Study on Matching Strategies and Simulation of Hydro-mechanical Continuously Variable Transmission System of Tractor

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***Abstract*-In this paper, the engine output torque model and fuel consumption model are established based on engine test results. The engine rotary speed feature denotes the relationship between the engine rotary speed and the throttle opening when engine works in the optimal modes of economic and power operating. On the basis of the above work, the matching strategies of hydro-mechanical continuously variable transmission (HMCVT) system are put forward. According to the different fieldwork of tractor, the matching strategies of HMCVT system are studied by simulation method. The research provides theoretical foundation for design and control method determination of HMCVT system.**

Keywords- Tractor; Hydro-mechanical continuously variable transmission; Matching strategies; Simulation

I. INTRODUCTION

The hydro-mechanical continuously variable transmission (HMCVT) is a new type transmission device which consists of a mechanical transmission (MT) combined in parallel with a hydrostatic transmission (HST) featuring a pair of hydraulic units. The HMCVT has a continuously variable shifting ratio by the combination of HST and MT and achieves high efficiency by MT [1, 2]. Only when the reasonable matching of HMCVT system and engine is realized, the advantage of HMCVT system can be exerted. The matching key is that according to the actual working conditions of tractor and the chracteristics of engine, the engine is worked at optimum condition by regulating the speed ratio of HMCVT system. The speed ratio regulation of HMCVT system of tractor can be realized by controlling the displacement ratio of variable hydraulic pump (PV) and fixed hydraulic motor (MF).

At present, the research of continuously variable transmission system matching at home and abroad is mainly concentrated in the automobiles [3, 4, 5], and the research about tractor has not been reported. The tractor not only has difference on structure with the automobile, but also has the bad working condition and the frequent outside load fluctuation. All those require the speed ratio to change timely to accommodate the variation of load and motion resistance, and ensure the dynamic performance and fuel economy of tractor. The purpose of this paper is to solve the matching strategies and simulation problem of HMCVT system for tractor, in order to provide theory basis for determination of tractor control method.

II. ENGINE OUTPUT CHARACTERISTIC

A. Engine Output Torque

The engine is a more complicated system, whose output torque is usually the functions of the throttle opening and rotary speed of engine. Based on engine test results, the relation between the engine steady state output torque and throttle opening and rotary speed can be established by using the polynomial fitting. The relation surface between the engine output torque and throttle opening and rotary speed can be gained as Fig. 1 by using the polynomial fitting.

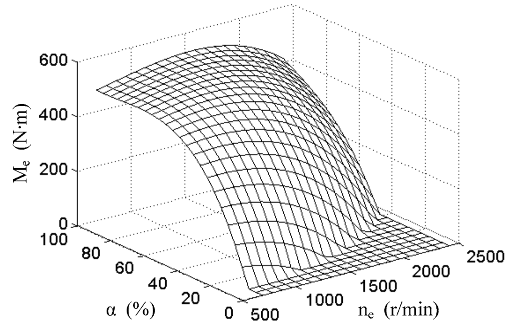

Figure 1. Relation of output torque with throttle opening and rotary speed of engine

B. Engine Universal Characteristic

The relationship between the engine power and fuel consumption can be achieved according to the load characteristic curve of each rotary speed of engine. Then the relation curve surface between the engine effective fuel consumption and rotary speed and torque can be gained by using the spline interpolation fitting. The universal characteristic curve of engine (Fig. 2) can be gained by using the numerical model of engine.

In Fig. 2, the curve ABC is the external characteristic curve; the oblique lines AU, BFS and CGT are the speed regulation characteristic curves; the points A, B and C are the maximum power output points, respectively. At the different throttle position, although the engine can work at the maximum power output point, the engine has pure anti-over loading ability at some maximum power output point such as points B and C, which is easy to cause the flameout of engine. Thus, at the different throttle position, the maximum power output point of engine should be set as the points A, F and G of Fig. 2. So, customarily, the curve AFG is called as the optimal power performance working curve,

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namely D curve.

If the minimum fuel consumption points (in Fig. 2) which have the same power are connected, the optimal fuel economy performance working curve of engine can be achieved as the curve AST of Fig. 2, namely E curve.

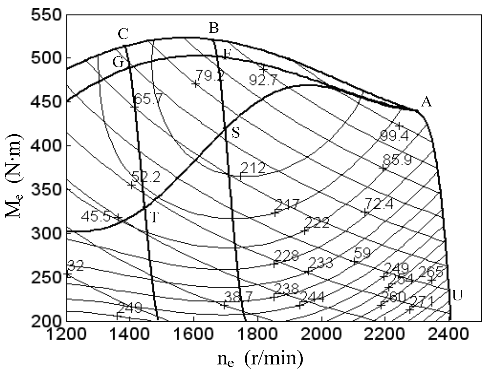

Figure 2. Engine universal characteristic curve

C. Regulating Feature of Engine Rotary speed

The regulating feature of engine rotary speed of engine is that when the load of output shaft changes, the speed ratios of vehicle transmission device are independently regulated in order to maintain the engine power at the relative value. If the engine works at the rotary speed of minimum fuel consumption at each relative power, the relationship between the throttle opening and rotary speed is the rotary speed of optimal fuel economy performance. If the engine works at the rotary speed of maximum power at each relative throttle opening, the relationship between the throttle opening and rotary speed is the rotary speed of optimal power performance. The regulating feature of engine rotary speed of engine can be drawn up as Fig. 3. In Fig. 3, curves D and E are the engine regulating feature curves of the optimal power and best fuel economy performance respectively.

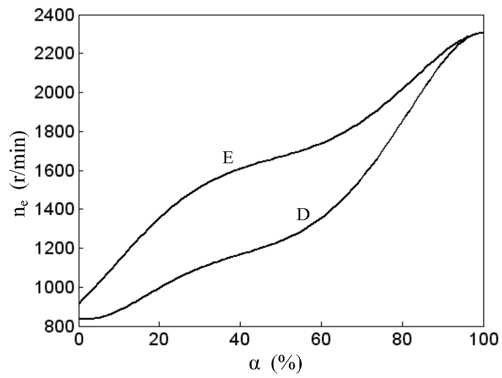

Figure 3. Regulating feature of engine rotary speed

III. MATCHING STRATEGIES OF HMCVT SYSTEM

The matching sketch of HMCVT system is given as Fig. 4. The engine can work at the optimal power performance working curve D or the best fuel economy performance working curve E by controlling the throttle opening of engine and regulating the speed ratio of HMCVT system. During the actual work, the working point should be fall on the area which is consisted of the minimum steady rotary speed curve l, external characteristic curve w and regulation speed characteristic curve t of engine.

For the HMCVT system of tractor, each point of effective working range of engine has the one to one correspondence of the driving force and tractor speed of the driving diagram of tractor, whose concrete expression formula are presented as follows:

$$F_q = \frac{M_e i \eta_c \eta_l}{r_d} \tag{1}$$

$$v = \frac{0.377 n_e r_d \eta_\delta}{i} \tag{2}$$

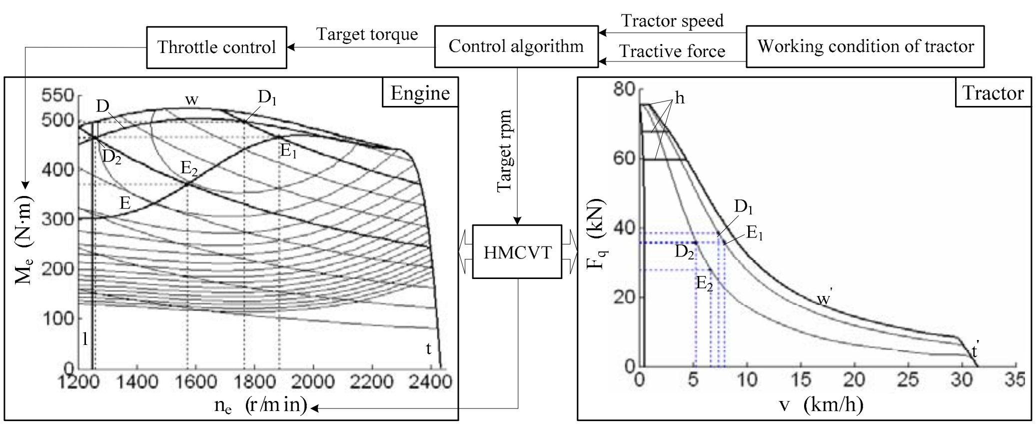

Figure 4. Matching sketch of HMCVT system

where, F_q is the driving force of tractor, kN; M_e is the engine torque, N·m; n_e is the rotary speed of engine, r/min; r_d is the dynamic radius of driving wheel, m; i is the transmission ratio of HMCVT system; η_c is the efficiency of HMCVT system; v is the tractor speed, km/h; η_δ is the wheelslip efficiency; η_l is the tracked driving range efficiency, for wheel type tractor $\eta_l=1$.

By referencing the calculation methods of the documents [6], each point of effective working range of engine is corresponded to the driving characteristic diagram of tractor (Fig. 4). In Fig. 4, the curves l', w' and t' are corresponded to the engine ideal working boundary curves l, w and t respectively; the line h is the line of the maximum driving force which the tractor restricted by the ground adhesive force can provide.

It can be seen that from Fig. 4, at the steady and optimal power and fuel economy performance condition, when the tractor works at a definite speed, there is a unique point of the ideal engine working curves which is corresponded to the working state of tractor. In the universal characteristic curve of engine, the working condition of each point is definitive. The engine throttle opening, ideal rotary speed and torque have the one to one correspondence of the speed ratio of HMCVT system. The engine can work at the optimal power performance working curve D or the best fuel economy performance working curve E by controlling the throttle opening of engine and regulating the speed ratio of HMCVT system. According to the beforehand determined corresponding relation between the throttle opening and output power of engine, the engine can work at the specific working point by controlling the throttle opening of engine and regulating the speed ratio of HMCVT system.

It can be seen that from Fig. 2 and Fig. 3, whether the optimal power performance or the best fuel economy performance, the engine throttle opening, rotary speed and output power have the one to one correspondence. In each engine throttle opening, to ensure that the tractor can work with the different speed, the HMCVT system must have the relative speed ratio to insure that the engine work at the optimal working point. The transmission target speed ratios are presented as Fig. 5 when the engine works at the optimal power performance. When the engine works at the best fuel economy performance, the transmission target speed ratios are presented as Fig. 6. The target speed ratios can be stored in the memory unit of controller. According to the actual working conditions of tractor, the engine working point can be controlled by regulating the speed ratios of HMCVT system. Then the tractor can work at the conditions of optimal power performance and best fuel economy performance.

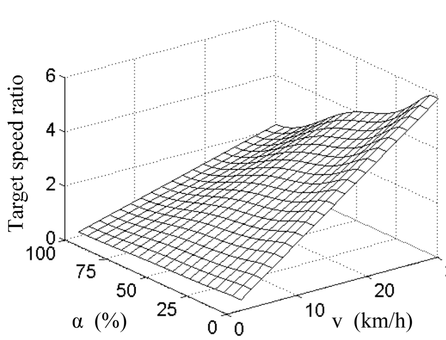

Figure 5. Target speed ratios of engine optimal power

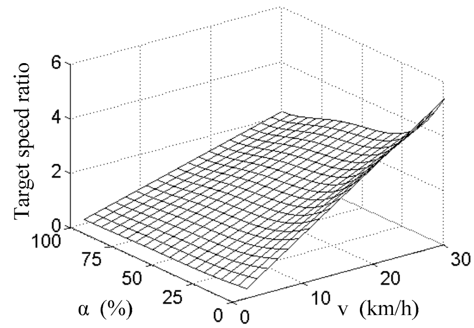

Figure 6. Target speed ratios of engine best fuel economy

IV. Simulation Analysis

During the actual operation of tractor, there are usually two typical working conditions: one is the working condition of constant traction resistance of tractor and variable throttle opening of engine, the other is the working condition of constant throttle opening of engine and variable traction resistance of tractor. Based on above, taking the best fuel economy performance of engine as an example, the simulation analysis of HMCVT system is carried out by two conditions in this paper: one is that the traction resistance of tractor is constant and the throttle opening of engine is variable, the other is that the throttle opening of engine is constant and the traction resistance of tractor is variable. In these conditions, the rotary speed of engine can work at the target working point by regulating the speed ratio of HMCVT system.

A. Constant Traction Resistance and Variable Throttle

The simulation working conditions are that the traction resistance of tractor F_t is equal to 40kN and keeps invariant, and the starting throttle opening of engine α is equal to 50%; after 10s of starting, the throttle opening of engine increases to 100%; when tractor runs to 30s, the throttle opening of engine decreases to 70%. The simulation results are presented as Fig. 7.

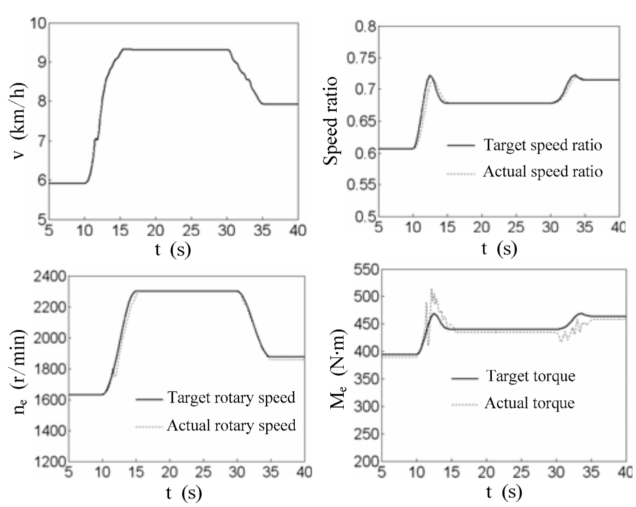

Figure 7. Simulation result curves of constant traction resistance and variable throttle working condition

It can be seen that from Fig. 7, at the time of t=10s, the throttle opening of engine increases suddenly from 50% to 100%, tractor is in the acceleration driving period, and the engine can work at the new target rotary speed by regulating the speed ratio of HMCVT system. Than, the throttle opening of engine maintains at 100%, tractor is in the uniform driving period. At the time of t=30s, the throttle opening of engine reduces suddenly from 100% to 70%, tractor is in the deceleration driving period, and the engine can also work at the new target rotary speed by regulating the speed ratio of HMCVT system. During the acceleration and deceleration driving periods, as HMCVT system has some time delay effect, the fluctuation of actual output torque of engine occurs. It can be seen that from simulation result curves, when the traction resistance of tractor is constant and the throttle opening of engine is variable, the output rotary speed and torque of engine can be basically stabilized at the best fuel economy performance working curve by regulating the speed ratio of HMCVT system.

B. Constant Throttle and Variable Traction Resistance

The simulation working conditions are that the throttle opening of engine α is equal to 70% and keeps invariant, the starting traction resistance of tractor F_t is equal to 60kN; after 10s of starting, the traction resistance of tractor reduces to 30kN; when tractor runs to 30s, the traction resistance of tractor increases to 60kN. The simulation results are presented as Fig. 8.

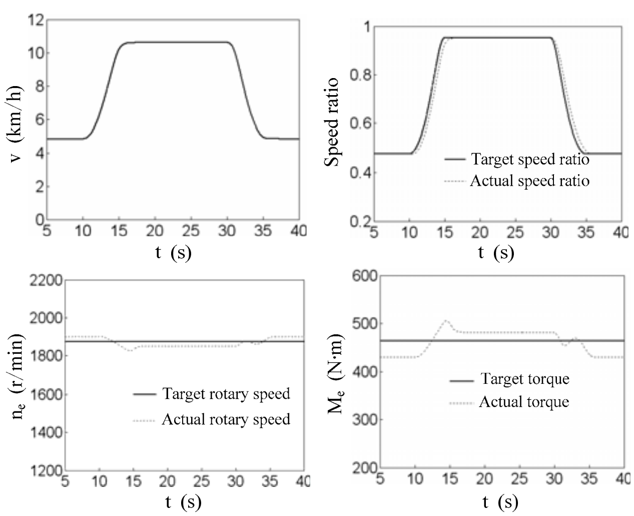

Figure 8. Simulation result curves of constant throttle and variable traction resistance working condition

It can be seen that from Fig. 8, before t=10s, the balance between the actual output torque of engine and the traction resistance torque of tractor can be keep, and the tractor is in the stable driving state. At the time of t=10s, the traction resistance of tractor reduces suddenly from 60kN to 30kN, the rotary speed of engine has an increase trend. In order to maintain the rotary speed of engine at the target rotary speed, the speed ratio of HMCVT system needs to be increased. Than, the tractor is in the acceleration driving period until the new power balance point occurs. Afterwards, the tractor is in the uniform driving period. At the time of t=30s, the traction resistance of tractor increases suddenly from 30kN to 60kN, the tractor is in the deceleration driving period. During the uniform driving period, as the speed ratio changing rate of HMCVT system is insufficient, there is a certain error between the working point of engine and the target working point.

V. CONCLUSIONS

Based on engine test results, the engine output torque model and fuel consumption model are established, and the regulation characteristics of engine rotary speed are determined. On the basis of the above work, the matching strategies of HMCVT system are studied. The two typical working conditions of tractor are analyzed by simulation method. The results show that the matching strategies determined in this paper are correct and feasible, and the reasonable matching of engine and HMCVT system is realized.

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