\\ 1 & (\alpha\geq 79.46^\circ)\end{cases} \quad (3)$$

$$PRI=1-\exp\left(9\cdot\left(\frac{P_m}{P_{atm}}-1\right)\right) \quad (4)$$

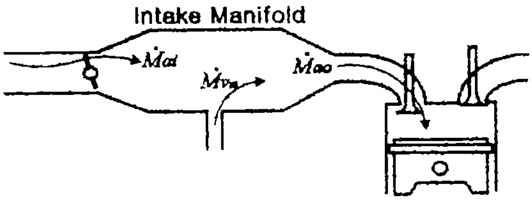


Fig. 3 Two state engine model

$\dot{m}_{vm}$ = Air mass flow rate from vacuum chamber to manifold

Another state is engine angular velocity, it can be written as follows.

$$J_e\dot{\omega}_e=T_i-T_f-T_p \quad (5)$$

where T_i = Indicated Torque, T_f = Friction Torque, T_p = Pump Torque

3. Experimental Evaluation of the EVB Model of the Brake Actuator

The EVB model has been validated by experiments. Figure 4 shows a comparison of simulation with experimental step responses. Simulations have been performed using the EVB model and the two state engine model. Simulated differential pressures of the EVB for various duty ratio to the solenoid are compared to the actual measured differential pressures. It has been shown that the simulation results are quite close to the experimental results.

Figure 5 shows displacements of the masses, m_1, m_2 m_3 of the EVB for 60% duty ratio to the solenoid. As the current in the coil increases, the airflow passage between the apply chamber and the vacuum chamber is closed, i.e. the gap between the mass m_2 and m_3($z_{g2}=0$). Then, the airflow passage between the atmosphere and the apply chamber is open, i.e., $z_3>0$("Apply" stage). As the air flows in to the apply chamber, the pressure at the apply chamber increases. The pressure difference between the apply chamber

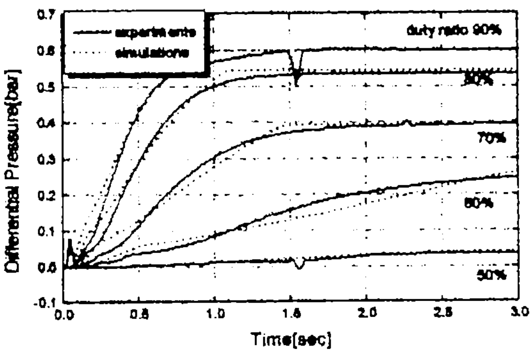


Fig. 4 A comparison of simulation with experimental results

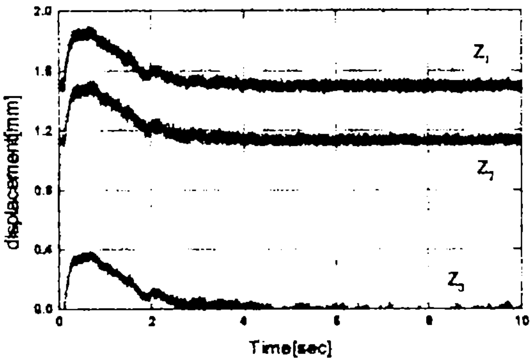
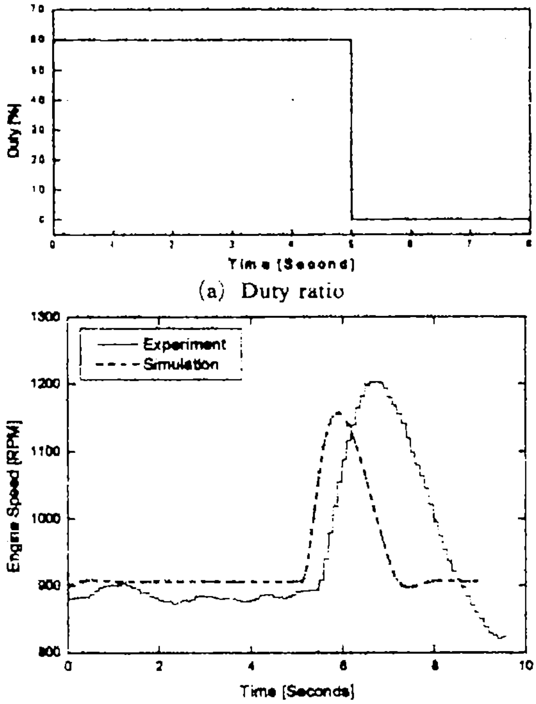


Fig. 5 Displacements of the masses, m_1, m_2 and m_3, of the EVB for 60% duty ratio to the solenoid

and the vacuum chamber moves back the masses and all the airflow passages are closed ("Hold" stage). As illustrated, it takes about 3 seconds from the apply stage to the hold stage in the case of 60% duty ratio. As illustrated in Fig. 4, the time constant of the differential pressure step response varies depending on the duty ratio. This is largely due to the friction forces and the time constant significantly decreases as the duty ratio increases.

Simulations and experiments have been performed to investigate the interaction between the engine and the EVB. Figure 6 shows the effect of the EVB actuation on the engine. It has been observed in the vehicle tests that the engine RPM increases after the EVB actuation. This is due to the airflow from the apply chamber to the engine intake manifold. Simulation and tests have been done for 60% duty input at the engine idle speed. The duty input was changed from 60% to 0% at 5 seconds. As the duty input is set to zero, the air in the apply chamber flows into the engine intake manifold ("Release" stage) and the intake manifold pressure increases. The engine RPM then increases for few seconds and goes back to the idle speed.

In order to develop a vehicle cruise control law, we should know the response characteristics of an EVB. Because the vacuum chamber is connected to the intake manifold, a brake force depends on the intake manifold pressure. Figure 7 shows change in differential pressure with a variation of intake manifold pressure under the 50% duty ratio input.



(a) Duty ratio

(b) Engine speed

Fig. 6 Engine RPM changes after the EVB actuation : simulation and experiment

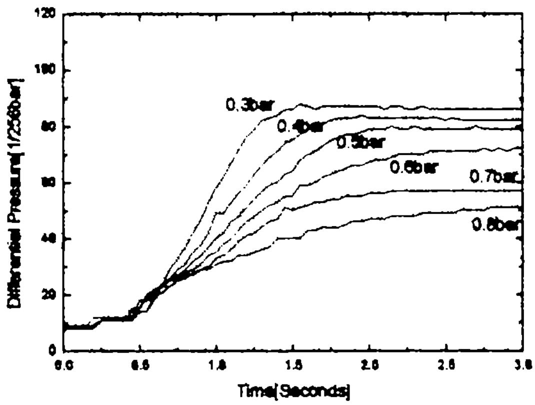


Fig. 7 Differential pressures with change of intake manifold pressure

4. Control Laws for Vehicle Cruise Control

Vehicle longitudinal control is an essential part of the ICC and the Stop-and-Go systems. Figure 8

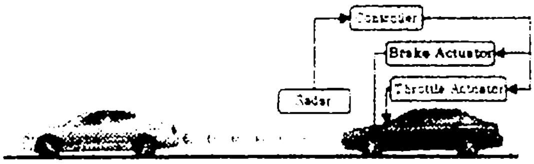
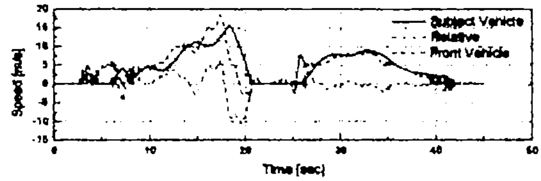


Fig. 8 Vehicle cruise control system

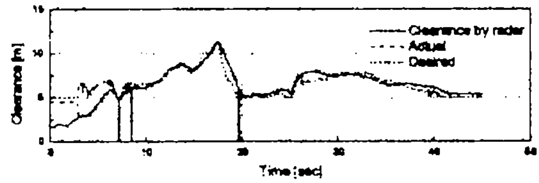
shows a vehicle longitudinal control system. The system consists of a radar sensor, a controller (ECU), a brake actuator (the EVB) and a throttle actuator.

The throttle and brakes should be gently controlled so that the driver is aware of activation of cruise control without being surprised by this action. It has been reported that automotive decelerations up to 2.5 m/sec^2 were comfortable to human passengers (Goldman et al, 1998). The vehicle-to-vehicle distance control algorithm has been so designed that the vehicle deceleration should not exceed this limit. The maximum the vehicle acceleration is limited to 1 m/sec^2 in order to prevent kick-down of the automatic transmission.

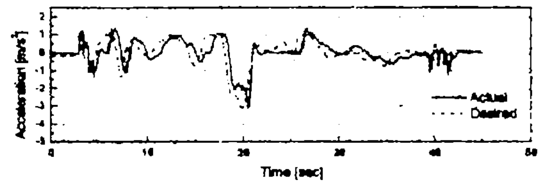
The distance to a preceding vehicle and the relative velocity are measured using a MMW radar sensor. Comparison of the headway distance with the distance to the preceding vehicle is used to determine control mode between the speed control and the distance control. In the case of speed control, the controller works like a conventional cruise control. The controller controls the throttle and brakes such that the vehicle acceleration tracks the desired acceleration, which is designed so that the vehicle-to-vehicle distance converges smoothly to the headway distance.



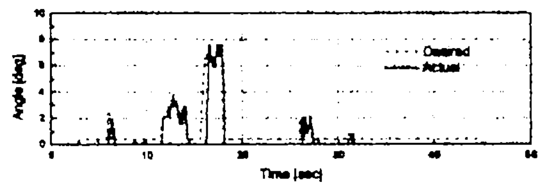
(a) Preceding and controlled vehicle speeds



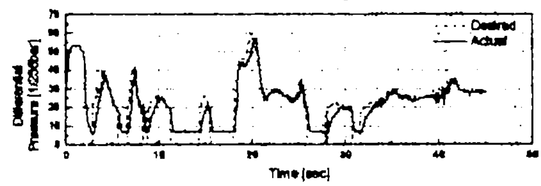
(b) Clearance



(c) Acceleration



(d) Throttle angle



(e) Differential pressure

Fig. 9 Experiment results of vehicle cruise control

5. Vehicle Test Results

Vehicle tests have been done to evaluate the performance of the vehicle cruise control system including the EVB. Vehicle tests have been conducted using a test vehicle, a 2000 cc passenger car equipped with a MMW radar distance sensor, a controller, an EVB brake actuator and a step motor controlled throttle actuator. The differential pressure, p_d, of the vacuum booster was controlled by a PWM solenoid valve. A pressure sensor was installed on the EVB to measure the differential pressure and the measured pressure was used as the feedback in the brake control. The already existing wheel speed sensors, engine RPM sensor, and a Throttle Position Sensor (TPS) have been used to estimate the vehicle accelerations and to implement the control laws.

Vehicle distance control tests were done using two vehicles : a controlled vehicle and a preceding vehicle. Figure 9 shows the test results : the controlled and the preceding vehicle speeds, the headway (desired) distance and the vehicle-to-vehicle clearance, a comparison of the desired acceleration with the actual acceleration, a comparison of the desired with actual throttle angles and a comparison of the desired with actual differential pressures of the EVB.

The preceding vehicle has various speed changes that at the beginning, a sinusoidal increasing speed and then, suddenly reduce the speed and increase the speed. It is illustrated that the vehicle acceleration tracks the desired acceleration very closely. Also vehicle speed and clearance smoothly track the preceding vehicle speed and the headway distance.

6. Conclusions

A mathematical model and test results for an Electronic-Vacuum Booster (EVB) for application to vehicle cruise control have been presented. The performance characteristics of the EVB and brake actuator have been investigated using the simulation model and vehicle tests. The performance of the EVB-cruise control system was investigated via simulations and vehicle tests. A vehicle equipped with a MMW radar sensor, a stepper-motor-throttle actuator, an EVB brake actuator, and a controller have been used for vehicle tests. It has been shown via the simulations and the vehicle tests that the EVB-cruise control system can provide a vehicle with good distance control performance. The control gain has been tuned so that the throttle and brakes were gently controlled and the driver is not surprised by the control action.

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