

Software Design of Engine Characteristic Simulation

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Abstract—Engine mathematical model can be used to simulate vehicle dynamic performance and fuel economy for vehicle design. Simulation of vehicle dynamic performance and fuel economy is based on mathematical model of engine. Least square method and multiple regression analysis were used to fit curve of external characteristics and universal characteristics when the test data of external characteristics and universal characteristics of engine are known. Torque and fuel consumption of engine can be calculated under the different operating conditions by the equation. Grid quantization method was used to simulate the characteristic when the test data of external characteristics and mapping characteristics are unknown and only the engine characteristics curve is known.

Index Terms– Engine; Simulation; universal characteristics; Partion Velocity characteristics

I. INTRODUCTION

Using engine mathematical model to calculate vehicle dynamic performance and fuel economy is an important tool for modern vehicle design. Vehicle dynamic performance and fuel economy simulation calculate is based on mathematical model of the engine. The engine mathematical model includes partial load characteristics, engine mapping characteristics and transient process simulation model. There are two main methods to achieve the mathematical model of the engine: one is using the fuel combustion model to establish simulation mathematical model, which is used by the internal combustion engine development; another is based on test data. The model reflects the engine dynamic performance and fuel economy. It can be used in the study of dynamic performance, fuel economy and the optimal shift law. Description of the main methods for engine characteristic is test data direct descriptive method and mathematical model descriptive method. Test data direct descriptive method has higher precision, but it occupies more computer memory. And speed is slow. Mathematical model descriptive method is more flexible. And it is convenient for computer processing [1]. Mathematical model descriptive method was used in the research.

II. DEVELOPMENT OF TEST BENCH AND ENGINE TEST

At first, we developed a test bench to get the characteristic data of an engine based on Virtual Instrument Technology.

Virtual Instruments are new instrument type based on computer. Computer software technology and test systems are combined together to become a virtual instrument. Virtual Instruments get data from Data Acquisition Card (DAQ) and process the data by the software. And it can process the data and display them on the human interface. Virtual instrument system is equipped with instrument hardware to a computer. The computer is the main part of the virtual instrument. DAQ card is connected to the computer by the way of BUS. Software system can complete communication between interface and instrument hardware. It is a bridge between the application program and the I/O. Meanwhile, it can achieve external and internal data exchange. The software provides a variety of instrument panel on a computer screen and provides man-machine interaction interface to transmit the test data, save the data etc..

Virtual Instruments(VI) technology use computer technology to extend the functions of traditional instruments. Its hardware include plug-in data acquisition card, I/O, IEEE488 Interface card or VXI controller etc.. The different interface has different characteristics. Now, PC system BUS is used more commonly.

Virtual instrument is a computer with special software and hardware to achieve its functions. It can fit the demand of data storage, data processing, data transmission and measurement. The software is the key of the total system. We can get different functions and meet the requirements of different occasions by changing the software. Virtual instrument software has all of the functions such as data collection, control, data analysis, output and display. These features make the traditional instruments replaced by the software. Moreover, the user can use some advanced digital signal processing algorithm to design a virtual instruments. It adds more

new functions to traditional instruments. It can detect specific system parameters, such as automotive engine speed and vehicle speed.

Virtual instrument has an graphical interface. It is easy to use. Its functions can be expanded easily. In addition, because virtual instrument is based on computer technology, thus VI develops quickly with the development of computers. So VI shows its flexibility and vitality. The rapid development of computer technology makes virtual instrument manufacturers improving the virtual instrument continuously.

It can be seen, virtual instrument not only can achieve data acquisition and transmission, but also has great flexibility. At the same time, it is convenient to use virtual instrument technology to generate virtual test system, draw the curve of experimental data and display it on the screen. So we can use this technology to develop the monitor system of engine.

To measure the test parameters quickly and accurately, people use virtual instrumentation to develop a control system. The measurement and control system achieves the engine operating condition signal with sensors and terminal. A data acquisition card read data into the computer, and then analyzed the data by the application software, and finally display and output in the form of curve or data files through the graphical interface of the virtual instrument.

Hardware includes a computer and data acquisition card. The system uses one PCI BUS data acquisition card PCI9111DG (ADLINK Technology Inc.). Its maximum sampling frequency is 110 KHz. It can meet the demand of real-time data acquisition. This system can be expanded to the acquisition of 16 analog signals according to the demand of the test system. The control system achieves the external signals with sensor and terminal. The data acquisition card read data into the computer. After the application software analyzed the data, then displays the data by graphical user interface or output them by data file. Through the analog output port, it can control the gas pedal of the engine. Schedule of the system is shown in Figure 1.

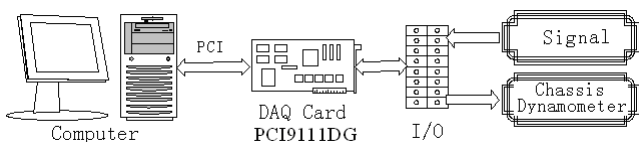


Figure 1 schedule of the system

The software is developed with Visual C++ and DAQBench kit.

We can change the parameters of test by Graphical User Interface (GUI). Man-machine interaction interface of the system are including control components and display components to control the system and display the data. Before the test, it is essential to change the sampling period according to the demand of test. When the system is working, we can slide the slide bar of gas pedal to control the dynamometer in order to change the work condition of the engine. When the slide bar was slid, the opening of the gas pedal can be changed and

displayed dynamically. And engine operating parameters were displayed on the screen by curves, such as: engine speed, torque and the opening of gas pedal. At the same time, the system can show the sampling points and sampling time. Moreover, the system can also automatically save the dynamic parameters of the engine. So we can use the data to study the performance of the vehicle engine.

The GUI of the system is showed in Figure 2. Engine speed, torque and the opening of gas pedal were displayed on the same interface. The horizontal coordinate of the figure is the sampling points which show curves of the dynamic test data. It can be transformed with time. Longitudinal coordinate is the voltage value of the sampling parameters. We can get the actual value of engine speed and torque after conversion. At this time sampling period is 500ms. According to the sampling theory of Shannon, the sampling frequency should be greater than 2 times the maximum frequency of the signal, especially should pay attention during the transition condition data acquisition.

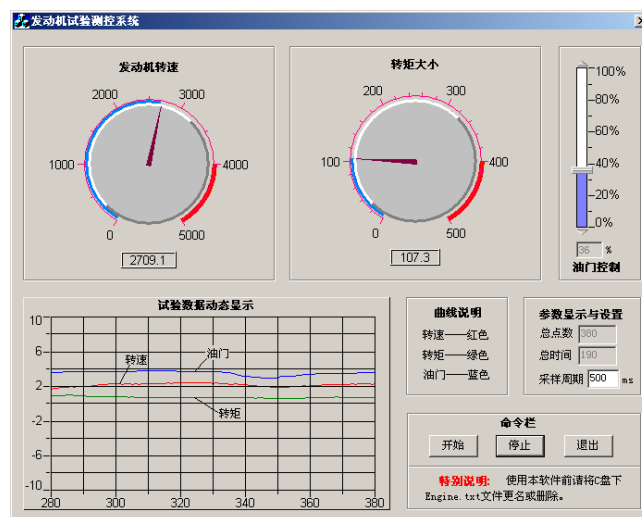


Figure 2 GUI of control software

The system that we developed can control an engine and a chassis dynamometer. It can get the signal of engine torque, the speed of the engine and the position of the gas pedal. It can work properly after we have an experiment in our lab. So we have a test on engine EQ6100- I . The Test data as Table 1.

TABLE 1 TEST VALUE OF ENGINE EQ6100- I

Engine Speed n(r/min)		800	1400	2000	2400	2800	3000
10%	Ttq(N·m)	59					
	ge(g/kw·h)	530					
20%	Ttq (N·m)	97	108	112	85	63	52
	ge(g/kw·h)	405	368	374	430	550	630
30%	Ttq (N·m)	132	154	163	150	130	116
	ge(g/kw·h)	350	317	328	348	380	400
40%	Ttq (N·m)	168	200	210	209	182	157
	ge(g/kw·h)	308	293	304	315	343	360

50%	Ttq (N·m)	192	221	238	242	203	173
	ge(g/kw·h)	298	285	293	304	327	356
60%	Ttq (N·m)	212	241	252	253	212	191
	ge(g/kw·h)	292	278	289	301	330	350
70%	Ttq (N·m)	233	254	261	258	225	202
	ge(g/kw·h)	291	276	288	300	327	340
80%	Ttq (N·m)	250	264	267	262	232	207
	ge(g/kw·h)	293	275	287	298	324	337
90%	Ttq (N·m)	264	278	274	264	234	210
	ge(g/kw·h)	295	276	286	297	322	335
100%	Ttq (N·m)	274	284	276	266	236	212
	ge(g/kw·h)	300	277	287	296	321	333

III. PORTION VELOCITY CHARACTERISTICS OF ENGINE

A. Least squares method

Least squares method was used to construct polynomial when the test data is known. So we can achieve the external characteristics model of the engine. For the engine of known experimental data, speed characteristics can be seen as a function of one variable of engine speed [2]. It is described as follows:

$$X_e = a_0 + a_1(n - \bar{n}) + a_2(n - \bar{n})^2 + \dots + a_k(n - \bar{n})^k \quad (1)$$

Where X_e is characteristic value of engine; n is engine speed, $r \cdot \text{min}^{-1}$; \bar{n} is mean engine speed, $r \cdot \text{min}^{-1}$; a_0, a_1, \dots, a_k is coefficient.

In order to reflect the better actual status, portion velocity characteristics and mapping characteristics of engine was chosen to reflect the actual work of engine under different throttle opening. We can get a group data from 10% to 100% throttle opening in a sequence of engine partial load characteristic curve by using the experimental data. By the interpolation method obtained the points not on the curve sequence, using this method can obtain torque and fuel consumption curves under any throttle opening. In general, the polynomial meets the required of precision when it is quintic [1]. The algorithm of linear interpolation as follows [3]:

$$X_{e\alpha} = X_{e10k} + \frac{X_{e10(k+1)} - X_{e10k}}{10} \cdot (\alpha - 10k) \quad (2)$$

Or

$$X_{e\alpha} = X_{e10(k+1)} - \frac{X_{e10(k+1)} - X_{e10k}}{10} \cdot [10(k+1) - \alpha] \quad (3)$$

Where $X_{e\alpha}$ is characteristics of throttle opening; α is throttle opening, $10k \leq \alpha \leq 10(k+1)$, $k = 0, 1, \dots, 9$; $X_{e10k}, X_{e10(k+1)}$ is characteristics of throttle opening $10k, 10(k+1)$.

Then, using linear interpolation, torque curves and fuel consumption curves at random throttle opening condition can be obtained. Because engine's torque T has certain relationship with engine's rotation speed n and throttle opening α under different course, we can also express torque as $T = f(\alpha, n)$, then using surface fitting can get coefficient matrix of it. Engine Speed

Curve at different throttle opening under non-load as Fig.3. Engine's torque fit curved surface in various throttle opening as Fig.4).

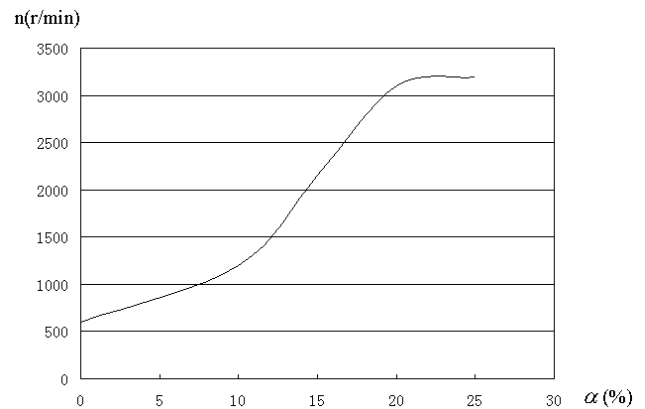


Fig.3 Engine Speed Curve at different throttle opening under non-load

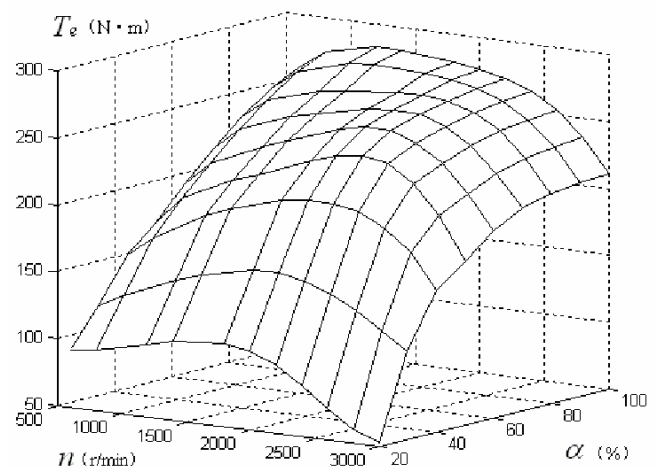


Fig.4 Engine's Torque Fit Curved surface in Various Throttle

B. Empirical formula method

When there is no test data of the engine characteristics or partial load characteristics, only know a few the characteristics parameters of the engine, such as: the lowest fuel consumption of engine, maximum engine power and speed. Then empirical formula can be taken to estimate all kinds of working conditions. The empirical formula is as follow [1] [5]:

$$T = T_{\max} - \frac{T_{\max} - T_p}{(n_p - n_M)^2} (n_M - n)^2 \quad (4)$$

where T_{\max} is the maximum torque of engine, $N \cdot m$; n_M is the engine speed corresponding to the maximum torque, $r \cdot \text{min}^{-1}$; T_p is the torque corresponding to the maximum power, $N \cdot m$; n_p is the engine speed corresponding to the maximum power, $r \cdot \text{min}^{-1}$; T is torque of unknown points, $N \cdot m$; n is engine speed of unknown points, $r \cdot \text{min}^{-1}$.

If the characteristic parameters of the engine are unknown, engine parameters can be obtained according to the type of engine by using engine manual.

IV. UNIVERSAL CHARACTERISTICS MODEL OF ENGINE

A. Surface fitting

Some methods can describe universal characteristics curve of the engine, such as the matrix descriptive method, binary Lagrange's interpolation, natural cubic spline interpolation, surface fitting etc. [4]. Surface fitting was chosen because of its convenience and flexibility. The fuel consumption g_e , engine speed n_e and torque T_e of engine operating points are known. g_e can be expressed by polynomial of n_e and T_e . Equation as follows [5] [6]:

$$g_e = \sum_{j=0}^s \sum_{i=0}^j a_{\frac{1}{2}(j+1)(j+2)-j-1+i} T_e^i n_e^{j-i} \quad (5)$$

Where g_e is fuel consumption of engine, g/kW·h; T_e is effective torque of engine, N·m; n_e is engine speed $n/100$, r·min⁻¹; a is multinomial coefficient; s is the order of fitting, $i \leq s$; $j \leq s$.

Using surface fitting method obtain the parameters in the above model. Surface fitting is Linear regression curve fitting. Each point on the plane Z (corresponding to g_e) is the function of coordinates (x, y) (x corresponds n_e , y corresponding to T_e), the regression model as follow:

$$\begin{bmatrix} Z_1 \\ Z_2 \\ \vdots \\ Z_N \end{bmatrix} = \begin{bmatrix} 1 & x_1 & y_1 & x_1^2 & x_1 y_1 & y_1^2 & x_1^s & x_1^{s-1} y_1 & \dots & y_1^s \\ 1 & x_2 & y_2 & x_2^2 & x_2 y_2 & y_2^2 & x_2^s & x_2^{s-1} y_2 & \dots & y_2^s \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & x_N & y_N & x_N^2 & x_N y_N & y_N^2 & x_N^s & x_N^{s-1} y_N & \dots & y_N^s \end{bmatrix} \times \begin{bmatrix} a_0 \\ a_1 \\ \vdots \\ a_{k-1} \end{bmatrix} + \begin{bmatrix} e_1 \\ e_2 \\ \vdots \\ e_N \end{bmatrix}$$

Where $\{Z_1, Z_2, \dots, Z_N\}$ is fuel consumption of coordinates $\{x, y\}$, g/kW·h; $\{a_0, a_1, a_2, \dots, a_{k-1}\}$ is undetermined coefficient; $\{e_1, e_2, \dots, e_N\}$ is error; N is test points.

Change to matrix as follow:

$$Z = G \cdot A + E$$

Where G is $N \times k$ matrix; Z and E are all $N \times 1$ column vector; the relation of column number k of G and polynomial s is:

$$k = \frac{(s+1)(s+2)}{2}$$

Fitting level of fitting value and test data can use degree of fitting to evaluate:

$$C = \left[1 - \frac{\sum_{i=1}^N (Z_i - \hat{Z})^2}{\sum_{i=1}^N (Z_i - \bar{Z})^2} \right] \times 100\% \quad (6)$$

Where \hat{Z} is fitting value; \bar{Z} is ensemble average.

By adjusting the fitting order, the error can be controlled in the appropriate range to meet the accuracy requirements. a can be calculated and change to a matrix.

After calculating the coefficient matrix, we can get fuel consumption rate of the curved surface equation. Using the equation can be obtained the contours line of fuel consumption rate and get universal characteristics curve. The corresponding torque can be gotten to different fuel consumption rate. Connecting these points together, it is equal fuel consumption rate curve. The method is as follows.

When the fuel consumption rate is known, substitution any speed of speed sequence, you can change Eq. (5) into Eq. (7).

$$P_n(x) = a_n x^n + a_{n-1} x^{n-1} + \dots + a_1 x + a_0 \quad (7)$$

Therefore, the problem of calculate the torque transform into the problem of root of equation (7).

Making $b_i = a_i / a_n$, $P_n(x)$ can be transformed into

$$Q_n(x) = x^n + b_{n-1} x^{n-1} + \dots + b_1 x + b_0 = 0$$

The above equation can be seen as the following matrix

$$Q = \begin{bmatrix} -b_{n-1} & -b_{n-2} & -b_{n-3} & \dots & -b_1 & -b_0 \\ 1 & 0 & 0 & \dots & 0 & 0 \\ 0 & 1 & 0 & \dots & 0 & 0 \\ \vdots & \vdots & \vdots & \dots & \vdots & \vdots \\ 0 & 0 & 0 & \dots & 1 & 0 \\ 0 & 0 & 0 & \dots & 0 & 1 \end{bmatrix}$$

Characteristic polynomial of the matrix as follows:

$$Q_n(\lambda) = \lambda^n + b_{n-1} \lambda^{n-1} + \dots + b_1 \lambda + b_0 = 0 \quad (8)$$

Therefore, calculating all the roots of equation $Q_n(x) = 0$ are transformed into calculating all eigenvalue problem of matrix Q , using the QR method can find all the eigenvalue. They are all the roots of Eq. (7), and then get the torque value.

After programming curved surface fit program, we can get polynomial's coefficient matrix. Engine's Fuel consumption Fit Curved surface as Fig5. The contour line in horizontal in Fig.5 is engine's universal characteristic curve. Simulation value as Table 2. We can have a contrast between From the above result, we can see the maximal relative error between Table 1 and Table 2. The error between simulation value and true value is 1.96%, fit degree is 99.95%.

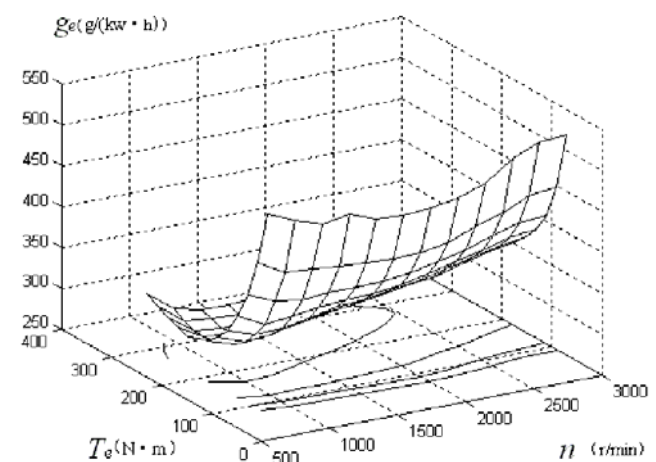


Fig.5 Engine's Fuel Consumption Fit Curved surface

TABLE 2 SIMULATION VALUE OF ENGINE EQ6100- I

Engine Speed(r/min)		800	1400	2000	2400	2800	3000
10%	Ttq (N·m)	59.0					
	ge(g/kw·h)	540.5					
20%	Ttq (N·m)	95.2	109.2	109.1	88.4	60.2	53.1
	ge(g/kw·h)	410.0	367.3	367.4	432.9	552.9	619.0
30%	Ttq (N·m)	130.8	153.3	162.1	151.6	128.5	116.5
	ge(g/kw·h)	345.9	317.1	327.1	346.1	379.7	399.4
40%	Ttq (N·m)	168	197.4	211.1	207.3	182.1	156.7
	ge(g/kw·h)	310.7	291.7	303.9	315.6	344.5	362.7
50%	Ttq (N·m)	192.5	217.4	238.8	237.8	203.9	172.2
	ge(g/kw·h)	298.1	283.5	293.4	303.1	333.9	353.6
60%	Ttq (N·m)	213.3	237.6	254.9	248.2	214.6	189.7
	ge(g/kw·h)	292.8	277.8	289.9	300.4	329.7	344.6
70%	Ttq (N·m)	233.4	252.3	262.7	255.2	224.8	201.7
	ge(g/kw·h)	291.6	275.6	288.4	299.5	324.3	339.6
80%	Ttq (N·m)	249.8	263.3	268.1	260.1	231.1	207
	ge(g/kw·h)	293.8	274.9	287.8	298.9	321.8	337.4
90%	Ttq (N·m)	265.2	277.9	274.2	262.7	234	209.6
	ge(g/kw·h)	297.3	275.2	287.5	298.6	321.1	336.1
100%	Ttq (N·m)	275.2	283.5	276.5	264.7	236.1	210.9
	ge(g/kw·h)	300.6	275.9	287.4	298.4	320.5	335.3

B. Empirical formula

When the test data is unknown, it can use verified empirical formula. The fuel consumption rate can be expressed as follows:

$$g_t = n(g_{0x}V_h + rT) \quad (9)$$

where: g_t is fuel consumption per minute, g/min ; g_{0x} is fuel consumption per revolution and liter engine idling, g/(r·L) ; r is coefficient, g/(N·m·L) ; V_h is engine displacement, L ; T is torque of unknown points(from 8), N·m ; n is engine speed of unknown points, r·min⁻¹.

The reference value of g_{0x} 、 r of gasoline and diesel engines as Table 3.

TABLE 3 REFERENCE VALUE OF g_{0x} 、 r

	g_{0x} [g/(r·L)]	r [g/(N·m·L)]
gasoline engine	0.0065~0.0080	0.00035~0.00045
diesel engine	0.0025~0.0040	0.00030~0.00042

V. SOFTWARE DESIGN OF ENGINE CHARACTERISTIC SIMULATION

Using the engine partial loading model and universal characteristics model of above introduce can develop engine characteristic simulation software. Based on the above theory, a system was developed by using VC++. The module can draw characteristic curves of the engine and universal characteristics, and inquire value of any point.

Visual C++ has been chosen as the software develop test bench. Visual C++ provides an Integrated Development Environment (IDE) that allows to write,

build, and debug 32 bit C/C++ programs, which can realize user's interface in graphics well and provide powerful data processing capacity and hardware control capacity and also can integrate with other development software8. The data acquire card carries with DAQBench control toolbox. in which includes 32bit ActiveX controls apply to measure and automatization field, and also can be embedded into Visual C++ expediently for build of virtual instrument panel and datasheet, developing monitor software with friendly human-machine interface.

To complete the drawing and inquire functions, the system defines OnMouseMoveThrottlemanual(), OnQuery() two response function and draw the dialog box of mapping characteristics curve. In order to curve with the throttle slider position can dynamic change, using the method is making the every time drag of throttle slider response a OnMouseMoveThrottlemanual () message. In the message ,firstly obtain a current position of throttle, then make judgments of throttle position and call the corresponding throttle angle data, drawn the current throttle curve. If the throttle location exactly the same with the experimental curve, directly called the fitting curve of the experimental data; if inconsistent with the experimental curve, judging the interval, and then call the corresponding linear interpolation procedures calculation, and draw the curve. Queries the method of characteristic parameter of any throttle opening the same as the method of dynamic display curve, the difference is directly display the data instead of drawing. In the system, it also provides setting options that can set the coefficient matrix of the torque equation and the fuel consumption equation.

System interface show in Figure 6(the curve is the simulation curve of the 30% throttle opening). Sliding the throttle control button in the right of Fig. 6, able to reappear torque and fuel consumption curves at any throttle, and can consult any current throttle opening degrees corresponding torque and fuel consumption values of engine speed. The figure shows the results when the engine speed is 1400r/min. You can also read the experimental data to draw universal characteristics curves (Fig. 7) by the methods that have been described previously.

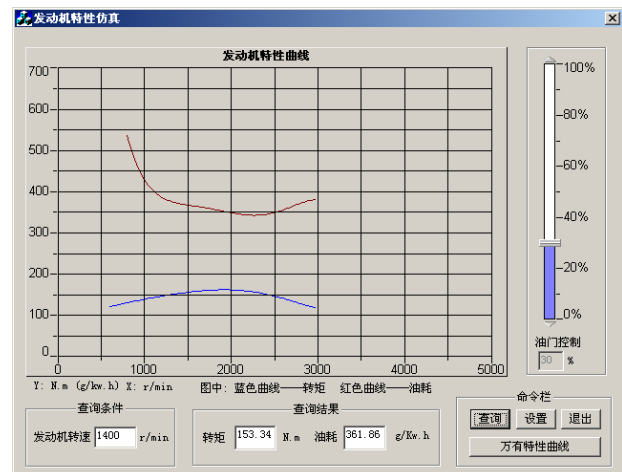


Figure 6 engine loading characteristics simulation picture

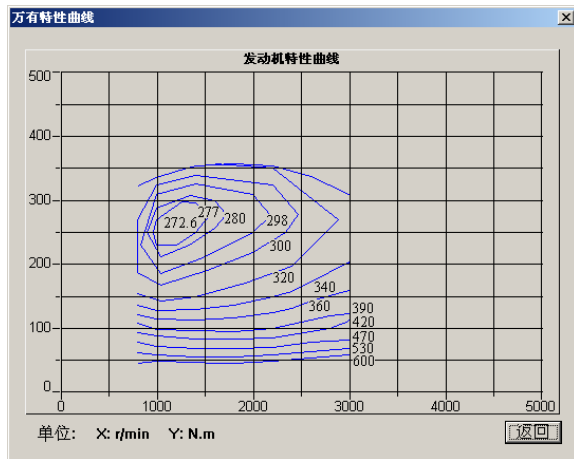


Figure 7 engine mapping characteristics simulation picture

Developed the engine characteristics simulation system can not only draw external characteristic curve, fuel consumption curve and mapping characteristics curve of any throttle, and can query any throttle opening corresponding torque fuel consumption, achieving the working conditions simulated of the engine.

VI. CONCLUSION

Mathematical model descriptive method was used to describe vehicle dynamic performance and fuel economy. Developed the engine characteristics simulation software can not only draw external characteristic curve, fuel consumption curve and universal characteristics curve of any throttle, and can query any throttle opening corresponding torque fuel consumption, achieving the working conditions simulated of the engine. It is a useful tool of a modern vehicle design.

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