Analysis and Matching Calculation of Hydraulic Drive System of Tractor

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Abstract—Firstly, the matching principle of engine and hydraulic torque converter working together is introduced. Then, the mathematical model of matching input and output between tractor engine and hydraulic torque converter is established. The least square fitting method is adopted to fit the characteristic curves of tractor engine and hydraulic torque converter. The vehicle performance is evaluated by calculating the traction characteristics of the vehicle, which not only reduces the workload, but also improves the calculation accuracy.

1. INTRODUCTION
In the design of traction vehicle, dynamic matching and traction calculation are the key links of vehicle design. Especially for the hydraulic driving tractor, due to the difference in the dynamic characteristics of the hydraulic driving device, it is necessary to find the operating point of the engine and the hydraulic torque converter working together, then the matching calculation of the power transmission device is carried out to make the power configuration of the tractor achieve the best performance. Fitting the characteristic curve of the engine and the torque converter correctly is the premise of solving the common working point of the engine and the torque converter[1].

2. MATCHING PRINCIPLE
The ideal match is that the working section of the engine that is intended to work together should be able to meet the requirements of the vehicle's dynamic performance and economic performance, while taking into account some special requirements, such as heat and noise [2]. And according to each link of the whole vehicle transmission system, the ideal match is finally determined as follows:

1) Give full play to the power of the diesel engine: use the highest efficiency of the torque converter to transfer the rated power of the engine, so that the vehicle can achieve the maximum average speed.

2) Stable starting operation and low fuel consumption: the highest efficiency of the torque converter is utilized to transfer the highest efficiency and torque of the engine at the lowest fuel consumption, so that the vehicle has good economy.

3) To meet the vehicle work and speed requirements: using the torque converter of the highest torque ratio condition, transfer the maximum torque of the engine, so that the vehicle has a greater traction.
3. ENGINE CHARACTERISTIC CURVE

The characteristic curve provided by the general engine factory is measured on the test bench without auxiliary device consumption power, which belongs to the engine calibration power and torque. Therefore, to solve the joint working point of engine and hydraulic torque converter, the characteristic curve of engine should be modified reasonably first. The loading power of the engine is selected for calculation, that is, the maximum effective power after deducting the reduced power value under certain conditions. Excluding auxiliary device consumption power mainly includes direct and indirect drive auxiliary device consumption power [3].

1) The engine torque ($M_e$) under external characteristics of the engine can be regarded as a function of the engine speed ($n_e$), which can be expressed by the following polynomial:

$$M_e = \sum_{i=0}^{K} A_i \times n_e^i (i = 0,1,2,\ldots, K)$$ (1)

- $M_e$ - the effective torque of the engine (N\cdot m);
- $n_e$ - Engine speed (r/min);
- $A_i$ - Polynomial coefficients to be fitted;
- $K$ - The order of a polynomial.

Let the test data of $N$ groups ($M_{ei}$, $n_{ei}$) be known, put each group of data ($M_{ei}$, $n_{ei}$) into the above equation, and record the random error ($e_i$), then:

$$
\begin{bmatrix}
M_{e1} \\
M_{e2} \\
\vdots \\
M_{en}
\end{bmatrix} = 
\begin{bmatrix}
1 & n_{e1} & n_{e1}^2 & \cdots & n_{e1}^k \\
1 & n_{e2} & n_{e2}^2 & \cdots & n_{e2}^k \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
1 & n_{en} & n_{en}^2 & \cdots & n_{en}^k
\end{bmatrix} 
\begin{bmatrix}
A_0 \\
A_1 \\
\vdots \\
A_k
\end{bmatrix} + 
\begin{bmatrix}
e_1 \\
e_2 \\
\vdots \\
e_N
\end{bmatrix}
$$ (2)

Write this in matrix form:

$$M_e = A \cdot G \cdot A + E$$ (3)

$G$ is a matrix of order $N \times (k+1)$;
$M_e$ and $E$ are $N$ by 1 column vectors.

$$J = \sum_{i=1}^{N} e_i^2 = E^T \cdot E$$ (4)

If

By applying the principle of least square method [4], according to the extreme value theory, it can be obtained:

$$\frac{\partial J}{\partial A} = 0$$ (5)

The following relationship can be obtained from the above formula:

$$A = (G^T \cdot G)^{-1} \cdot G^T \cdot M_e$$ (6)

So

$$M_e = G \cdot A$$ (7)

2) According to the above principles, the curve fitting program is compiled to calculate the $A_i$ and $k$, and the external characteristic curve of the engine can be obtained.

$$M_e = 9549 \times \left[0.9 - 0.95 \times N_{\text{eff}} \times \frac{n_{\text{max}} - n_e}{n_{\text{max}} - n_{\text{eff}}} \times \frac{1}{n_e} \times \frac{N_n}{n_e} \right]$$ (8)
3) In order to calculate fuel consumption, a curved surface can be used to fit the fuel consumption characteristics of the engine, and a two-dimensional polynomial of fuel consumption \((g/kW\cdot h)\) with engine power and speed as independent variables is obtained.

4. PERFORMANCE CHARACTERISTICS OF HYDRAULIC TORQUE CONVERTER

The performance characteristics of the hydraulic torque converter can be described by the curve of the torque coefficient\((\lambda_B)\), torque ratio\((K)\) and the efficiency of the pump wheel changing with the transmission ratio\((i)\).

\[
\begin{align*}
\lambda_B &= f(i) \\
K &= f(i) \\
\eta &= f(i)
\end{align*}
\]

Data points were collected from the original characteristic diagram of the hydraulic torque converter, and the three curves were fitted by the method of least square fitting.

5. OUTPUT CHARACTERISTICS OF HYDRAULIC TORQUE CONVERTER

The input characteristics of the engine working together with the hydraulic torque converter refer to the variation characteristics of the torque and speed of the hydraulic torque converter working together with the engine at different speed ratios of the hydraulic torque converter. The load performance of the hydraulic torque converter applied to the engine is completely determined by the torque variation characteristics of the pump wheel:

\[
T_B = \rho g \lambda_B n_B^2 D^5
\]

\(T_B\) — Pump torque\((N\cdot m)\);
\(\rho\) — Working oil density\((kg/m^3)\);
\(g\) — Gravitational acceleration\((m/s^2)\);
\(\lambda_B\) — Pump wheel torque coefficient\((min^2/(m\cdot r)^2)\);
\(n_B\) — Pump speed\((r/min)\);
\(D\) — Effective diameter of pump\((m)\).

According to the input characteristics of the joint work, determine the torque\((M_T)\) and speed\((n_T)\) at the intersection point of load parabola of hydraulic converter and external characteristics of engine torque at different speed ratios \((i)\), select the different speed ratio\((i)\) and by the original characteristic curve, hydraulic torque converter can be respectively corresponding to the eta K value and efficiency value. According to the selected speed ratio\((i)\) and the \(n_B\) value of the speed at which the load parabola intersects with the external characteristics of the engine at this speed ratio, the turbine speed\((n_T)\), torque\((M_T)\) and power\((P_T)\) can be calculated:

\[
\begin{align*}
(n_T) &= i \times n_B \\
M_T &= K \times T_B \\
P_T &= \eta \times (T_B \times n_B) / 9549
\end{align*}
\]

Tabulate the data obtained from the above calculation, with \(n_T\) as the abscissa and other parameters as the ordinate, the output characteristics of the engine and the hydraulic converter working together can be obtained. According to the characteristics of the engine torque and torque converter corresponding to the joint point, the output characteristics of the torque converter are calculated.

6. VEHICLE TRACTION CHARACTERISTICS CALCULATION

According to vehicle parameters, transmission parameters, slip rate parameters and output characteristic parameters of engine and hydraulic torque working together, corresponding to each of the mechanical
transmission gear, theory of computing speed ($V$), traction power ($N_{KP}$), traction efficiency ($\eta_{KP}$) and fuel consumption $g_{KP}$, as the change of the traction force ($P_k$).

They are calculated as follows:

\begin{equation}
V = 0.377 \times \frac{n_i \times r_d \times (1 - \eta_\delta)}{\eta_m \times \sum i}
\end{equation}

\begin{equation}
P_{kp} = \frac{M_i \times \sum i \times \eta_m - m_0 g_f}{r_d}
\end{equation}

\begin{equation}
N_{KP} = \frac{P_{KP} \times V}{3.6}
\end{equation}

\begin{equation}
\eta_{KP} = \frac{N_{KP}}{P_e} \times 100\%
\end{equation}

\begin{equation}
g_{KP} = \frac{B}{N_{KP} \times 1000}
\end{equation}

\[\eta_m\] — Mechanical efficiency of transmission train;

\[r_d\] — The power radius of the drive wheel, (m);

\[\sum i\] — The total mechanical ratio of a gear;

\[\eta_\delta\] — Slip efficiency;

\[m_0\] — Total vehicle mass;

\[f\] — Rolling resistance coefficient.

7. **Calculation Example**

The CA4D32TC engine and YJH265 (high energy capacity) hydraulic torque converter are used in a tractor which is taken as an example to calculate..

7.1. **Engine characteristic curve**

The original data of CA4D32TC engine performance test are shown in table 1.

| Engine speed $n$ (r/min) | Torque $M_i$ (N·m) | Fuel consumption (kg/h) |
|--------------------------|-------------------|------------------------|
| 1 200                    | 200               | 2                      |
| 1 600                    | 260               | 6.5                    |
| 2 000                    | 275               | 8                      |
| 2 400                    | 265               | 14                     |
| 3 200                    | 250               | 19                     |

7.2. **Characteristics of YJH265 Hydraulic Torque Converter**

The test characteristics of YJH265 hydraulic torque converter are shown in table 2.

| $i$ | $M_{bg}$ (N·m) | $k$ | $\eta$ |
|-----|----------------|-----|--------|
| 0   | 36             | 3.1 | 0      |
| 0.3 | 38.5           | 2   | 0.6    |
| 0.65| 32             | 1.2 | 0.79   |
| 0.8 | 24.6           | 1   | 0.8    |
| 0.92| 13             | 0.93| 0.855 6 |
| 0.98| 2              | 0.84| 0.823 2 |
According to the characteristic curves of the engine and the hydraulic torque converter, the equation is approximated. Matlab software was used to represent the two curves in the same coordinate, and then the input characteristic curve of joint work was obtained as shown in figure 1. Then the output characteristic curve of joint work (figure 2) and the traction characteristic curve of each gear condition (figure 3 ~ figure 6) can be obtained.

Figure 1. Input characteristic curves working together

Figure 2. Output characteristic curves working together

Figure 3. First gear traction characteristic curve

Figure 4. The second gear traction characteristic curve
7.3. Vehicle Performance Analysis

1) When the total mass of the maximum traction is 40t (when the car is traveling at first gear speed), the required traction force is:

\[ P = 40000 \times 9.8 \times 0.03 = 11.8 \text{KN} \]

According to figure 3, the corresponding speed at this time is 14 km/h, the traction power is 42 kW, and the traction efficiency is 72.8%.

2) According to the traction characteristic curve of the forth gear shown in figure 6, the maximum speed of the car is 67.3 km/h;

3) The maximum traction force is:

\[ P_{\text{max}} = \frac{M_{\text{t, max}} \cdot i_c \cdot i_{sl} \cdot \eta_t \cdot \eta_h}{r} = 35 \text{ KN} \]

8. Conclusion

In this paper, the least square method is used for curve fitting and drawing, which improves the working efficiency and test accuracy. According to the matching principle and experimental data, the matching can meet the requirements for the highest speed and also for the maximum traction force at low gear. The engine works near the rated power and the fuel consumption rate is in the low zone, which provides a better method for the matching of hydraulic transmission system.

References

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