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The Control System Modeling and The Mechanical Structure Analysis For EMCVT

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Abstract

The current automotive metallic belt continuously variable transmission (CVT) mostly uses hydraulic system to push the cone disc and achieve the speed ratio control. A new Electrical Mechanical Continuously Variable Transmission without hydraulic control (Electrical Mechanical CVT, EMCVT) studied in this paper, uses the rolling screw mechanism to press cone disc, achieves speed regulation through the electronic control mechanism, and abandons the energy-intensive hydraulic system. In this paper, based on the analysis of mechanical configuration, the EMCVT's transmission system and its speed regulation process, speed ratio control characteristic and the clamping force control feature are studied and modeled. Besides, the Control strategy of the transmission system driven by motor is built, so as to provide an important theoretical basis for the further building of EMVCT's control system and the selection and implementation of Control strategy.

***Keywords**: EMCVT, system analysis, theoretical modeling, control strategy, transformation, detail sub-band feature encoding*

1. Introduction

Traditional automotive metallic V-belt continuously variable transmissions (CVT) are all electro-hydraulic control, which achieves the speed regulation through the hydraulic system driven by engine. The cost of pumps and valves are high and they are easy to malfunction, what's more, the efficiency loss of hydraulic torque converter and hydraulic system is as much as 25 percent, so the energy consumption is also a problem. However, if we replace the hydraulic part by pure electric control system, the performance and reliability of the vehicular CVT will be highly improved, while the cost and fuel consumption will be further decreased [1].

The topic of this thesis is the control system of the newly-developed EMCVT (Electrical Mechanical Continuously Variable Transmission). This CVT, which abandons the energy-intensive hydraulic system, uses the rolling screw mechanism to add pressure to the cone disc and modulates velocity by the electric-controlled mechanical speed regulation mechanism. As a result, the fuel consumption, cost and failure rate will be dramatically decreased [2].

2. Mechanical Configuration of EMCVT

The mechanical configuration of the EMCVT is shown in Figure 1. The torque of the engine is transmitted to the driving pulley shaft by clutch, then to the metal belt through the fixed and movable cone discs. Disk spring provides pressure with elastic force to clamp the metal belt. The metal belt transmits the power to the driven cone discs through friction and output by the driven movable pulley. Then the synchronizer and its reverse mechanism (similar to the reverse device of the traditional transmission) will achieve the change of the direction of rotation and finally transmit the power to differential mechanism. A speed regulating motor which is able to rotate in both directions transmits the controlling power and motion to the screw by gear reducer (three-stage gear reducer), then the screw rotates in the corresponding direction

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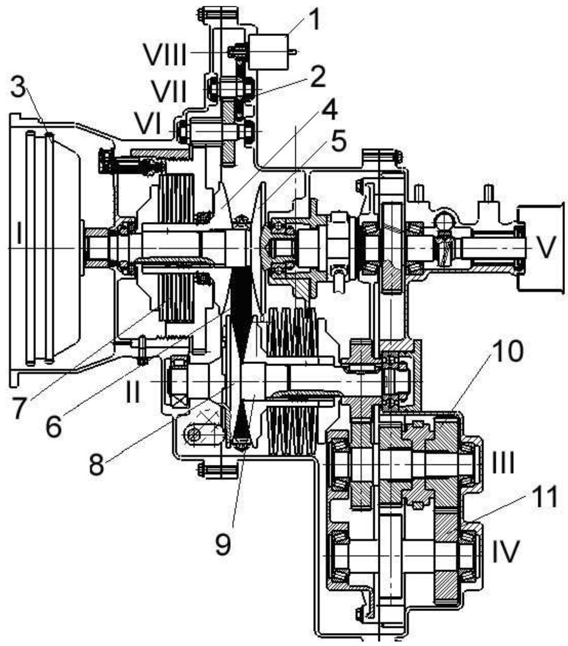
relative to the nuts fixed in the box. Finally, the driving movable cone disc is pulled by the screw, which leads to the change of the working radius of the metal belt and the change of speed ratio.



1) motor for position control of cone disc. 2) deceleration system. 3) dry friction clutch. 4) driving movable cone disc. 5) driving fixed cone disc. 6) metal belt. 7) Energy storage system. 8) driven fixed cone disc. 9) driven movable cone disc. 10) shift mechanism. 11) gear reducer

Figure 1. The mechanical configuration of EMCVT

3. Model Building of Transmission System of EMCVT

The structure diagram of transmission system of EMCVT is shown as Figure 2. If the clutch is in a combination state4, that is to say the car is running forward straightly, the metal belt has no slip phenomenon in the transmission process. The EMVCT's speed ratio is:

$$i = \frac{\omega_e}{\omega_s} = \frac{T_s}{T_e \eta} \tag{1}$$

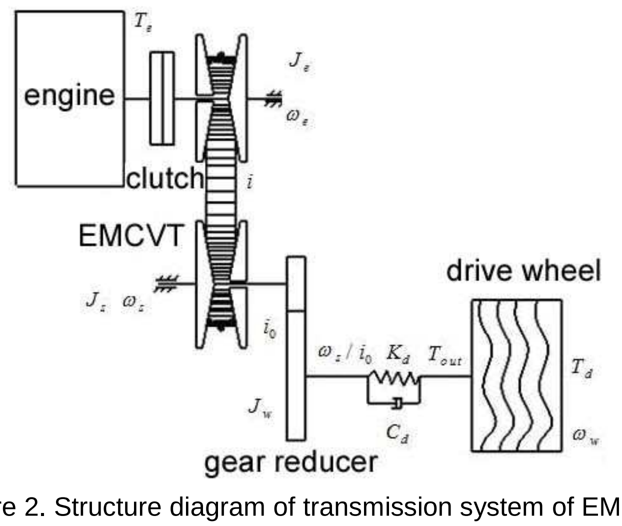


Figure 2. Structure diagram of transmission system of EMCVT

Where, ω_e is not only the engine's rotating speed, but also the CVT's input rotating speed in steady-state; ω_s is the CVT's output rotating speed; T_e is the engine's output torque; T_s is the output torque of the driven pulley; η is the CVT's transmission efficiency between driving and driven pulleys.

The EMCVT's dynamic model in transmission process is[3]:

$$\begin{cases} J_e \dot{\omega}_e = T_e - T_{in} \\ J_s \dot{\omega}_s = T_{in} i\eta - \dfrac{T_{out}}{i_0 \eta_0} \\ \dot{\omega}_e = \dot{\omega}_s + \omega_s \dfrac{di}{dt} \end{cases} \tag{2}$$

Where, J_e is the rotational inertia of the input shaft; T_{in} is the torque of CVT's driving pulley; J_s is the rotational inertia of the output shaft; T_{out} is CVT's output torque; i_0 is CVT's main reduction ratio; η_0 is the transmission efficiency of the main gear reducer group.

Because the transmission system has been simplified to an elastic system with concentrated mass, considering the relative torsional stiffness and the viscous damping coefficient of the driving shaft in the model, the dynamic model of the driving shaft is:

$$\begin{cases} T_{out} = C_d \cdot \dot{\theta}_t + K_d \cdot \theta_t \\ J_w \dot{\omega}_w = T_{out} - T_d \\ \dot{\theta}_t = \dfrac{\omega_s}{i_0} - \omega_w \\ \omega_w = \dfrac{v_{veh}}{R_w} \end{cases} \tag{3}$$

Where, C_d is the viscous damping coefficient of the driving shaft; K_d is the stiffness coefficient of the driving shaft; θ_t is the rotation angle of the driving shaft; ω_w is the angular velocity of the driving wheels; T_d is the load torque of the driving wheels, and the gradient resistance, air resistance, rolling resistance and braking force can all be converted to the load torque of the driving wheels; v_{veh} is vehicle's modal speed; R_w is the radius of the driving wheels.

In order to simulate the EMCVT's experiment process on test bench, v_{veh}, T_d and the speed ratio i are specified as input of the EMCVT transmission system model, and the engine's torque T_e as the output. In fact, v_{veh} is determined by the initialized engine speed and the speed ratio. It is controlled indirectly in the course of the experiment; T_d is loaded by the dynamometer on test bench, which can be specified arbitrarily within its given range in the model; i is the output of the speed ratio model. EMCVT's transmission system model in Matlab / Simulink is shown in Figure 3.

4. Model Building of Speed Ratio

CVT's transmission ratio is determined by the radiuses of driving (R_{DR}) and driven (R_{DN}) wheels1, as shown in Figure 3.

$$i = R_{DN} / R_{DR} \tag{4}$$

In speed-change process, the length of the metal belt can be regarded as constant (the length caused by elastic deformation is little), so there:

$$L = (\pi + 2\phi)R_{DR} + (\pi - 2\phi)R_{DN} + 2d\cos\phi \tag{5}$$

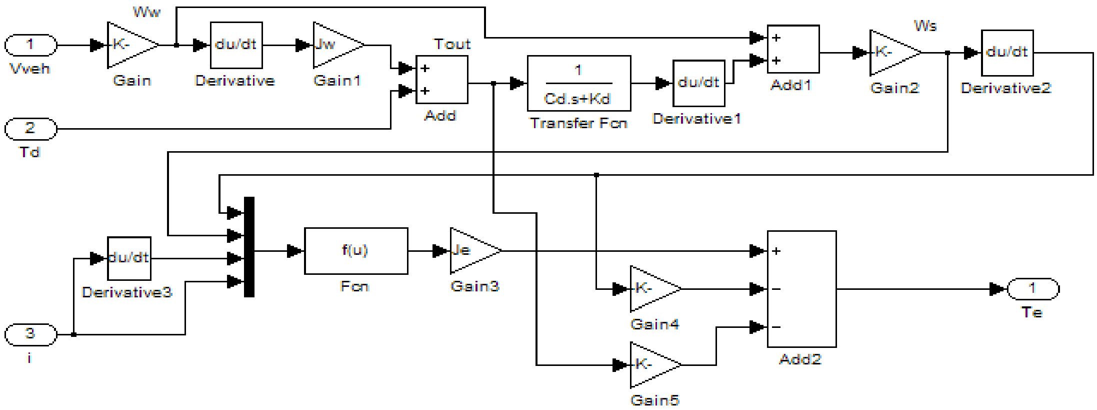


Figure 3. Transmission system model in Matlab/Simulink

Where, $\phi \approx \sin\phi = (R_{DR} - R_{DN})/d$, d is the distance between centers of transmission shafts.

The approximate formula between speed ratio and the radius of driving pulley can be obtained from the two equations above:

$$i = (-B + \sqrt{B^2 - 4AC}\,)/2A \tag{6}$$

Where, $A = R_{DR}/d$; $B = \pi - 2R_{DR}/d$; $C = \pi + R_{DR}/d + 2d/R_{DR} - L/R_{DR}$. The relationship between transmission ratio i and the axial displacement of driving movable cone disc x_p is:

$$i = \frac{R_{DN\max} - x_p/(2\tan\varphi)}{R_{DR\min} + x_p/(2\tan\varphi)} \tag{7}$$

Where, $R_{DN\max}$ is the maximum working radius of driven pulley; $R_{DR\min}$ is the minimum working radius of driving pulley. φ is pulley's cone angle(cone disc with straight generatrix).

In fact, x_p can be regarded as the absolute position parameter of driving movable cone disc, whose definition domain is [0, 18mm] in the current developed EMCVT. The transmission ratio is progressively smaller, while x_p is becoming larger. Therefore, the model can be expressed by the function $i = f(x_p)$. The input is the axial displacement x_p of driving movable cone disc, and the output is the CVT's transmission ratio i. Transform the above model appropriately, because the relationship between the working diameter of driving pulley and x_p is [5]:

$$R_{DR} = R_{DR\min} + \frac{x_p}{2\tan\varphi},\quad A = \frac{R_{DR}}{d},\quad B = \pi - \frac{2R_{DR}}{d},\quad C = \pi + \frac{R_{DR}}{d} + \frac{2d}{R_{DR}} - \frac{L}{R_{DR}},\quad i = \frac{-B + \sqrt{B^2 - 4AC}}{2A}$$

So we can get $i = f(x_p)$, the model in Matlab/Simulink is shown in Figure 4.

5. Model Building of the Clamping Force

The relationship between the largest torque which could be transmitted by the metal belt CVT and the axial clamping force of the hydro-cylinder of the driven pulley is 5.

$$F_{DN} = T_{in} \cdot \beta \cdot \cos\varphi / (2\mu \cdot R_{DR}) \tag{9}$$

Where, T_{in} is the input torque from the input terminal of the CVT; φ is the cone angle of the cone disc; μ is the friction coefficient between belt and cone discs; R_{DR} is the working radius of driving pulley; β is the coefficient of torque reserved.

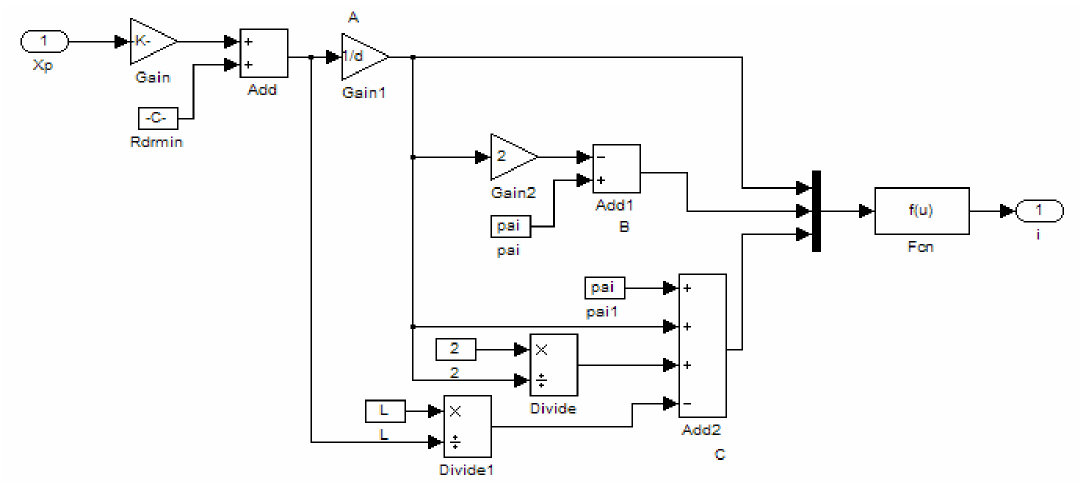


Figure 4. Speed ratio model in Matlab/Simulink

In order to get the relationship between the axial clamping force of the driving pulley F_{DR} and the driven pulley F_{DN}, Japanese scholars Toru Fujii and Miloiu have done a lot of experiments. They conclude that the relationship between the ratio of the clamping force of the driving and driven pulleys $k = F_{DR} / F_{DN}$, the speed ratio i and the ratio of the torques $\lambda = T_e / T_{e\max}$ is:

$$k = f(i, \lambda) \tag{10}$$

The relationship shows that the clamping force of the driving and driven cone discs changes along with the speed ratio and the torque transmitted by metal belt. After further testing analysis, the influence on the ratio of the clamping force k is small when $\lambda > 0.4$. For the actual working state of CVT, the ratio of torques is generally above 0.5, so we just consider the influence of speed ratio when determining the clamping force ratio. Thus, when the clamping force of the driven cone disc is determined, the clamping force of the driving cone disc transmitted by metal belt can be determined by the clamping force ratio k. In other words, to control the CVT's speed ratio in a given value stability, the clamping force of the driving movable cone disc must satisfy the formula (10). The axial load on driving cone disc, which is provided by the clamping force of the disk spring on driven pulley, can also be calculated when the transmission system reaches dynamic equilibrium. From the empirical formula 7:

$$\begin{cases} F_{DN} = \dfrac{\cot(\alpha + \rho_1)}{4} \cdot \theta_{DR} \cdot \left(\dfrac{T_{in}}{R_{DR}} + F_{DR}\right) \\ F_{DR} = \dfrac{B + \sqrt{B^2 - 4AC}}{2A} \end{cases} \tag{11}$$

where: $A = \theta_{DN}$;

$$B = a\frac{\sin\alpha}{\mu_2}\cdot\frac{T_{in}}{R_{DR}}+\frac{T_{in}}{R_{DR}}\theta_{DN}-2tg(\alpha+\rho_2)\frac{T_{in}\cdot\cos\alpha}{R_{DR}}(\frac{1}{\mu_2}-\frac{\beta}{\mu})\quad C = a\cdot\frac{\sin\alpha}{\mu_2}\cdot(\frac{T_{in}}{R_{DR}})^2.$$

and θ_{DR},θ_{DN} are respectively the wrap angles of the metal belt around driving and driven pulleys; μ_1,μ_2 are the modified friction coefficient between metal belt and driving and driven pulleys, while the speed ratio i changes, $\pi/\theta_{DR}\cdot\mu=\mu_1,\pi/\theta_{DN}\cdot\mu=\mu_2$; ρ_1,ρ_2 are the modified friction angles between metal belt and driving and driven pulleys, while the speed ratio i changes; α is constant.

In fact, clamping force is an important factor that cannot be ignored in EMCVT system. EMCVT abandons the actuating and slave cylinders, which are used to keep clamping force in traditional CVT, and adopts disk spring as the energy storage element. When the car's external load increases, there is no doubt that the torque transmitted by metal belt will gradually become larger. The static friction force between driving and driven pulleys and metal belt will also increase, as well as the axial force of movable cone discs on driving and driven pulleys. Therefore, the speed ratio control motor will be loaded by the axis force of movable cone disc on driving pulley when the output terminal has load in the speed-change process. According to the characteristic of the motor, the load of CVT's output terminal will affect the rotate speed of speed ratio control motor. The control program can now control the speed ratio motor with PWM timing. It controls the duty cycle of pulse signal to change the electrical potential across the motor armature, so as to change the motor speed and get a better control quality of speed ratio at different external load.

6. Model Building of Speed Ratio Control Motor

As shown in Figure 1, DC motor is used as the driving force of the speed ratio control system, which consists of synchronous toothed belt and two-stage gear reducer. The power is transmitted to the disk spring through the ball screw, and then the disk spring press the driving movable cone disc to generate clamping force that can control speed ratio. The pressure will reach a new equilibrium state with the reaction force of the disk spring on driven pulley. The driving and driven pulleys both consist of fixed cone disc and movable cone disc. The driving force between the two pulleys is transmitted by the thrust-type metal belt. While in working, the movable cone discs of the two pulleys move on the axial direction by the force of disk spring. The metal belt's working radius around pulley changes, so as to achieve the change of speed ratio.

Disk spring is the energy storage element, used for energy transmission. In order to facilitate further analysis, we can just convert the load of motor shaft and the screw part to motor shaft, as shown in Figure 5.

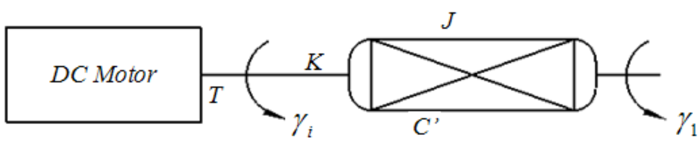


Figure 5. Convert of speed ratio control motor driving

Converting the quality firstly, moment of inertia of the motor shaft J is:

$$J = J_0+\left(\frac{\omega_1}{\omega}\right)^2 J_1+\left(\frac{\omega_2}{\omega}\right)^2 J_2+\left(\frac{v}{\omega}\right)^2 m_3 \quad (12)$$

Equivalent to:

$$J = J_0 + \left(\frac{1}{i_1}\right)^2 J_1 + \left(\frac{1}{i_1 i_2}\right)^2 J_2 + \left(\frac{1}{i_1 i_2 i_3}\right)^2 m_3 \qquad (13)$$

In equations above: J_0 is the moment of inertia of the motor shaft; J_1 is the moment of inertia of shaft 1; J_2 is the moment of inertia of shaft II; ω_1 is the rotating speed of shaft 1; ω_2 is the rotating speed of shaft II; v is the moving speed of movable cone disc on driving pulley; m_3 is the quality of the screw moving translationally. i_1 is the speed ratio between shaft 1 and the motor shaft; i_2 is the speed ratio between shaft 2 and the motor shaft; i_3 is the speed ratio between shaft 3 and the motor shaft, $i_3 = 2\pi / P$, P is the lead of screw.

Converting the static force secondly, then using the theory of power conservation:

$$F_{DR} v = T\omega\eta_m = T\frac{n \cdot 2\pi}{60}\eta_m \qquad (14)$$

and

$$T = \frac{30 F_{DR} v}{n\eta_m} \qquad (15)$$

In equation (15), F_{DR} is the axial force of the movable cone disc on driving pulley. It can be determined by the CVT's external load, and $F_{DR} = f(T_d)$, which can be obtained by empirical formula (15); η_m is the transmission efficiency. From the motor shaft to screw; n is the rotating speed of motor shaft, $n = (30/\pi)\omega$.

Converting the damping coefficient of screw to the motor shaft, the damping coefficient converted is C, it follows:

$$\frac{1}{2} C \dot{\gamma}_1^{2} = \frac{1}{2} C' \dot{x}_p^{2} \qquad (16)$$

and

$$C = \frac{C'}{i_1^2 i_2^2 i_3^2} \qquad (17)$$

The system dynamic equation after conversion is:

$$J\ddot{\gamma}_1(t) + C\dot{\gamma}_1(t) + K[\gamma_1(t) - \gamma_i(t)] = 0 \qquad (18)$$

thus: $\gamma_1(t) = i_1 i_2 i_3 x_p(t)$, and

$$J\ddot{x}_p(t) + C\dot{x}_p(t) + Kx_p(t) = K\frac{\gamma_i}{i_1 i_2 i_3} \qquad (19)$$

Using laplace transform on both sides:

$$(Js^2 + Cs + K)X_p(s) = K\frac{\Gamma(s)}{i_1 i_2 i_3} \qquad (20)$$

The input is the motor's rotation angle, and the output is the displacement of movable cone disc on driving pulley. The transfer function is:

$$\frac{X_p(s)}{\Gamma(s)} = \frac{K/i_1 i_2 i_3}{Js^2 + Cs + K} \tag{21}$$

Known from the article above, in equation (21), $C = \frac{C'}{i_1^{\,2} i_2^{\,2} i_3^{\,2}}$.

The speed ratio control motor system model in Matlab/Simulink is shown in Figure 6

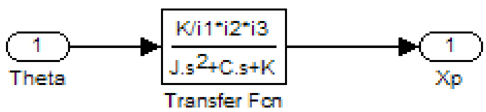


Figure 6. Speed ratio control motor system model in Matlab/Simulink

7. Conclusion

EMCVT is a new vehicular CVT, which adopts dc motor to control rolling screw to add pressure to the cone disc to modulate velocity. Compared with the traditional CVT, it removes the hydraulic system completely, so its convenience of controlling, fuel conservation and its low cost are the greatest advantages. The analysis and modeling of the control factor of the EMCVT will provide the theoretical support for the construction of the control system and the selection of the control strategy in EMCVT.

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