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Kinematics and nonlinear control of an electromagnetic actuated CVT system for passenger vehicle †

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Abstract

An electromagnetic actuated continuously variable transmission (EMA-CVT) system is developed by two sets of electromagnetic actuators (solenoid) located on primary and secondary pulley. A set of solenoids are attached to the primary and secondary pulley to develop the attraction and repulsive forces. The relationships between the speed ratio and electromagnetic actuation and clamping force and output torque of the CVT are established based on the kinematics of the EMA-CVT system. A fuzzy logic controller (FLC) is developed to control the EMA precisely based on the feedback of the RPM sensor and slope sensor. The EMA-CVT performance with controller has found 28% more than the performance of the EMA-CVT without controller. The solenoids of the EMA were activated by varying the current supply with the Fuzzy-Proportional-Derivative-Integrator (FPID) to maintain the non-linearity of the CVT in response of the vehicle traction torque demand. Result shows that the solenoid is able to pull the plunger in the desired distance with supply current of 12.5 amp while push the plunger to the desired distance with 14.00 amp current supply to the windings when the vehicle is considered in 10% grade. The acceleration time of the ¼ scale car has been recorded as 5.5 s with the response of drive wheels torque.

Keywords: EMA-CVT; Fuzzy logic controller; Fuzzy-proportional-derivative-integrator; Accelerating time; Transmission loss

1. Introduction

The continuously variable transmission offers an optimal way to alter the gear ratio between a car's power plant and its wheels. The continuously variable transmission is a stepless gearbox with an unlimited number of gear ratios. In 1886, for example, Germany automotive pioneers Daimler and Benz fitted their first gasoline-fueled car with a rubber V-belt CVT. The researches on the development of modern CVT are carrying out by the researchers as time is approaching. There are many reasons for this, according to Emery Hendriks, Van Doorne's general manager for research and development, CVT is designed and developed mainly for two reasons: Firstly, the fuel economy and driving performance provided by the latest CVTs are matching and even overtaking those of today's complex and costly gearboxes. Secondly, increasingly stringent government regulations regarding fuel consumption and exhaust emissions are forcing auto engineers to consider the use of high-efficiency steady-state engines designed to run in a limited revolution band--a perfect match for CVTs. Further down the road, these environmental mandates are expected to force the development of hybrid-drive vehicles using single-speed power plants of various types--another highly suitable application for CVTs. Precisely, it could be noted that the ultimate goals of the CVTs design are to provide more torque and power than traditional transmissions, to have smooth speed change, wider-range speed ratio and simple mechanism with low cost and less maintenance [1-9]. The performance of a vehicle equipped with a 3000cc engine for the speed of 100 km/h in terms of acceleration time taken is reported as 10.20 s for manual transmission, 10.76 s for automatic transmission and 7.85 s for conventional CVT system [10]. Previous attempts to develop CVTs have resulted in numerous prototype designs. With almost no exceptions, however, these have not moved out of the laboratory and into mass production.

This study presents an Electromagnetic Actuated Continuously Variable Transmission (EMA-CVT) system which is mainly designed for a ¼ scale city car. The main objective of this study is to reduce significantly the delaying accelerating time of the vehicle and improve the transmission loss. The pulleys of this proposed EMA-CVT is considered same as that of the previous CVT. But the EMA-CVT pulleys movable sheaves controlling system is different from that of the others. The movable sheaves of the proposed EMA-CVT are con-

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trolled by developed electromagnetic actuator (EMA) with a FLC and FPID. A small city car Kancil (600cc) made by Malaysian local car company (Perodua) is considered in this study. Replacing the traditional synchronized gear box by proposed EMA-CVT, the car weight was found 623 kg. The proposed CVT is designed for ¼ scale Kancil car which weighs 155.75 kg including current EMA-CVT system. It offers an opportunity to meet the challenge by its improved traction torque control strategy, first acceleration and better fuel economy. The fundamental components, configuration, and the kinematics of an EMA-CVT are discussed in this paper. A fuzzy logic controlled electromagnetic actuated CVT system is developed with two sets of electromagnetic solenoids which are located in each side of the primary and secondary pulleys. To start the vehicle from rest, the primary (input) pulley radius will be smaller than the secondary one which results in higher torque multiplication. During speeding up of the car gradual synchronized manipulation of both pulleys give proper belt tension, less slip as well as exact gear ratio.

2. Kinematics of the EMA-CVT

2.1 Traction torque of the car

The simplified dynamic model of the EMA-CVT has been developed by considering the dynamic behavior of the engine, EMA-CVT and driving wheel. The analysis begins with the engine speed dynamics model as a single inertia system which can be modeled as:

$$\omega_e = \frac{1}{J_e}\left[T_e - T_{in}\right] \tag{1}$$

where T_e is the torque generated by the engine and T_{in} is the torque applied by the engine to the CVT. The transmission dynamics of the EMA-CVT could be modeled as:

$$T_{inw} = \left[T_e - J_t\omega_e\right]GR \tag{2}$$

where T_{inw} is the torque applied to the wheels by the EMA-CVT and GR is the gear ratio. For electromagnetic actuated CVT system, CVT speed ratio is changed with the axial movement of pulley movable sheave through attraction and repulsion of the stopper energizing the solenoids. The instantaneous torque for the secondary pulley of the EMA-CVT is calculated by using the equation:

$$\Delta T_{ins} = \frac{T_{out(\max)} - GR_{ins}T_{in(\min)}}{GR_{ins} + 1} \tag{3}$$

where $GR_{ins} = 1 + \dfrac{\tan\theta(L_s - 2ds)}{r + \tan\theta ds}$, GR_{ins} is the instantaneous gear ratio, L_s is the stroke length in m, ds is the instantaneous displacement of the movable sheave in m, $T_{out(max)}$ and $T_{in(max)}$ are the maximum output from the CVT and minimum input torque to the CVT in Nm and ΔTins is the instantaneous torque incremental. Upon computing the instantaneous gear ratio the torque of the EMA-CVT can be computed. Now the traction torque of the car needs to be simulated in different road conditions to identify the desired GR and developed torque of the proposed EMA-CVT. The traction torque of the car is computed by using the equation:

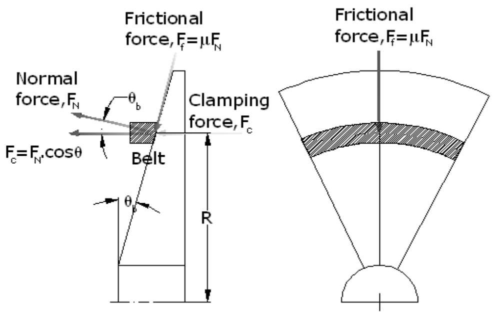


Fig. 1. Force analysis on the pulley surface.

$$T_{t(\theta)} = \left[\mu mg\frac{\left(l_f - f_r h\right)/L_w}{1 + \mu h/L_w} + W\sin\theta\right]\left(R_w\right) \tag{4}$$

where μ is the adhesion coefficient of the road, m is the mass in kg, f_r is the rolling motion resistance coefficient, h is the height of the center of gravity in m, L_w is the wheel base in m, lf is distance of the CG from the front wheel in m, θ is the slope angle of the road, g is the acceleration due to gravity, $T_{t(0)}$ and $T_{t(10)}$ are the traction torque of the car in Nm for 0% and 10% grade, respectively [11]. The traction torque of the car is computed as 185 Nm. While on the 10% grade the traction torque of the car is 210 Nm.

2.2 EMA-CVT clamping force

In this study, EMA mainly controls the removable sheaves by developing electromagnetic force. It is noted that the EMA gets the advantage to pull the movable sheave but the difficulty arises in pushing the sheave against the rotating belt. The pushing force (compressive force) in this study can be considered as the clamping force. The basic clamping force as shown in Fig. 1, is set by maximizing the frictional coefficient and transmission torque. For optimizing the required electromagnetic force generated by the EMA, the clamping force is computed. The solenoid electromagnetic force needs to develop just to overcome the clamping force for controlling the torque of the driving wheel or the gear ratio of the CVT.

This study investigates the performance of an EMA-CVT theoretically and experimentally on the operation of a ¼ scale vehicle in terms of operating speed, clamping force and acceleration time. The clamping force for the primary and secondary pulley of the EMA-CVT system can be formulated as [5]:

$$F_p = \frac{T_{in}\cos\theta_b}{2\mu_p R_p} \tag{5a}$$

$$F_s = \frac{T_{out}\cos\theta_b}{2\mu_s R_s} \tag{5b}$$

while the acceleration time of EMA-CVT system ¼ scale vehicle can be formulated as:

$$t = \frac{Wr_{wheel}{}^{R_p}\!/_{R_s}}{T_e g}(v_c)\ . \tag{6}$$

It is noted that the slip velocity Δv is incurred in both the pulleys during transferring the power to the driving wheel. The slip velocity for the primary pulley and the secondary pulley can be calculated as, $\Delta v_p = \omega_p R_p - v$ and $\Delta v_s = v - \omega_s R_s$,where $\omega_p R_p$ and $\omega_s R_s$ are the speed of the primary and secondary pulley, v is the belt speed, Δv_p and Δv_s are the slip velocities. So the exact power transferred from the engine to the primary pulley and from the primary to secondary pulley can be computed as:

$$P_{in} = \left[\frac{\Delta v_p + v}{R_p}\right](T_{in}) \tag{7}$$

$$P_{out} = \left[\frac{v - \Delta v_p}{R_s}\right](T_{out}) \tag{8}$$

where P_{in} is the power generated by the engine or input power of the primary pulley in Watt and Pout is the output power of the primary pulley in Watt.

2.3 Solenoid development for electromagnetic force

In order to push and pull the movable sheaves of the pulleys at desired transmission GR, the EMA-CVT solenoid is developed in this study to develop the maximum electromagnetic force to overcome the clamping force of 210 N. It is noted that the EMA is developed by two sets of solenoids one set for each pulley. The solenoid turns to electromagnet as soon as a current is supplied to the solenoid. Coil consists of multiple turns of copper wire in a helical geometry around a cylindrical plastic housing which is called a solenoid. The mathematical models are developed for the EMA by considering the dynamic behavior of the magnetic flux, density, strength, electromagnetic force and energy according to the Faraday's Law, Ampere's Law and Lenz's law, Maxwell's dynamic condition and the modified equations [12, 13]. The magnitude and the direction of electromagnetic force F_{em} at the magnetic field of current carrying conductor is given by the general equation of Fleming's rule,

$$F_{em} = BIl\ . \tag{9}$$

The magnetic force vectors on the coil elements as shown in

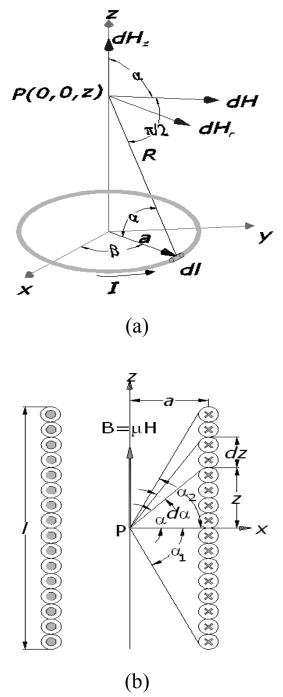


Fig. 2. Magnetic field of single coil.

Fig. 2 shows the development of electromagnetic force, F_{em} due to the development of magnetic field B. The force F_{em} squeezes to the x direction and expands it along the solenoid axis z. The largest force is generated in the middle of the solenoid with horizontal direction due to magnetic field saturation. Therefore, the magnetic field (B) in the solenoid is developed by controlling the current supply to generate electromagnetic force which is greater than clamping force.

The properties of the device depends crucially on the factors, such as the geometry of the magnetic core; the amount of air gap in the magnetic circuit; the properties of the core material; the operating temperature of the core and whether the core is laminated to reduce eddy currents. In the geometry of magnetic core the turns of the coil is considered as circular loop although the turns are slightly helical in shape. The total B at point P is obtained by integrating the contributions from the entire length of the solenoid.

$$B = \frac{\mu N I}{2l}(\sin\alpha_2 - \sin\alpha_1) \tag{10}$$

Therefore, the electromagnetic force,

$$F_{em} = \mu H I l = \mu\frac{NI^2}{2}(\sin\alpha_2 - \sin\alpha_1)\ . \tag{11}$$

If the solenoid length l is much larger than its radius a, $\alpha_1 \approx 90^o$ and $\alpha_2 \approx 90^o$, in which case the above equation reduces to $F_{em} = \mu N I^2$. The smooth response of the solenoid is mainly the function of eddy current (i.e. $F_{em} \approx f(I_e)$) which is developed due to the self induction of the coil itself. Therefore, due to

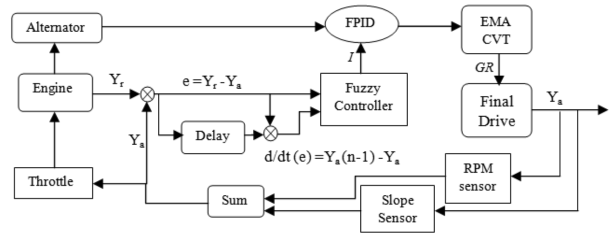


Fig. 3. Block diagram of control system.

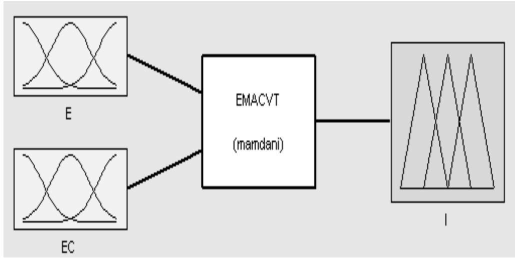


Fig. 4. The structure of the fuzzy inference system (FIS).

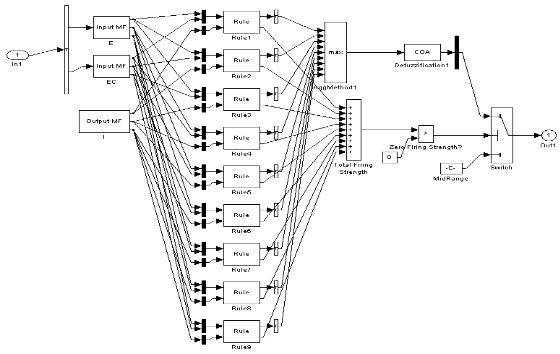


Fig. 5. FIS wizard of fuzzy logic controller.

eddy current there was regeneration of some magnetic field to the coil which is of course less than the magnetic force generated due to the main current source. The self induction of the solenoid coil can be defined as the ratio of the magnetic flux linkage and the current flowing through the coil is represented as:

$$L_i = \mu \frac{N^2}{2l}(\sin\alpha_2 - \sin\alpha_1)S \,. \tag{12}$$

The electromagnetic energy in the solenoid inductor due to its induction for the flowing current from 0 to I can be formulated as,

$$E_{eng.Li} = \frac{1}{4}\mu H^2 V_s \,. \tag{13}$$

The energy in the conductor due to the self induction for the flowing of current *I*:

$$E_{eng.L} = 2\mu H^2(V) + \Delta.\left(\frac{E \times B}{\mu_0}\right)u + \frac{\delta}{\delta t}\left[\frac{\varepsilon_0 E^2}{2} + \frac{B^2}{2\mu_0}\right]. \tag{14}$$

3. Fuzzy logic control strategies

When dealing with nonlinear processes, the fixed gains of PID controller need to be adequately retuned. Various types of modified PID controllers involving auto tuning and adaptive PID controllers have been proposed lately [16-18]. However, fuzzy controller can also be applied for tuning PID parameters based on nonlinear mapping of system error and its derivative to PID parameters. The main advantage of fuzzy logic is that no mathematical modeling is required and the fuzzy controller rules are constructed mainly based on the knowledge of the system behavior and the experience of the control engineer. This combination of fuzzy and PID controllers forms the Fuzzy-Proportional-Derivative-Integrator (FPID) controller which acts as a self PID tuner. The structure of the FPID controller is shown in Fig. 3. The fuzzy logic controller (FLC) with FPID is preferred to control the EMA of the proposed study to control the EMA-CVT. The FLC is used in this study to control current flow to the EMA for maintaining the desired traction torque of the vehicle in different road conditions. In the control system of the EMA-CVT, Y_r is considered as the input torque while Y_a is considered as the output traction torque of the controller.

The error (*e*) is the difference between the reference and the output. The derivative of the error (i.e., *de/dt*) is the value of how big the error has changed. The PID gains are tuned by the fuzzy controller to reduce output overshoots, to eliminate the steady state errors and to minimize trajectory tracking errors. The error (*e*) and change of error (*de/dt*) are continuously measured throughout the operation of the EMA-CVT in order to investigate the performance of the EMA.

3.1 Implementation of fuzzy logic controller

For implementation of fuzzy values in the system by using fuzzy expert system (FES), error (*e* or *E*) and change of error (*de/dt* or *EC*) are used as input parameters and the supply current (*I*) is used as output parameter as shown in Fig. 4. For fuzzification of these parameters the linguistic variables small (S), medium (M) and high (H) are used. A Mamdani max-min inference approach with the logical operator AND has been used for inference mechanism which employs the individual rule based inference scheme and derives the output when subjected to a crisp input [14, 15]. For the two inputs and one output, a fuzzy associated memory or decision rule is formed with 9 rules. Fig. 5 shows how the rule fires according to fuzzy inference system (FIS). In (input) 1 means the two inputs *E(e)* and *EC (de/dt)* to be manipulated and the respective Out (output)1 is the fuzzy manipulated output based on the fuzzy rules.

There is a degree of membership for each linguistic term that applies to that input variable. Fuzzifications of the used factors are made by aid follows functions.

$$E(i_1)=\begin{Bmatrix} i_1; 0 \le i_1 \le 300 \\ 0; otherwise \end{Bmatrix} \tag{15}$$

$$EC(i_2)=\begin{Bmatrix} i_2; 0 \le i_2 \le 10 \\ 0; otherwise \end{Bmatrix} \tag{16}$$

$$I(o_1)=\begin{Bmatrix} o_1; 0 \le o_1 \le 15 \\ 0; otherwise \end{Bmatrix} \tag{17}$$

Using MATLAB FUZZY Toolbox, prototype triangular and trapezoidal fuzzy sets for the fuzzy variables, namely, torque error (*E*), change of error (*EC*) and current flow (*I*) are set up. The membership values used for the FLC are obtained from the above formulas. These membership functions help in converting numeric variables into linguistic terms. The linguistic expressions and membership function of torque error (*E*) obtained from the developed rules given as follows:

$$\mu_S(i_1)=\begin{Bmatrix} \dfrac{75-i_1}{75}; 0 \le i_1 \le 75 \\ \dfrac{100-i_1}{25}; 75 < i_1 \le 100 \\ 0; otherwise \end{Bmatrix} \tag{18}$$

$$\mu_M(i_1)=\begin{Bmatrix} 0; otherwise \\ \dfrac{138.5-i_1}{54.7}; 83.8 \le i_1 \le 138.5 \\ \dfrac{208-i_1}{39}; 169 < i_1 \le 208 \\ 1; 138.5 < i_1 \le 169 \end{Bmatrix} \tag{19}$$

$$\mu_H(i_1)=\begin{Bmatrix} 0; i_1 < 171 \\ \dfrac{257.5-i_1}{86.5}; 171 \le i_1 \le 257.5 \\ 1; i_1 > 257.5 \end{Bmatrix}. \tag{20}$$

In defuzzification, truth degrees (μ) of the rules were determined for each rule by the aid of the minimum (min) and maximum (max) between working rules. Due to its popularity, the "center of gravity" (COG) defuzzification method is used for combining the recommendations represented by the implied fuzzy sets from all the rules. The COG method computes I^{crisp} ($Output^{crisp}$) as follows:

$$I^{crisp}=\frac{\sum b_i \mu_i}{\sum \mu_i} \tag{21}$$

where b_i is the position of the singleton in i^{th} universe, and μ(*i*) is equal to the firing strength of truth values of rule *i*.

Using MATLAB the fuzzy control surface is developed as shown in Fig. 6. It may serve as visual depiction of how fuzzy logic system operates dynamically over time. The plot is used to check the rules and the membership functions and to observe if they are appropriate and whether modifications are necessary to improve the output.

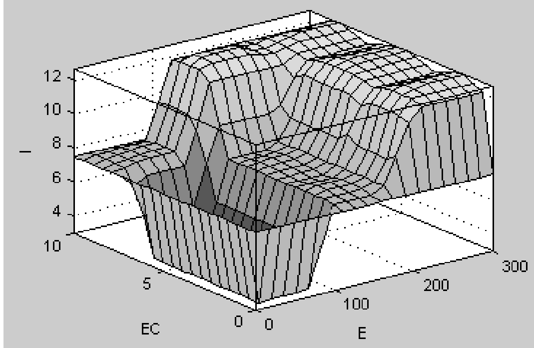


Fig. 6. Control surface of the fuzzy controller.

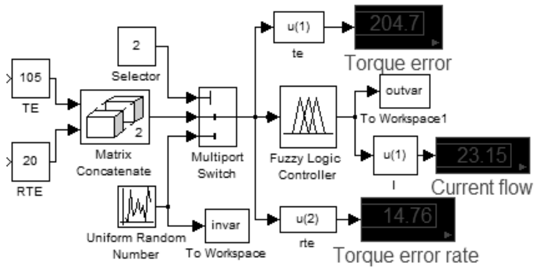


Fig. 7. Fuzzy logic controller simulation for current flow (*I*).

3.2 Simulation results of control system

A Fuzzy logic controller is designed to simulate the fuzzy logic system once it has been verified with the rule viewer using MATLAB SIMULNIK. The Fuzzy logic controller block in Simulink has two inputs: torque error (TE) and rate of torque error (RTE), and one output: current flow (I). Fig. 7 shows the finalized Fuzzy logic controller simulation for the current flow (I) with all the sources and sinks connected to it. Since the gear ratio affects the wheel speed and hence wheel torque significantly, so wheel torque (T_w) is used as a controlled variable in the control system of EMA-CVT. From Fig. 7, Fuzzy logic controller shows the output result of current flow as 23.15 amp based on two inputs of wheel torque error and rate of torque error as 204.7 Nm and 14.76 Nm/s respectively.

3.3 Assembly and control

Four solenoids are designed and developed for developing an effective EMA to control the GR as well as torque of the CVT .The EMA controls the back and forth movement of the pulleys moveable sheaves. Microcontroller determines the on/off mode for the individual solenoids detecting the measurement of rotation of final drive through RPM (dynamo) and slope sensor.

4. Experimental results

Fig. 9 shows the designed and developed EMA-CVT. Four solenoids each has 1200 turns and able to develop electromagnetic power 150- 300 N for the current in the range of 10

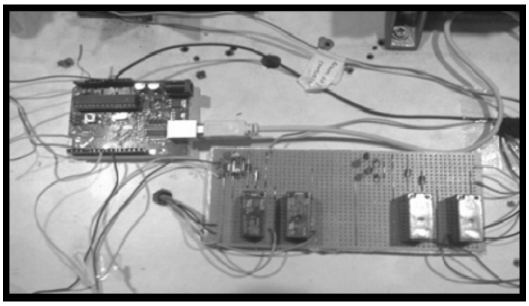


Fig. 8. Fuzzy logic controller and relay circuit assembly.

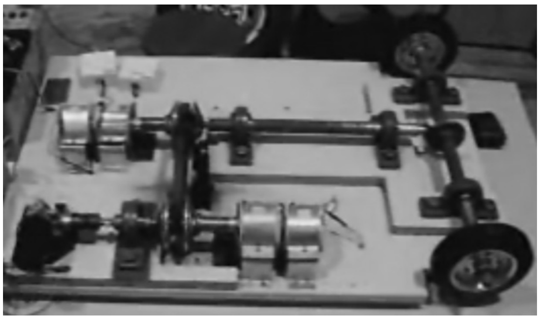
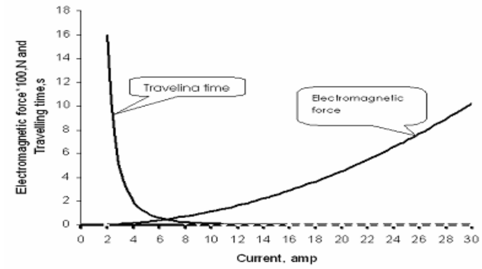


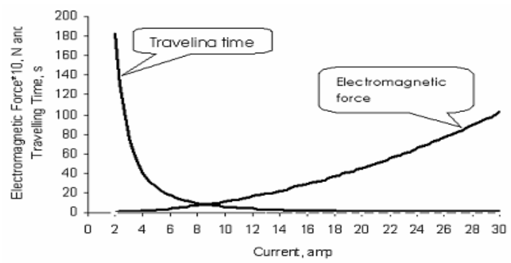
Fig. 9. Photo of the EMA-CVT.

– 20 amp. The only problem will be faced is heat generation. The heat management system is not considered in this study which could be developed due to the supply of the current to the solenoids. Solenoid is wrapped with thick aluminum bracket in order to avoid the leakage of magnetic flux. The FLC has been programmed for the EMA-CVT to maintain the vehicle traction torque and speed "HIGH, MEDIUM and LOW". Gear ratio is initially considered HIGH for the vehicle of starting and climbing the slope while it is MEDIUM and LOW at moderate and low speed respectively. The performance of EMA is evaluated based on its ability to exert force to push or to pull the pulleys per unit time.

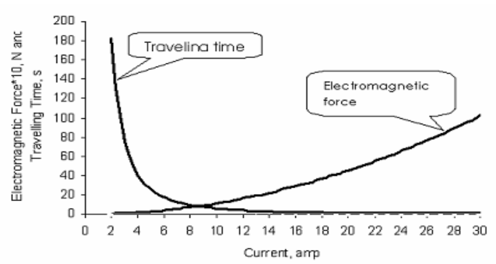
The performance of the EMA-CVT is measured for the vehicle in two operating road conditions, (i) 0% grade and (ii) 10% grade by varying the current supply in the range of 2-15 amps for developing the electromagnetic forces (equivalent of clamping forces) 170 N and 210 N respectively. The supply current was measured by using a digital ammeter and travelling time was measured by using a digital stop-watch while the acceleration was measured by measuring the rotational speed of the driving wheel. Fig. 10(a, b, c, d) shows the performance of the EMA with varying payload. By referring to the current supplied to the coil, the variety of responding (travelling) time of the movable sheave is recorded. The travelling time (responding time) of the plunger of the EMA for pulling mechanism was found lower than the travelling time of pushing mechanism. The basic reason was the higher load on matching area of the sheaves and the pulling of the sheave was found easier than the pushing. Furthermore, clamping releasing force always tends to pull the movable sheave of the pulley towards the solenoid of the EMA. While, clamping force push the movable sheave against the rotating belt. In case of vehicle in 0% of grade and initial lower velocity (higher gear ratio), the solenoid was able to pull the plunger of secondary pulley in the desired distance when the current supplied was 11 amp while the solenoid push the plunger of primary pulley to the desired distance when the current supplied was 12.5 amp. It should be noted that the movable sheave of the secondary pulley needs to push against the rotating belt to create the higher GR for the higher torque of the vehicle in starting as well as climbing the slope.



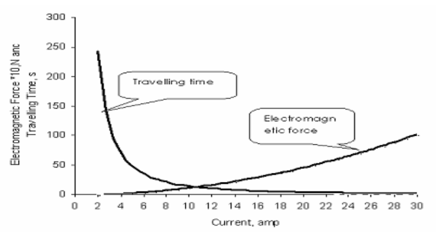
(a) Pulling the secondary sheave



(b) Pushing primary the sheave.

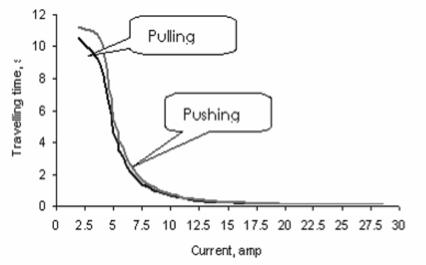


(c) Pulling secondary the sheave

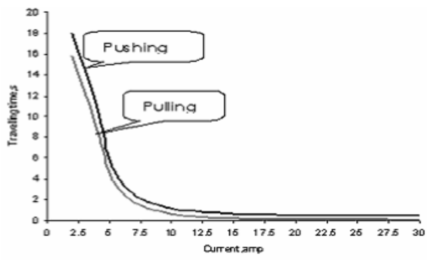


(d) Pushing primary the sheave

Fig. 10. EMA operating performance (a &b) for 0% grade and (c & d) for 10% grade.

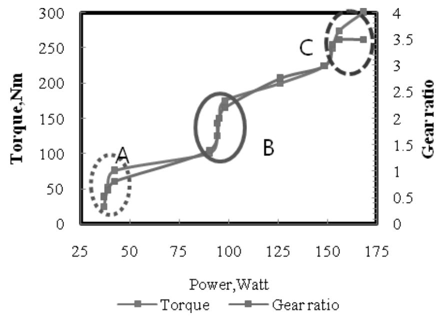


(a) Grad = 0%

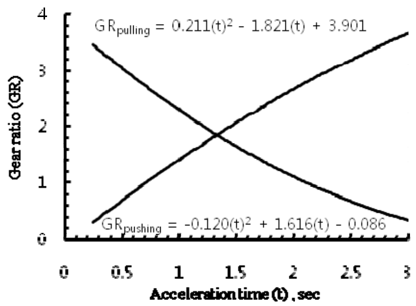


(b) Grad = 10%

Fig. 11. Accelerating time of the vehicle.



(a)



(b)

Fig. 12. FLC performance: (a) torque; (b) accelerating time.

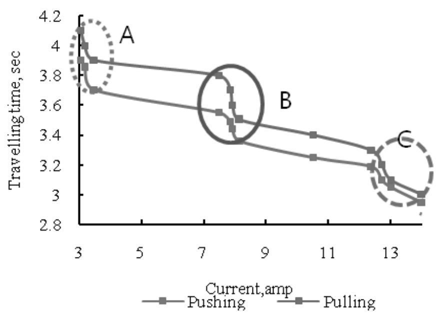


Fig. 13. EMA-CVT performance with controller.

In case of vehicle in 10% grade, the solenoid was able to pull the plunger in the desired distance when the current supplied was made to the windings of the solenoid 12.5 amp while the solenoid push the plunger to the desired distance when the current supplied was made to the windings of the solenoid 14.00 amp (initial condition). Fig. 11(a, b) shows accelerating time of the vehicle. The pushing and pulling operations of the sheave of the pulleys have been performed for maintaining the accelerating time of the vehicle. In this study, the pulling operation represents to accelerate the vehicle and to decrease the dynamic torque while the pushing operation represents to decelerate the vehicle and to increase the vehicle dynamic torque. Fig. 12(a) shows the accelerating time of the vehicle is 0.73 sec in case of pulling while 1.1 s in case of pushing. Fig. 12(b) shows the accelerating time of the vehicle is 0.86 s in case of pulling while 1.34 s in case of pushing. Experimental result of the EMA-CVT on the accelerating time of the vehicle is performed better than the simulated result. This reason may be the shielding of the solenoid with the aluminium for protecting the leaking of the magnetic field intensity.

To maintain the torque, the car needs the gear ratio of 3.9 for 10% grade and less than that for 0% grade. Fig. 12(a) illustrates the transmission ratio and torque with respect to power. It was observed that the higher the power, the higher the torque and the gear ratio under any pushing condition of primary and secondary pulley sheaves. Fig. 13 shows the performance characteristics of the EMA-CVT with Fuzzy Logic Controller. The areas that are shown in Figs. 13(a)-14, A represents H (High), B represents M (medium) and C represents S (small), the linguistic variable of the membership function. Those rapid characteristics change of the CVT with respect to the current and power supply to the EMA occur due the fast response of FPID. This FPID performs according to the fuzzy rules embedded in FIS. However, the smooth response of the EMA-CVT could be made by increasing the number of membership functions (i.e. rules) for the controller. The EMA-CVT performance distinction has been made based on Fig. 12 and 14. It is found that the EMA-CVT with controller has improved the performance in terms of accelerating time (travelling time) by 28% power consumption over the EMA-CVT without controller for average condition. It is to be noted that the vehicle transmission loss can be improved by the EMA-CVT with the developed Fuzzy Logic Controller.

5. Conclusions

The following conclusions are achieved based on the contents of this paper:

(1) The pulley and its shaft diameter are optimized based on the traction torque of the driving wheel.

(2) Number of windings of the solenoid and coil diameter are optimized based on the desired output magnetic force of the EMA for pushing and pulling operations of the pulley's movable sheave.

(3) The solenoid is able to develop the electromagnetic force which is equivalent to the pushing force of the movable sheave for the supply current of 12-15 amp if the number of windings is considered in the range of 1400-1700. Number of windings 1200 is considered in this study for avoiding the heat generation. The electromagnetic actuator accelerates the vehicle in 2.5 – 4.75 s in response to the vehicle driving wheels desired torque with controlling the movement of the CVT desired gear ratio.

(4) The electromagnetic actuator (EMA) develops the electromagnetic force equivalent to the clamping forces of the pulleys (170-210 N) with supplying current in the range of 10-20 amp.

(5) Fuzzy Logic Controller was developed to control the EMA-CVT for the vehicle at different load conditions. The EMA-CVT performance has improved 28% when the EMA is controlled by Fuzzy Logic Controller.

(6) The FLC with FPID is attractive to control the EMA because of its ability to maximize acceleration and deceleration regardless of road conditions.

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