Optimization of the speed regulation performance of a rubber belt CVT for a vehicle

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Abstract. The structure of a CVT in a vehicle is explained, and its characteristics is analyzed. The optimal scheme is selected, according to the influence of various parameters on the speed regulation characteristics of the transmission. The results show that the speed regulation performance can be optimized by changing the structure of the transmission, and the state of working near the maximum power point can be maintained for the engine. Compared with the general transmission, CVT (continuously variable transmission) has the advantages of simple operation, smooth transmission, less noise and small size. The speed regulation characteristics of the rubber belt CVT refers to the CVT's own structure is changed with the changing driving conditions of the vehicle, so that it can achieve the purpose of a better speed regulation. CVT’s speed regulation characteristics affect the degree of matching between CVT and the vehicle's power transmission system, and the power transmission performance of the whole vehicle.

1. Introduction
The rubber belt CVT of the vehicle is composed of three parts: driving cone wheel, driven cone wheel and V-shaped transmission belt. The power is transmitted from the engine to the driving cone wheel through the crankshaft, and then transmitted to the driven cone wheel through the V-shaped drive belt. Finally, it is transmitted from the driven cone wheel to the driving wheel. The movement principle of the driving and driven cone wheel is based on the transmission of the V-shaped transmission belt. Since the length of the V-shaped transmission belt is basically unchanged, the application rules of the two cone parts basically correspond to each other. The rubber belt CVT realizes the stepless speed change by changing the working radius of the V-shaped transmission belt [1].

1.1. The driving cone wheel
The main components of the driving cone wheel include fixed wheel, movable wheel, speed control hoof block, return spring, tripod and platen and so on. The specific structure is shown in Figure 1.
Figure 1. The structure of the driving cone wheel.

1. Driven cylinder 2. Movable disc of driven wheel 3. Transmission belt 4. Input shaft 5. Fixed driving disk 6. Driving cylinder 7. Movable disc of driving wheel 8. Fixed disc of driven wheel 9. Output shaft

The minimum distance between the cone surfaces of the driving cone wheel is slightly larger than the maximum width of the transmission belt. When the engine is idling, the centrifugal force is too small. So the wheel disc is not enough to support the belt rotation, and the power transmission is interrupted. As the engine speed rises, the centrifugal force becomes larger, the axial movement of the wheel disc makes the belt tight and the power can be transmitted. And the engine speed can directly affect the position of the active cone wheel disc. The purpose of adjusting the speed ratio can be achieved by changing the radius of the driving cone wheel.

1.2. The driven cone wheel

The main components of the driven cone wheel include fixed wheel, movable wheel, torsion spring and platen and so on. The specific structure is shown in Figure 1.

A torsion spring acts between the fixed wheel and the movable wheel. The fixed wheel is fixed on the output shaft. Under the condition of stable speed and load, the torque and load transmitted by the entire transmission system are in a balanced state. When the external load increases, the fixed wheel and the movable wheel will rotate relatively in a short time. An angular displacement difference will be produced. At this time, the difference in angular displacement between the two wheels causes the movable wheel to move axially towards the fixed wheel, thereby reducing the opening of the wheel groove and increasing the working radius of the transmission belt on the cone wheel, in order to increase the output torque of the transmission system, and balanced with the externally increased load. Conversely, when the external load is reduced, the moving wheel moves outwards to reduce the output torque, while reducing the speed ratio.

1.3. Transmission belt

The transmission belt in the rubber belt CVT uses a toothed wide V-belt. Compared with the ordinary V-belt, the toothed wide V-belt has a large area to withstand the side pressure, which enhances the lateral rigidity of the belt and wear resistance, and improves the stability, softness, heat resistance and oil resistance of the V-shaped transmission belt on the small cone wheel performance. So it has a good match with the cone wheel, reducing the bending hysteresis loss, improving the transmission efficiency and the stable speed ratio between the wheel discs.

2. The analysis of the speed regulation performance

The main goal of CVT speed regulation is to make the engine to maintain within the optimal speed range of the power function, and to ensure the transmission characteristics and the power of the vehicle. Table 1 shows the main parameters of the rubber belt CVT. Bring it into the mathematical model of the CVT in the steady state, and numerically solving it in Matlab, different values can be calculated, including engine speed, working radius of driving cone wheel under load, the wrap angle
of the driving and driven cone wheel, the tight tension of the V-shaped drive belt, and the moving amount of the movable cone disk. Furthermore, the speed regulation performance of the rubber belt CVT can be analyzed, and the performance of the CVT can be evaluated from the aspects of geometry and force parameters [2].

Table 1. Main parameters of the rubber belt CVT.

| Item                        | Parameter                              | Index |
|-----------------------------|----------------------------------------|-------|
| Installation parameters of  | Maximum transmission ratio of structure| 3.1   |
| the CVT                     | Maximum working diameter of cone wheel /mm| 90    |
| Cone wheel                  | Maximum working diameter of cone wheel /mm| 272   |
| Cone angle of symmetrical  | Center distance /mm                    | 308   |
| cone wheel                 | Coefficient of friction between driving belt and conewheel | 0.6   |
| Transmission belt           | Top width /mm                          | 35    |
| Cone wheel                  | Height /mm                             | 15    |
| Belt length /mm             | Mass /kg                                | 0.689 |
| Wedge (/°)                  |                                       | 30    |
| Spring                      | Stiffness of return spring /N/mm       | 20.2  |
|                           | Length of spring /mm                   | 65.4  |
|                           | Spring length while at limitworking state /mm | 36.9 |
|                           | Stiffness of torsion spring /N/mm      | 5.2   |
|                           | Initially compressed length /mm        | 33    |
|                           | Compression while at limit working state /mm | 72   |
| Speed control hoof block    | Mass /kg                               | 0.0045 |

2.1. Speed regulation mechanical model of the CVT

When the CVT adjusts the speed, the speed control hoof block induces a horizontal axial component produced by the engine speed. The CVT overcomes the spring precompression force to move the movable wheel of driving cone wheel to the fixed wheel and transmits the power to the belt through the clamped transmission belt, and overcoming the resistance torque at the driven wheel [3]. The calculation begins by determining whether the CVT is at the maximum transmission ratio or the minimum transmission ratio. If not, it means that the axial thrust exerted by the hoof block on the movable cone of the driving cone and the axial thrust of the transmission belt acting on the drive pulley are in a state of force balance. Therefore, the effective pitch radius of the belt is in balance between the maximum and minimum transmission ratios position. Using Newton's Method to solve nonlinear equations

\[ f_i(x_1, x_2, \ldots, x_9) = 0, \ i = 1, 2, \ldots, 9 \]  \hspace{1cm} (1)

So we can find its equilibrium position. The joint equations can be established according to the force balance principle and the geometric relationship, with reference to the mechanical model of the driven and driving cone wheel in this rubber belt CVT and mechanical principle, and the V belt transmission experience formulas obtained in the literature [4] and [5]. F(x) can be divided into a 9-component vector \( f_1, f_2, \ldots, f_9 \), \( X = [r_1, r_2, \Theta, \Theta_0, \tau, F_1, F_2, \Delta \omega, x] \) is the solution to the system of equations. Among them, r1 and r2 are the pitch circle radius of the driving and driven cone.
wheels respectively. \( \theta \) is the change of the speed control hoof block angle with the axial displacement. \( \theta_r \) is the amount of change of the contact angle with the axial displacement. And \( \tau \) is the initial contact angle of the pressure roller of the speed control hoof block and the extrusion. \( F_1 \) and \( F_2 \) are respectively the tight-side tension and loose-side tension in the drive belt. \( \Delta \alpha \) is the amount of change of the speed control hoof block in the swing angle. And \( x \) is the axial movement of the movable cone.

Let \( X_{n+1} \) be the value of \( X \) in the \((n+1)\)th iteration, then \( X_{n+1} = X_n + \Delta X_n \). Newton's method for solving equations can be written as

\[
X_{n+1} = X_n - \frac{F(X_n)}{J_b(X_n)}
\]

(2)

Among them, \( J_b(X_n) \) is the Jacobian matrix of \( F(X_n) \), which can be obtained by partial derivative of 9 variables, namely

\[
J_b(X_n) = \begin{bmatrix}
\frac{\partial f_1}{\partial \theta} & \frac{\partial f_1}{\partial \theta_r} & \frac{\partial f_1}{\partial \tau} & \frac{\partial f_1}{\partial \Delta \omega} & \frac{\partial f_1}{\partial x} \\
\frac{\partial f_2}{\partial \theta} & \frac{\partial f_2}{\partial \theta_r} & \frac{\partial f_2}{\partial \tau} & \frac{\partial f_2}{\partial \Delta \omega} & \frac{\partial f_2}{\partial x} \\
\vdots & \vdots & \vdots & \vdots & \vdots \\
\frac{\partial f_9}{\partial \theta} & \frac{\partial f_9}{\partial \theta_r} & \frac{\partial f_9}{\partial \tau} & \frac{\partial f_9}{\partial \Delta \omega} & \frac{\partial f_9}{\partial x}
\end{bmatrix}
\]

(3)

The error between the approximate solution and the true solution obtained by Newton's method is

\[
\delta_f = \sqrt{f_1^2 + f_2^2 + \cdots + f_9^2}
\]

(4)

When it continuously iterates by using the Newton method until the error is less than the set precision, the Newton method reaches convergence and we obtain the numerical solution. The calculation accuracy of the Newton method we set is 10^-4. In Matlab, the Newton Gauss iterative method is used to solve the nonlinear equations, and the structural parameters of the CVT are brought in. Given the engine speed and the torque of the driven wheel, the equations can be approximate solution.

2.2. Analysis of speed regulation performance

Use Matlab to obtain the change of transmission ratio under different engine speeds and load conditions. When the vehicle starts, the engine must be combined at a certain speed, so as to have enough power to drive the vehicle [4]. After calculation, the combined speed of the CVT can be obtained as 3227r/min. Based on the relationship between the transmission ratio and the engine speed and load, under the condition of constant speed variable load, the CVT speed ratio decreases with the load increasing and under the condition of constant load variable speed, the CVT speed ratio decreases with the speed increases. The transmission ratio changes in the range of 0.8-2.98. The load torque range of the engine at the maximum power point speed of 6,000r/min is 10-68N•m. Under no-load operating conditions, the engine speed range is 3,500-6,500r/min [5].

After calculation, when the engine speed reaches 6,700r/min, the power balance point is reached, the corresponding maximum speed is 70km/h, and the speed regulation range is 4,500r/min-6,800r/min. Since the end point of the vehicle speed regulation is 6,800r/min, which is much higher than the engine's maximum power point speed of 6,000r/min, the optimal speed control performance of the CVT speed control can not be reached. This will cause the rubber belt CVT gear ratio to suddenly increase when the vehicle encounters climbing or acceleration during driving to overcome load changes. However, the power and torque output by the engine at 6,800r/min are very small. The engine can only provide greater output power by reducing the speed, resulting in frequent changes in engine speed, thus losing the best CVT speed control performance.
2.3. Optimization of speed regulation performance

By analyzing the CVT speed regulation characteristics, it can be seen that the prototype cannot maintain the engine speed around the maximum power point, which affects the power of the equipment [6]. The 3 optimization schemes are proposed (shown in Table 2) through the establishment of the mechanical model and the analysis of the speed regulation performance, according to the working principle of the rubber belt CVT, combined with the characteristics of the engine, by adjusting the mass center position and mass of the speed control hoof block, the return spring parameters and the torsion spring parameters in Matlab.

Table 2. The parameters of optimization scheme.

| Optimization scheme | Centroid position Width /mm | High /mm | Hoof mass /g | Return spring Stiffness /N/mm | Pre-compression /mm | Torsion spring Stiffness /N/mm | Pre-compression /mm |
|---------------------|-----------------------------|----------|--------------|-------------------------------|---------------------|-------------------------------|---------------------|
| Original scheme     | 1.79                        | 60.6     | 45           | 20.2                          | 16                  | 5.2                           | 33                  |
| Scheme 1            | 1.79                        | 60.6     | 56           | 11.1                          | 13.5                | 7.51                          | 51.5                |
| Scheme 2            | 2                           | 58       | 54           | 18                            | 15                  | 5.8                           | 50                  |
| Scheme 3            | 2.05                        | 57.6     | 50           | 14.8                          | 13                  | 7.2                           | 55                  |

The combined speed, the range of clutch speed, the range of speed regulation and the corresponding transmission ratio range are obtained and shown in Table 3, according to the optimization scheme, through the calculation of the relationship between the combined speed and transmission ratio with the engine speed and load, as well as the equipment power balance and speed regulation characteristics.

Table 3. Comparison of CVT transmission characteristics of optimization schemes.

| Scheme    | Combined speed /r/min | Clutch speed /r/min | Speed regulation range /r/min | Transmission ratio range |
|-----------|------------------------|---------------------|-------------------------------|--------------------------|
| Original scheme | 3227                   | 3800-4550           | 4500-6800                     | 0.8-2.98                 |
| Scheme 1  | 2515                   | 3200-3850           | 3880-5750                     | 0.8-2.98                 |
| Scheme 2  | 2879                   | 3420-4075           | 4075-5950                     | 0.8-2.98                 |
| Scheme 3  | 2690                   | 3420-4100           | 4100-6000                     | 0.8-2.98                 |

It can be seen from the characteristics of the engine [6] that the maximum torque point of the engine is around 5,000r/min and the maximum power point is around 6,000r/min. The ideal goal of the CVT speed regulation is that the engine is maintained near the maximum power point to ensure the equipment power. By comprehensively comparing the above three optimization schemes, it can be seen that the transmission characteristics of CVT in the above three schemes have been greatly improved compared with the original scheme. Scheme 2 and scheme 3 are slightly better than scheme 1, with the speed regulation range of 4,000-6,000r/min, which is basically maintained at the best working area and ensures the smooth start and acceleration of the vehicle. The range of drag that can be tolerated near the maximum power point of the engine is also relatively large, which can meet the requirement that the CVT continues to maintain the maximum power during climbing and rapid acceleration during driving near the point is unchanged. By changing the CVT speed ratio we can meet the driving power needs of the vehicle.

In the above schemes, the maximum speed of CVT is maintained at 85km/h, mainly because of the theoretical calculation of the maximum speed without considering of the effect of transmission efficiency. The transmission efficiency of CVT at different speed ratios also has a great relationship with the side pressure of the driven and driving cone wheels. By changing the structural parameters of CVT, multiple sets of optimization solutions can be found to meet the requirements of speed regulation performance. But to achieve the most optimal for dynamic performance, the influence of transmission efficiency must also be considered. According to the mechanical model, it is hoped that the rigidity of the active cone spring is small and the resistance of the movable cone is reduced; the rigidity of the driven cone spring is too large to prevent the load sensing ability from being too
sensitive and causing the speed regulation to be too fast during driving. Taking all factors into consideration, it is considered that the optimal solution 3 is the best.

3. Conclusions

Three optimization schemes are proposed, and the optimal schemes are calculated and analyzed respectively, in order to make the vehicle get better power performance, through the analysis of CVT transmission characteristics, according to the influence of various parameters on CVT speed regulation characteristics. By changing the own structure of CVT, the speed regulation performance is optimized, and the engine is maintained near the maximum power point for operation in a stable state to achieve the purpose of optimization.

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