A development of electromagnetic retarder controller to stabilise vehicle speed by using PWM technique

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Abstract: Deceleration of heavy vehicles on long downhill runs is an important problem. Because of heavy loads, they have a huge amount of kinetic energy to be absorbed. Electromagnetic retarders are widely used on heavy vehicles owing to low operating and maintenance costs. In this study, a braking control system that can be easily applied to existing electromagnetic retarders of vehicles was designed and tested experimentally. The goal of the proposed system is deceleration of the vehicle and stabilisation of the speed at a desired value by using an electromagnetic retarder. To achieve this goal, a closed-loop pulse width modulation (PWM) braking controller was designed. For the experiments, an experimental set-up consisting of an electromagnetic retarder and an engine was built. As a result of experiments, the engine running at a constant speed was decelerated in a controlled manner with a 4% steady-state error according to setpoint values.

Keywords: electromagnetic retarder; PWM; pulse width modulation; PID controller; speed stabilisation; heavy vehicle.

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1 Introduction

Electromagnetic retarders (ER) are auxiliary safety equipments that enhance driving safety during the braking with supporting the most important safety equipments service brakes. Besides safety braking, they reduce maintenance costs by extending the life of service brakes. They provide extra safety working with the other braking support units like anti-lock braking system (ABS) during emergency braking. Because of their frictionless working principle, electromagnetic retarders do not require short-term periodic maintenance and are widely used on vehicles having high kinetic energy, such as trucks and coaches.

In the literature, it is possible to find many studies related to braking performance of ERs. These studies are mainly interested in ERs' structural parameters to enhance braking ability and mostly consist of three-dimensional finite element method (3D FEM) analysis. For example, in the research by Long and Li (2009), magnetic field intensity of air-gap was studied. Ihm et al. (2008) found that slit construction of rotor disk has a tendency to reduce the braking torque. Long et al. (2009) investigated the effects of air-gap, number of coil windings and excitation current to the braking torque of ER. Ying et al. (2010) investigated the effect of rotor thickness to braking torque. Kim et al. (2003) proposed a layered rotor structure to obtain constant braking performance. This rotor structure consists of two different materials. According to these studies, the parameters related to ERs' braking performance can be described as rotor material, rotor structure, air-gap between poles and rotor disk, number of coil windings and excitation current of coils. Except excitation current, all of these parameters consist of ER's structural properties and cannot be adjusted on vehicle during operation.

Existing ER manufacturers also produce controller units for their products. To examine these control units, a number of local authorised technical services of heavy vehicles were visited by the authors. The examinations implemented at these technical services show that these controller units mostly consist of electromechanical relays or semiconductor electronic components. The control signal for ER is produced by a

multi-position electro-mechanic lever switch or a foot pedal at driver's cab. Using these control units, the braking has been provided in stages. According to the lever switch position, the relays in control unit are activated and coils of the ER are energised in pairs. With the increase in lever position, a couple of coils are energised in addition to the previously energised group. Because of the number of ER coil pairs, amount of braking can be adjusted only in 3 or 4 stages. By using this type of controller unit, braking ability of ER has been restricted according to lever arm position and the vehicle's speed cannot be controlled effectively. Furthermore, the driver has to control the amount of braking, continuously. As a result, driving comfort is badly affected.

As it has been discussed, the braking torque is related to the coil current. The structure of the coils is related to coil diameter, number of windings, wire diameter and material (copper or aluminium), and they are predetermined depending on ER's braking torque. Because of this, resistance value of the coils is constant. By varying the voltage value obtained from the vehicle's battery within the range of 0–24 Vdc, coil currents can be adjusted. In this way, it is also possible to adjust braking torque of the ER.

Nowadays, a well-known technique called the PWM technique is applied effectively to DC motor speed controlling applications. For example, Olden et al. (2001) proposed a computer-based open-loop PWM speed controller for DC motors. Liu and Jiang (2011) studied a microcontroller-based PWM speed controller for small DC motors. As it is described by Bolton (2003), PWM is a technique that controls the average voltage by dividing constant voltage into pulses of a square wave. If active duration of the pulse, the so-called Duty Cycle, is changed as a percentage of the period, average voltage of the square wave also changes. By using PWM technique, if the average voltage is adjusted, coil currents are adjusted, as well. Thus, braking torque of the ER is adjusted.

On the other side, PWM technique can be combined with various closed-loop control algorithms. In the literature, there are many application examples according to this like DC motor speed and position controlling. For example, a speed controller for a brushless DC motor using PWM–proportional derivative integral (PID) control combination was represented by Yang et al. (2012). Also, a similar approach was implemented by Zhou (2008). Furthermore, most of the industrial motor controlling devices are based on PWM and closed-loop control algorithms with encoder feedback.

In the literature, it is possible to find various closed-loop braking control applications of ERs. One of the best of them was designed by Anwar (2003). In his work, the rotor speed and retarder coils current were used as feedback data for estimation of braking torque of ER. According to estimated and desired torque values, the proposed controller calculates the necessary excitation current of the ER. Similar to the other closed-loop control systems, his study also aims for shortening the response time with stable behaviour of the controller.

In conventional PID closed-loop control applications, PID gains are tuned for the fastest response time. In some situations, this may lead to unstable behaviour of controller. It is essential in the emergency braking situations that the vehicle must be slowed down or stopped in the shortest time. But, for the comfort-purposed applications like speed stabilising, it is possible to make concessions in fast response characteristic. In speed stabilisation applications, first, vehicle speed is lowered by using the engine or service brakes to a desired speed value and the controller is engaged. According to this, the controller designed in this study increases the applicability of PID controller and provides the prevention of unstable situations by extending the response time. Thus, the

controller is simplified by eliminating the need for a comprehensive controller, which requires additional information from the other systems like engine brake or gearing sensors.

In this study, an experimental system was developed to control heavy vehicles' speed by adjusting ER's braking torque. According to RPM value, the braking torque has been adjusted by the system, and using PWM technique, speed of the engine has been set at desired value. Speed data obtained from engine has been evaluated at PC-side control software using a PID control algorithm. As an output of the software, a PWM duty cycle to control ER's braking has been produced. Hence, the speed of the engine is decreased to desired setpoint. As a result of experiments, the engine speed has been reduced in a controlled manner with a 4% steady-state error according to setpoint values.

2 Controlled braking at long downhill

When heavy vehicles go downhill, they continuously tend to accelerate owing to the gravity according to their load. So, regularly braking of the vehicle is necessary and the vehicles speed should be kept in a safe range. At this point, ERs play an important role to brake the vehicle safely. In existing ER-based braking systems, braking control is driver dependent. If the driver wants to decelerate the vehicle, ER is switched on. If the vehicle slows down extremely, the driver switches off the ER. This kind of controlling method can be considered as an open-loop control system; therefore, the vehicle's speed changes continuously. As a result, the driver would be occupied with braking tasks and driving comfort is reduced.

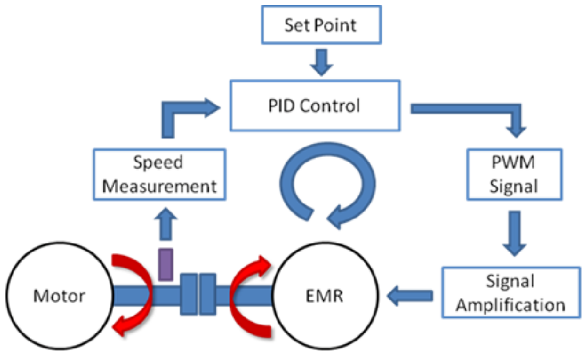
ER's braking torque is related to excitation current. By adjusting coil currents using a closed-loop control algorithm, the braking torque of ER can be adjusted. Thus, the driver will only be responsible for setting the speed parameter according to road slope and engaging the controller. If the speed is higher than the desired level, braking amount of ER is increased by the controller until the speed is stabilised at the desired level. If the speed is lower than the desired value, the vehicle will accelerate until desired speed is obtained by lowering the braking amount of ER. By using this kind of a control system, the vehicle will be slowed down in a controlled manner, and the braking will only be controlled by the driver in emergency situations.

3 Experimental set-up

For the experiments, an ER consisting of six coils and able to provide 100 Nm braking torque at 24 Vdc was designed and produced. The ER is joined to an internal combustion (IC) engine using a coupling. The experimental set-up also includes an electrical panelboard, signal amplification unit, a speed sensor, a DC power supply, current sensor and a load-cell attached to ER's stator.

Block diagram of the ER control system is shown in Figure 1. The speed data measured from the IC engine's shaft is used as a feedback to PID control algorithm. As an output of the controller, a PWM duty cycle value is produced. After the amplification of the PWM signal, braking torque of the ER is adjusted by changing the excitation voltage of ER's coils according to PWM duty cycle.

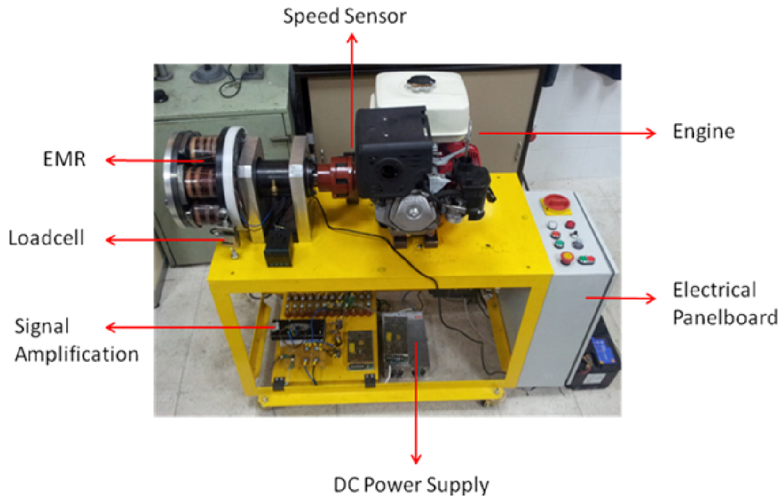
Figure 1 Block diagram of the ER control system (see online version for colours)



3.1 Mechanical design

The stator of the ER was mounted to body of the set-up using roller bearings and carriers. Besides, the stator was mounted to body using a load-cell, which prevents rotation of the stator owing to opposing forces caused by eddy currents. By using this load-cell, braking torque measurements can also be achieved. The rotor carrier shaft was placed at the centre of the stator with roller bearings and the other side of the shaft was mounted to IC engine's crankshaft using a coupling. An inductive sensor for speed measurement was mounted to the body of the set-up near the coupling. The experimental set-up is shown in Figure 2.

Figure 2 Experimental setup (see online version for colours)



3.2 Electronic design

PWM signal, which adjusts the ER's braking, was produced by a DSPIC30F series microcontroller from microchip and able to provide 16-bit PWM output. PC-side control software produces the commands required to obtain desired duty cycle of PWM signal and sends them to the microcontroller unit (MCU).

To amplify transistor–transistor logic (TTL)-level PWM signal produced by MCU, a mosfet-based signal amplification circuit was designed. The circuit amplifies the high level of TTL voltage to 24 Vdc, and it is able to provide 60 A to ER. The circuit also provides optical isolation between MCU and high current side of the set-up.

The speed measurement unit consists of Microchip PIC18 series microcontroller and an inductive sensor with level converter circuit. The inductive sensor, which was used for speed measurement, produces a 24 Vdc output signal per rotation of the engine. The signal level is converted to TTL level by using an optocoupler.

Braking torque was measured using a USB data acquisition board (USB-6008) from National Instruments. By means of a load-cell signal amplifier, the force signal produced by load-cell is amplified within a range of 0–10 Vdc. The output voltage of the load-cell amplifier is digitised by analogue input of USB-6008 to calculate the ER's braking torque.

3.3 Software design

The system has been basically controlled by a personal computer (PC)-side software. The speed data used as controller feedback and the PWM signal were obtained by using two different MCU software. First, PC-side software collects the speed data from MCU over RS232 bus. Then, PWM duty cycle value required to brake the ER is calculated according to setpoint. Finally, the calculated value is sent to the other MCU over RS232 bus.

Microcontroller software flow charts used for speed measurement and PWM signal generation are shown in Figure 3. The speed measurement is implemented by using capture module of the MCU. The time between two pulses of the sensor is measured and the engine speed is calculated. Finally, the speed data is sent to PC-side software over RS232.

The PWM signal is generated by using the PWM module of the second MCU. PC-side software sends the PWM duty cycle value to the MCU over RS232. When the data arrives in MCU, an interrupt is produced. Inside the interrupt subroutine, the data is analysed. If there is no error, the data is saved to a variable. Then, another variable, the so-called (Data_OK), is set to 'True' to inform the main program that the data was arrived. Inside the main program, Data_OK is checked continuously. If it was set, the calculations are performed to generate desired PWM duty. Then, PWM output is updated and Data_OK is set to 'False' to wait for new PWM duty data from PC.

To stabilise the engine speed at a desired setpoint, a control and data acquisition software, which runs at PC side, was designed as shown in Figure 4. The software was coded in LabVIEW graphical programming language from National Instruments.

The PC-side software gets the speed data over RS232 bus and processes it using a PID algorithm. According to working frequency and hardware specifications of the MCU, the PWM duty cycle is set by an integer value between 0 and 8000. So, the controller output is limited to the range 0–8000. Here, a value of 8000 denotes 100% PWM duty cycle. Output of the controller is sent to MCU, which generates the PWM signal over RS232 data bus again. At the same time, the software records the speed of engine, braking torque and total coils current of ER, calculated PWM duty (controller output) at 50 ms intervals.

Figure 3 Speed measurement and PWM output software flowcharts (see online version for colours)

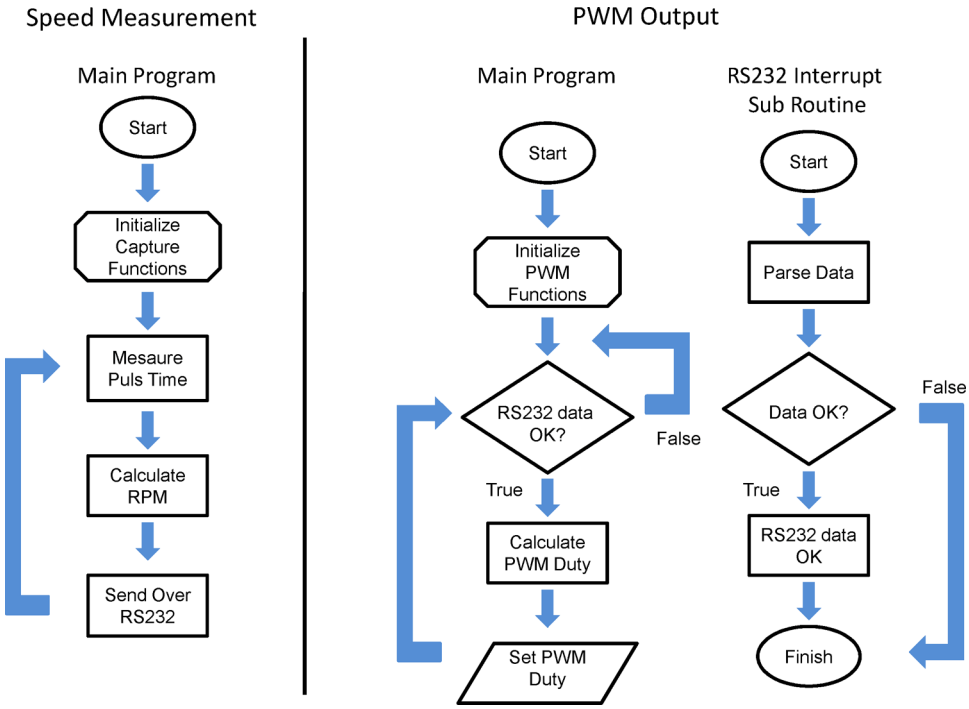
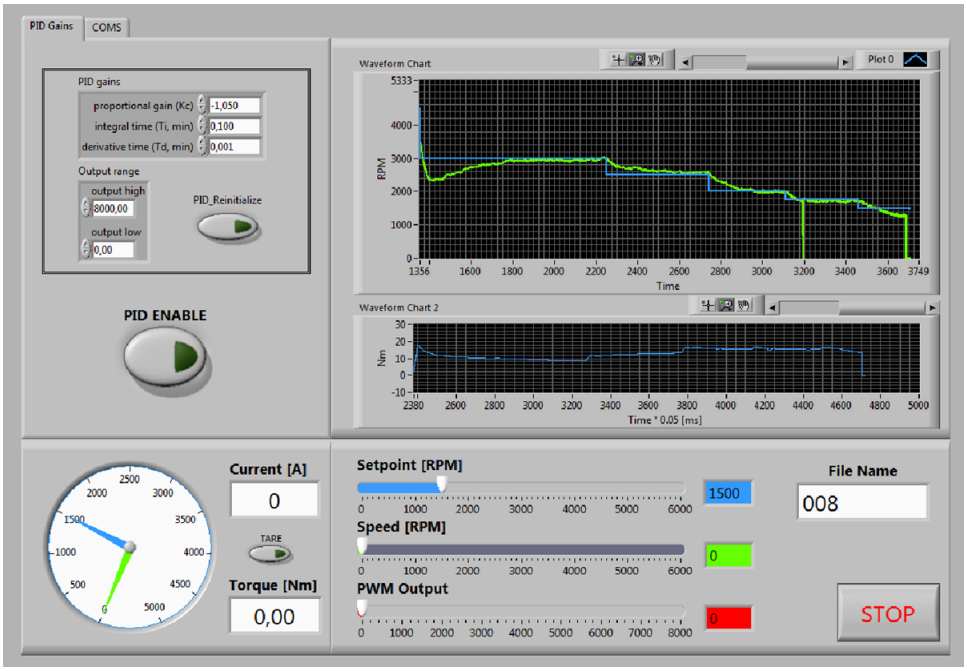


Figure 4 Control and data acquisition software interface (see online version for colours)



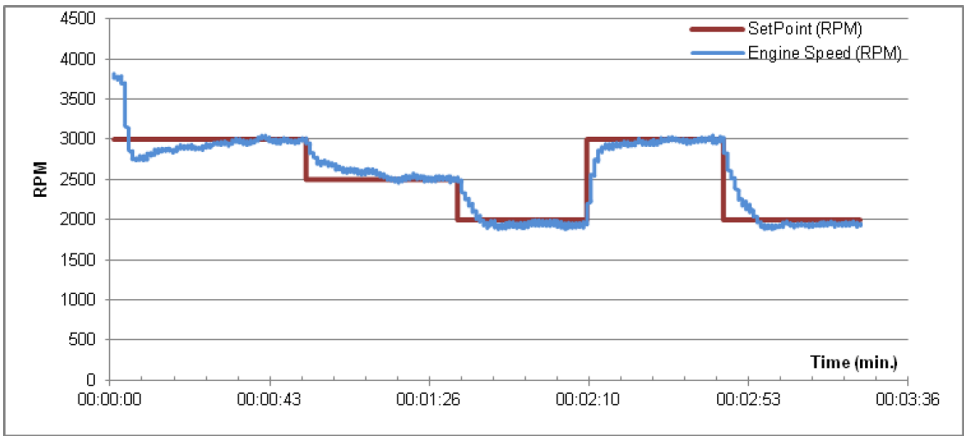
4 Experimental results

During the experimental tests, the engine speed was set to 3750 rpm using the throttle. While the control algorithm was enabled, responses of the system at different setpoint values were investigated. Setpoint values were arranged to 3000, 2500, 2000, 3000 and 2000 rpm, respectively. PID gains of the system were tuned manually. The control loop was executed at 50 ms intervals and the measurement data were recorded at the end of each cycle.

Figure 5 shows the graph of engine speed according to setpoint values. It can be seen from Figure 5 that the system has low overshoot and a settling time of 10 s. When the slowing down of a vehicle with a high deceleration that affects the driving comfort badly is considered, the system has a proper settling time for a braking, which does not require sudden speed change. As the settling time period is reached, a steady-state error of 4% with respect to the setpoint values was obtained. The steady-state error is very low with respect to conventional control systems of ER and does not affect driving comfort negatively.

Figure 6 shows the PWM output of the controller over time owing to setpoint values. It has been discussed before that PWM output of the controller is limited in the range 0–8000. When the controller is enabled, the output of the controller rises suddenly to 4000, and then, slowly decreases to stabilise the engine speed at the setpoint. With the change of setpoint values, the controller's output shows sudden changes; but, it never reaches the maximum value of the output.

Figure 5 Engine speed graph vs. setpoint values (see online version for colours)



The power supply of ER provides 24 Vdc. When the PWM signal is in 100% duty cycle, it means the coils are excited with 24-Vdc voltage. During the experiments, the excitation voltage of the coils was reached 12 Vdc according to PWM duty cycle.

Coils of the ER consume totally 16 A of current at 24 Vdc. Figure 7 shows measured current consumption of ER. By enabling the controller, the current value rises to a maximum of 8 A. Then, it slowly changes until the engine reaches to a desired speed value. When the setpoint value changes, coils current makes a sudden change, too. But, it is less than that of the traditional controlling technique. It can also be seen in Figure 7 that consumed current stays under 8 A. Thus, the ER does not operate at full load.

When the coil current changes, the braking torque amount of the ER also changes. Figure 8 shows braking torque change of the ER during experiments. When the desired setpoint speed is achieved, the braking torque is stabilised to preserve steady speed of the engine.

Figure 6 PWM output of the controller (see online version for colours)

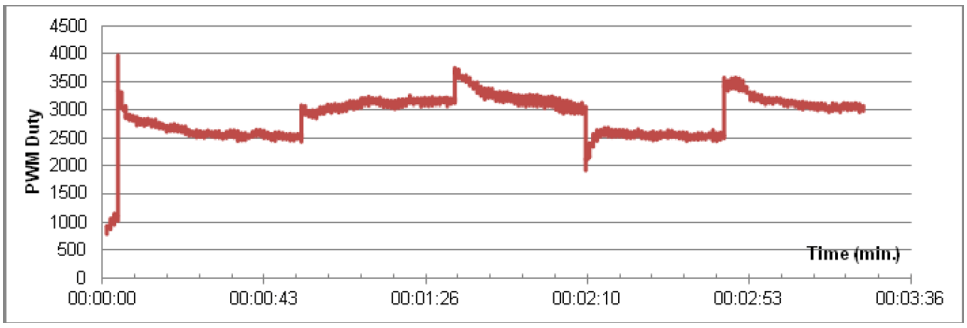


Figure 7 Current consumption of ER (see online version for colours)

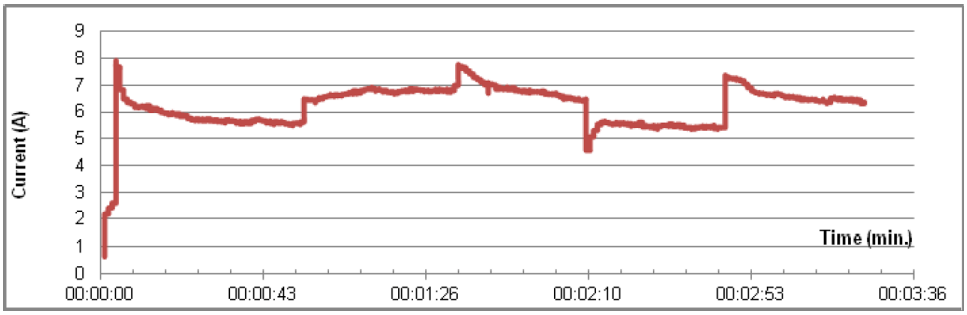
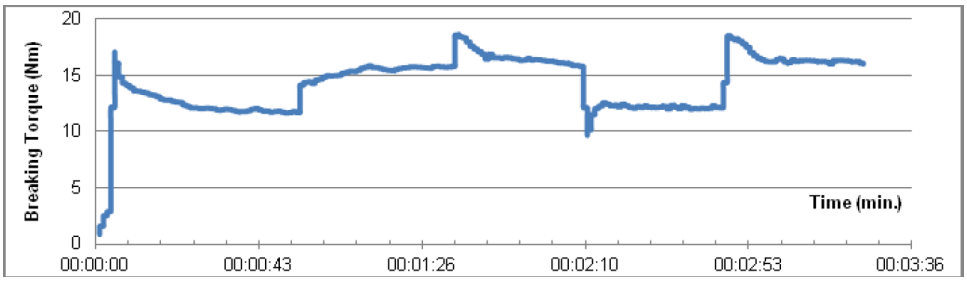


Figure 8 Braking torque change of the ER (see online version for colours)



In accordance with the measurement data mentioned earlier, it can be said that the speed stabilisation of heavy vehicles at long downhill can be achieved by controlling ER's braking using PWM technique.

The step response of the controller is investigated at the experimental study mentioned earlier. But, in real applications, the slope of the road will not be the same continuously. As a result of the changes in the slope of the road, the vehicle will tend to accelerate or decelerate. Consequently, some experimental tests have been

performed to simulate the changes in road slope and the response of the controller was investigated.

In the experimental tests, the throttle position of the engine was lowered or increased to simulate the changes in the slope while the controller was enabled and the engine speed was stabilised to a setpoint value. Figure 9 shows a 5-stage graph of the engine speed according to the throttle position. In the figure, the arrows pointing in upper and lower directions mean an increase or a decrease in the throttle position, respectively. Figures 10 and 11 show the changes in PWM output of the controller and braking amount of the ER according to the engine speed graph, respectively.

Figure 9 The engine speed according to throttle position changes (see online version for colours)

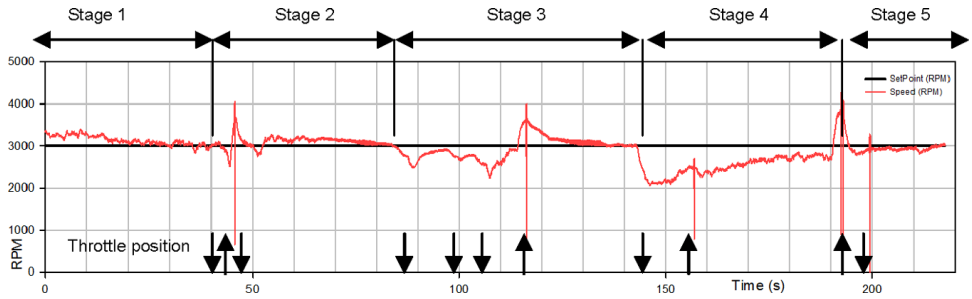


Figure 10 PWM output change of the controller (see online version for colours)

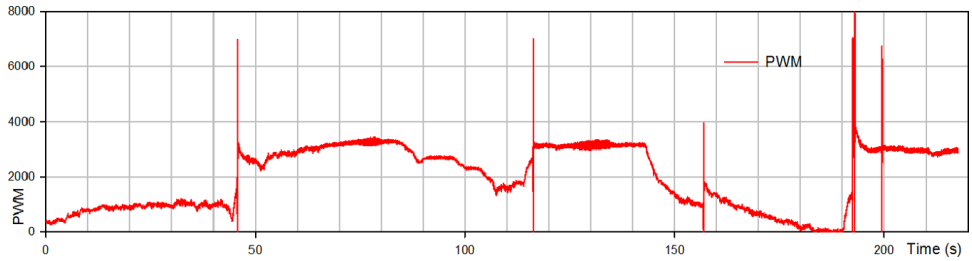
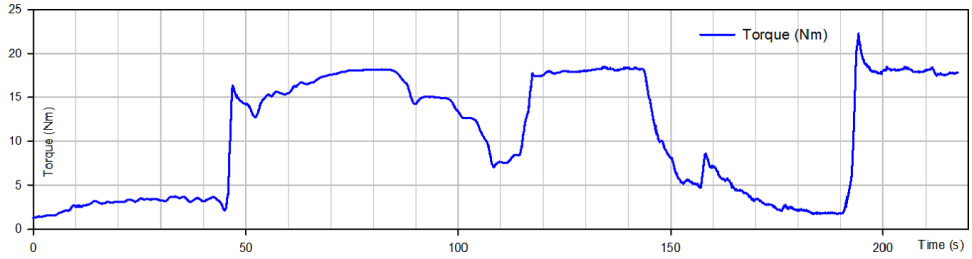


Figure 11 Braking torque change of the ER (see online version for colours)



To simulate the vehicle's acceleration or deceleration conditions according to changes in the road profile, the engine speed was set to 3400 rpm by using the throttle. Then, setpoint value was set to 3000 rpm and the controller was enabled. At the end of stage 1 in Figure 9, it can be seen that the engine speed was stabilised to 3000 rpm by the controller.

At stage 2 in Figure 9, the throttle position of the engine was first decreased and then increased to simulate a hump in the road profile. Then, it was lowered again to decrease the road slope. At the end of stage 2, the engine speed was stabilised to the setpoint by the controller.

At stage 3 in Figure 9, the response of the controller was investigated according to gradual decrease and a sudden increase in the slope of the road profile. PWM output was reduced by the controller to stabilise the speed at setpoint value for each decrease in slope. With the sudden increase in the slope, the braking amount of ER was increased, as well. Thus, the speed of the engine was stabilised to the setpoint.

At stage 4 in Figure 9, a scenario that consists of a huge decrease and a small increase in the slope of the road was investigated. Accordingly, the engine speed was decreased below the setpoint and, then, increased again to a value under the setpoint. PWM output was decreased to 0% duty by the controller to accelerate the engine to the setpoint value. But, the engine speed was stabilised at 2750 rpm owing to low throttle position that is already under the setpoint value.

As it can be seen at stage 5 in Figure 9, to simulate a small decrease after a huge increase in the road slope, the throttle position was increased to full throttle and then decreased a little bit. With the increase in engine speed, the braking amount of ER was increased by the controller and the speed was stabilised at 3000 rpm.

The peaks seen in Figures 9 and 10 represent the disturbances owing to measurement faults or unexpected faults that may occur during the operation. To eliminate the disturbance effects, the controller resulted in momentarily very high or zero PWM output. But, fortunately the braking torque of the ER was not affected because of instantaneous extreme PWM output changes. The engine speed has been stabilised to setpoint effectively against varying acceleration and deceleration conditions.

As expected, the vehicle load and road slope will not be the same during the driving of the heavy vehicles. Therefore, these parameters should be considered in real applications. Although the vehicle load is not the same, during the driving it can be considered as constant. The more the vehicle load increases, the more the kinetic energy occurs. This will cause longer settling time in the proposed system.

The road slope may also change during the driving. A micro-electro-mechanical systems (MEMS) inclinometer sensor may be added to the controller to monitor the road slope. According to the changes of road slope, the gains of the controller may be rearranged using a lookup table.

It is well known that the engine and jake brakes are efficient at higher engine speed. At high velocities of the vehicle, it is needed to down shift for obtaining the maximum efficiency. But, this case also applies high stresses at crankshaft. According to this phenomenon, if the engine/jake brake is activated at high vehicle speed without down shifting, it will support the ER to stabilise the speed of the vehicle.

But, ERs are more efficient at high vehicle speed. With the slowing down of the shaft speed approximately 1000 rpm, ERs start to lose their efficiency. At low vehicle speeds, engine/jake brake may be employed to operate as absorbing some of the kinetic energy of the vehicle.

For employing to operate of the engine/jake brake, an additional control signal may be implemented to the controller proposed in this study.

5 Conclusion

In this study, an experimental braking system was designed to stabilise the vehicle speed at long downhill by adjusting ER's braking. The designed system was verified experimentally by stabilising the engine speed at various setpoint values.

Instead of controlling of ER by using electromechanical switches and relays, the system developed in this study adjusts the vehicle speed effectively. The system allows accelerating and decelerating the vehicle in a controlled manner.

At the existing controlling of ERs, adjusting task of the vehicle speed is driver dependent. The ER control system designed carries the control task and lessens the driver's workload. Thus, the driving comfort is increased. The system was realised by using PID, which is a well-known closed-loop control algorithm. By changing the PID coefficients, the deceleration time of the vehicle can be adjusted. For the collection of experimental data, the control software was designed to run on a PC. But, it can be adapted easily to a microcontroller. So, this study has a structure that can be made compact and user-friendly. The system can easily be applied to heavy vehicles without changing the mechanical structure of the existing ER.

Furthermore, in the future works, more sophisticated control algorithms to adjust deceleration of the buses and heavy vehicles without disturbing the passengers and preventing the slippage of the load will be designed and integrated to this study.

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