Chapter 42
Research on Parameters Optimization of Transmission System of Military Off-Road Vehicle

Bo Li, Xueyuan Li, Wei Wu, Junjie Zhou and Chaoheng Qin

Abstract The working conditions of Military off-road vehicles are harsh and complex, which put forward higher requirements on vehicle dynamic performance. Parameters of the transmission system obtained by the traditional geometric series division method is usually difficult to achieve good dynamic property and fuel economy. This paper proposed a comprehensive objective function of dynamic property and fuel economy based on weight coefficient method. On the basis of the traditional geometric series division method, considering the dynamic constraint conditions of off-road vehicles, a set of optimal transmission parameters are confirmed using the nonlinear optimization function fmincon in Matlab optimization toolbox. Simulation results show that the acceleration time and fuel consumption reduced after optimization, and the military off-road vehicles achieved a better dynamic property and fuel economy.

Keywords Powertrain system · Dynamic property · Fuel economy · Optimization and simulation · Vehicle dynamics

42.1 Introduction

Military off-road vehicles are always working on the harsh conditions such as desert, earthen road and hills. It put forward higher technical and tactical requirements to dynamic property of vehicles. The traditional geometric series division method based on experience is difficult to satisfy the higher requirements on

B. Li · X. Li · W. Wu · J. Zhou · C. Qin
Science and Technology on Vehicular Transmission Laboratory,
Beijing Institute of Technology, Beijing 100081, P.R. China

X. Li (✉)
Beijing Institute of Technology, Room 412, Building 9, Beijing 100081, P.R. China
e-mail: bit_libo@foxmail.com

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dynamic property and fuel economy. Generally speaking, there are two effective schemes to improve the vehicle dynamic property: (1) use engines with higher power and larger torque; (2) improve the matching of powertrain systems to exploit the maximum dynamic property of the engine. In the case of the selected engine, the second scheme is usually adopted [1]. In recent years, many researchers have done lots of research on powertrain matching and optimization and proposed some useful methods. Yao et al. established automatic transmission powertrain system optimal model, and developed powertrain parameters simulation programs. Lei built powertrain system model in ADVISOR software, and optimized the vehicle powertrain parameters using genetic algorithm [2]. Wang et al. built joint multi-objective powertrain optimization model on the basis of GT-Drive and GADST direct search toolbox. However, the optimization methods above are complex and need large amount of programs, which cost too much simulation time. To simplify the optimization process, this paper build powertrain model of off-road vehicles based on nonlinear optimization function fmincon in Matlab optimization toolbox. The maximum speed, dynamic factors, maximum climbable gradient, and road adhesion are regarded as constraint conditions of extreme driving mode. Main reducer ratio and gear transmission ratios are chosen as design variables. Acceleration time and fuel consumption of six cycle conditions are chosen as objective functions to indicate dynamic property and fuel economy of the vehicles. Weight coefficient method is adopted to allocate proportion of dynamic property and fuel economy. Better dynamic property and fuel economy is achieved after simulation and optimization in Matlab.

42.2 Mathematical Model of Powertrain Optimization

42.2.1 Definition of Design Variables

Powertrain system of vehicles includes engine, gear transmission, main reducer and differential. In the case of the selected engine, total transmission ratios of the powertrain system make a big difference on vehicle dynamic property and fuel economy, that is the product of the main reducer ratio and gear transmission ratio of each level [3]. In the process of the powertrain optimization, this paper neglect the reverse gear and just consider the forward gears. The optimal object is a 5-leveled military off-road vehicles, and the design variables are as follows:

$$x = [x_1, x_2, x_3, x_4, x_5, x_6] = [i_{g1}, i_{g2}, i_{g3}, i_{g4}, i_{g5}, i_0]$$

where i_{gj} (j = 1, 2, … 5) is the transmission ratio of j level, i_0 is the main reducer transmission ratio.

42.2.2 Establishment of Objective Functions

The matching and optimization of the vehicle powertrain parameters is a multi-objective problem. It aims at improving the dynamic property and fuel economy at the same time. However, the various objectives of the multi-objective optimization problem in general conflict with each other. Improvement of dynamic property leads to deterioration of fuel economy, the same as the inverse. So it is difficult to objectively evaluate the superiority-inferiority of the solution to a multi-objective optimization problem [4]. One non-domination optimal solution set is obtained in general, elements of which are named Pareto optimal solution. So it is very important to choose a proper weight coefficient between dynamic property and fuel economy to get the Pareto optimal solution.

42.2.2.1 Dynamic Property Sub-objective Function

Vehicle dynamic property includes three indicators: maximum velocity v_{max}, maximum climbable gradient α_{max} and acceleration time t respectively. The first two indicators focus on the extreme driving capability of the vehicles, while acceleration time indicates the comprehensive dynamic property of the vehicles. The continuous shift acceleration time t on the flat pavement is chosen as the dynamic property sub-objective function, while the maximum velocity v_{max} and the maximum climbable gradient α_{max} are regarded as constraint conditions. According to the vehicle driving equation, the acceleration expression is as follows in Eq. (42.1):

$$\frac{du}{dt} = \frac{1}{\delta m} \cdot [F_t - F_f - F_\omega] \tag{42.1}$$

Then, dynamics sub-objective function $f_1(X)$ is obtained. The mathematical expression is as follows in Eq. (42.2):

$$f_1(X) = t = t_0 + \int_{u_{\min}}^{u_t} \frac{\delta \cdot m}{3.6 \times [F_t - F_f - F_w]} du \tag{42.2}$$

where m is the mass of vehicle, kg; δ is the conversion factor of vehicle rotational mass; t is the continuous shift acceleration time, s; F_t is the driving force, N; F_f is the rolling resistance force, N; u is the velocity, km/h; F_w is the air resistance force, N; t_0 is the initial time, s; we usually assume that the vehicle is at a minimum starting velocity in the initial time, and neglect the slipping and friction process of the clutch, that is $t_0 \approx 0$; shift time t_s is regarded as a constant, t_s = 0.45 s.

The mathematical expression of F_t is as shown in Eq. (42.3):

$$F_t = \frac{T_{tq} \cdot i_0 \cdot i_{gj} \cdot \eta_T}{r} \tag{42.3}$$

where η_T is the transmission efficiency of powertrain system, the value is 0.85; T_{tq} is the engine output torque, N m; r is the rolling radius of the wheel, m;

The mathematical expression of F_f is as shown in Eq. (42.4):

$$F_f = f \cdot F_N \tag{42.4}$$

where f is the rolling resistance coefficient, $f = 0.03$ in the field environment; F_N is the normal force, N; $F_N \approx G = mg$ in the flat pavement, g is the acceleration of gravity, m/s^2.

The mathematical expression of F_w is as shown in Eq. (42.5):

$$F_\omega = \frac{C_d A u^2}{21.15} \tag{42.5}$$

where C_d is the air resistance coefficient; A is the frontal area of the vehicle, m^2.

42.2.2.2 Fuel Economy Sub-objective Function

Fuel consumption per 100 km at a constant velocity is commonly used as the evaluation index of fuel economy. It doesn't fully characterize the fuel consumption in the actual conditions. This paper adopt the fuel consumption per 100 km in six-cycle conditions as the fuel economy sub-objective function $f_2(X)$. The expression is as shown in Eq. (42.6):

$$f_2(X) = Q_s = \frac{\sum Q}{s} \times 100 \tag{42.6}$$

where $\sum Q$—total fuel consumption in the whole process, mL; s—total distance, km.

42.2.2.3 Comprehensive Objective Function

Comprehensive objective function of the dynamic property and fuel economy is established using weight coefficient method. The expression is as follows in Eq. (42.7):

$$F(X) = \lambda_1 f_1(X) + \lambda_2 f_2(X) \tag{42.7}$$

where λ_1, λ_2 is the weight coefficient of vehicle performance. Considering the special requirements for the dynamic property of the military off-road vehicles, the value of λ_1 is set as 0.7 while λ_2 is 0.3.

42.2.3 Automative Engine Model

For the automative engine model, we adopt the following fitting method to obtain the external and universal characteristic curves of the engine.

(1) External characteristic equation of engine output torque is as shown in Eq. (42.8):

$$M_e = \sum_{i=0}^{k} A_i n_{ei}^{i}, \quad i = (0, 1, 2, 3\ldots, k) \tag{42.8}$$

where:

M_e engine output torque, N m;
n_e engine speed, r/min;
A_i engine external characteristics fitting coefficient;
k polynomial order, $k \leq 5$, the higher the k value, the higher the fitting accuracy is obtained, k = 4 in this paper.

(2) Universal characteristics fitting equation of engine:

In universal characteristics, fuel consumption rate b_e is regarded as two-variables-function of n_e and M_e. According to the definition, the expression of b_e is as follows in Eq. (42.9):

$$b_e = \sum_{j=0}^{s} \sum_{i=0}^{j} A_{\left[\frac{1}{2}(j+1)(j+2)-j-1+i\right]} M_e^{i} n_e^{j-i} \tag{42.9}$$

where:

b_e fuel consumption rate, g/kWh;
A coefficient matrix;
S the order of mathematical model;

The engine data of a certain military off-road vehicle are shown in Table 42.1.

According to the mathematical fitting model and the data above, universal characteristic curves of the engine are obtained as shown in Fig. 42.1.

Table 42.1 Engine external characteristic data of prototype vehicle

T_{max} (N m)	$\boldsymbol{n}(\boldsymbol{T}_{max})$ (r/min)	$\boldsymbol{P}_{max}$ (kW)	$\boldsymbol{n}(\boldsymbol{P}_{max})$ (r/min)
169	4120	82	5100

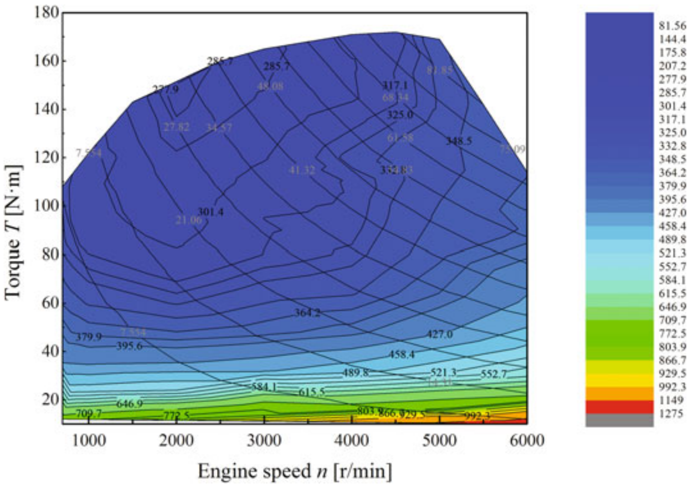

Fig. 42.1 Universal characteristic curves of prototype vehicle

42.2.4 Constraint Conditions

After the establishment of the powertrain optimization mathematical model and objective functions, appropriate constraints of the design variables are needed. The main constraint conditions include the dynamic requirements of the vehicle and the adjacent gear ratio interval of the shift comfort.

a. Constraint conditions of the vehicle dynamic property
(1) The limit of maximum dynamic factor in first gear:

$$\frac{F_{t1} - F_{\omega}}{m \cdot g} \geq D_{1\max} \tag{42.10}$$

where D_{1max} is the maximum dynamic factor index of *I* gear, D_{1max} = 0.62 for off-road vehicles; F_{t1} is the maximum driving force of *I* gear, N.

(2) The limit of maximum dynamic factor in direct gear:

$$\frac{F_{td} - F_{\omega}}{m \cdot g} \geq D_{d\max} \tag{42.11}$$

where D_{dmax} is the maximum dynamic factor index of direct gear, D_{dmax} = 0.06 for off-road vehicles; F_{td} is the maximum driving force of direct gear, N.

(3) The limit of minimum stable velocity:

$$\frac{0.377n_{e\min} \cdot r}{i_0 \cdot i_{g1}} \leq u_{a\min} \tag{42.12}$$

where n_{emin} is the minimum stable RPM of the engine, r/min, the value is 600–800; u_{amin} is the index of the minimum stable velocity, km/h.

(4) The limit of the maximum velocity:

$$\frac{0.377n_{e\max} \cdot r}{i_{g5} \cdot i_0} \geq u_{a\max} \tag{42.13}$$

where n_{emax} is the maximum RPM of the engine, r/min; u_{amax} is the index of the maximum velocity, km/h, u_{amax} = 160 km/h in this paper.

(5) The limit of maximum climbable gradient:

$$\frac{T_{e\max} \cdot i_0 \cdot i_{g1} \cdot \eta_T}{r} \geq G(f \cos \alpha_{\max} + \sin \alpha_{\max}) + \frac{C_d \cdot A \cdot u_n^2}{21.15} \tag{42.14}$$

where T_{emax} is the maximum torque of the engine, N m; α_{max} is the maximum climbable gradient, °, u_n is the climbing velocity, $u_n \leq 15$ km/h.

(6) The limit of road adhesion:

$$\frac{T_{tq} - T_f}{r} \leq F_z \cdot \varphi \tag{42.15}$$

where φ is the adhesion coefficient, determined by the road and tire conditions, for the asphalt pavement, φ is set as 0.7; F_Z is the normal force of the driving wheels, N.

b. Constraint conditions of adjacent interval gear ratios

Considering the high utilization rate in high gears and shift comfort, adjacent interval gear ratios is usually limited to 1.7–1.8. The constraint conditions of adjacent interval gear ratios are as follows in Eq. (42.16):

$$\begin{aligned} &1.7 \le g_1(x) = \tfrac{i_{g1}}{i_{g2}} \le 1.85 \\ &g_2(x) = \tfrac{i_{g2}}{i_{g3}} - \tfrac{i_{g1}}{i_{g2}} \le 0 \\ &g_3(x) = \tfrac{i_{g3}}{i_{g4}} - \tfrac{i_{g2}}{i_{g3}} \le 0 \\ &g_4(x) = \tfrac{i_{g4}}{i_{g5}} - \tfrac{i_{g3}}{i_{g4}} \le 0 \end{aligned} \tag{42.16}$$

42.3 Model Optimization and Solutions in Matlab

According to the optimization model above, the powertrain parameters of a certain military off-road vehicle is optimized. The vehicle parameters and technical requirements of the military off-road vehicle are as shown in Table 42.2.

Original powertrain parameters of the vehicle are shown in Table 42.3.

Fmincon function in Matlab optimization toolbox specifically to solve the optimization problem of multi-variables with nonlinear constraints [5]. The mathematical model is as follows in Eq. (42.17):

$$\begin{cases} \min f(x) \\ c(x) \le 0 \\ ceq(x) = 0 \\ A \cdot x \le b \\ Aeq \cdot x \le beq \\ lb \le x \le ub \end{cases} \tag{42.17}$$

where x, b, beq, lb, ub are vectors; A, A_{eq} are matrix; $c(x)$, $ceq(x)$ are constraint functions.

The original transmission gear ratios are initial conditions, X_0 = [3.8, 3.72, 2.04, 1.34, 1.0, 0.8]. When setting the relative parameters, if there is no constraint, the parameters are set as []. According to the methods and conditions above, put the relative parameters into Matlab optimization model and simulate.

Table 42.2 Vehicle parameters and technical requirements of prototype vehicle

Parameters	Value	Parameters	Value
m (kg)	1515	A (m^2)	1.94
C_d	0.32	f_r	0.04
r (m)	0.30	φ	0.7
$\alpha_{\max}$ (°)	32	n_{emin} (r/min)	700

Table 42.3 Original powertrain parameters of prototype vehicle

Parameters	i_0	i_1	i_2	i_3	i_4	i_5
Value	3.8	3.72	2.04	1.34	1.0	0.8

42.4 Simulation Results and Analysis

Comparisons on powertrain parameters before and after optimization are as shown in Table 42.4:

Comparisons on dynamic property and fuel economy before and after optimization are as shown in Table 42.5.

Comparisons on dynamic factor curves, acceleration curves and driving power curves are as shown in Figs. 42.2, 42.3, 42.4, 42.5, 42.6, and 42.7 respectively.

Simulation results show that the acceleration time, fuel consumption and maximum velocity reduced after optimization. As shown in Figs. 42.2–42.5, the

Table 42.4 Comparisons on powertrain parameters before and after optimization

Parameters	Before optimization	After optimization	Rate of change (%)
i_0	3.8	4.98	31.58
i_{g1}	3.72	3.959	6.42
i_{g2}	2.04	2.14	4.90
i_{g3}	1.34	1.339	0.07
i_{g4}	1.0	0.935	−6.50
i_{g5}	0.8	0.751	−6.13

Table 42.5 Comparisons on dynamic property and fuel economy before and after optimization

Parameters	Before optimization	After optimization	Rate of change (%)
0–100 km/h acceleration time (s)	15.2972	14.0168	−8.37
Fuel consumption (L/h km)	7.4939	7.1670	−4.36
Maximum velocity (km/h)	201.19	192.57	−4.28

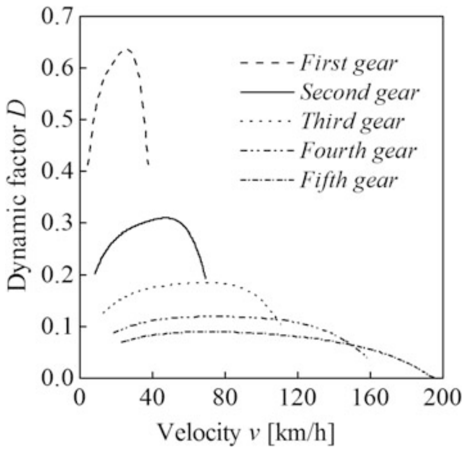

Fig. 42.2 Dynamic factors after optimization

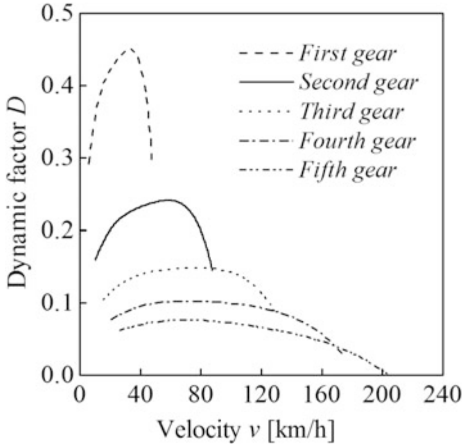

Fig. 42.3 Dynamic factors before optimization

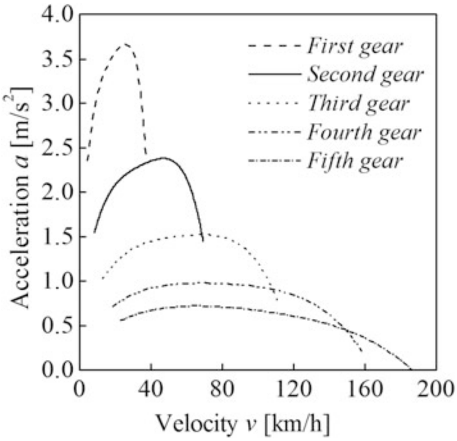

Fig. 42.4 Acceleration after optimization

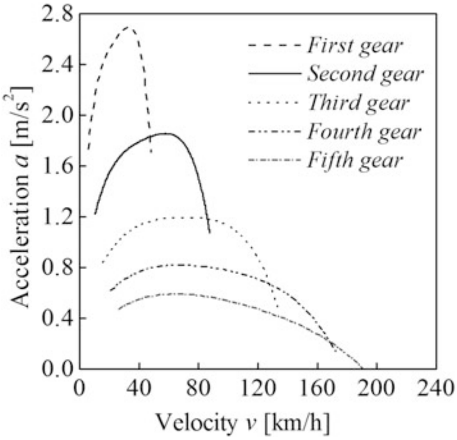

Fig. 42.5 Acceleration before optimization

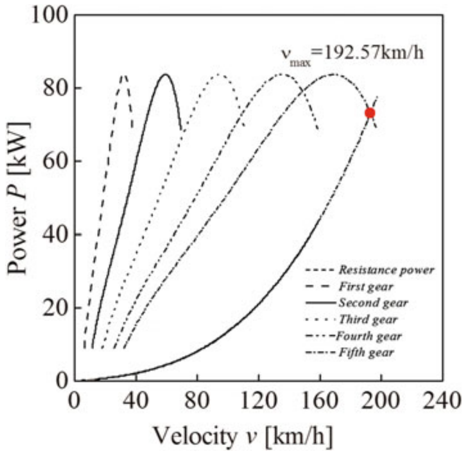

Fig. 42.6 Driving power after optimization

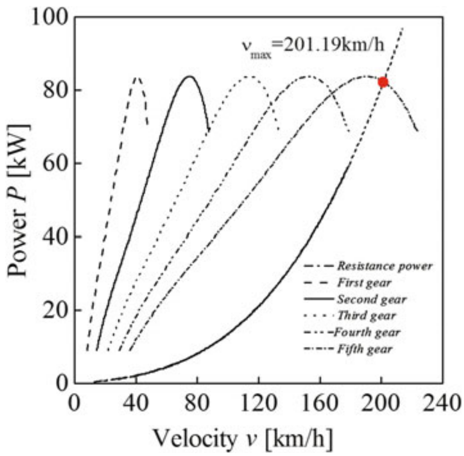

Fig. 42.7 Driving power before optimization

dynamic factors and acceleration increase obviously. Though the maximum velocity decrease 4.28%, the optimization results are relatively ideal in general.

42.5 Conclusion

Powertrain parameters of the military off-road vehicles are optimized in Matlab using nonlinear optimization function fmincon. The dynamic property and fuel economy improved obviously compared to the traditional geometric series division method. The simulation process is completely calculated in computer. Optimization time is shortened and efficiency is higher. There is a good practicability and application value to the design of the vehicle powertrain system in the future.

However, the optimization results couldn't be used to design gear transmission directly. In the future work, practical gear design will be considered into the optimization process.

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