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Simulation of Sequential Turbocharging Switching Delay Process based on MATLAB/SIMULINK

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Abstract

The sequential turbocharging charging (STC) is applied to solve the matching contradiction between Marine diesel engine and supercharger. This technology can improve the performance of Marine diesel engine at the low operating conditions, but this technology also has some problems. When the switching time of air valve and bypass valve is delayed, it is easy to cause the surge of Marine compressor. When the switching point is not selected properly, the fuel consumption rate of the ship will appear an upward trend. The simulation model of sequential turbocharged diesel engine is established by MATLAB/SIMULINK simulation platform. The performance change of Marine diesel engine in the process of switching from 1TC to 2TC operation is studied, then the delay switching between air valve and bypass valve at different time is studied. The results show that the optimal switching time of the diesel engine from 1TC to 2TC is 1.8s. Under the switching time, the diesel engine, the basic compressor and the controlled compressor are in stable working condition, and no surge occurs during the switching process.

Keywords

Sequential Turbocharging; Switch Delay; Air Valve; Diesel Engine.

1. Introduction

With the aggravation of environmental problems, the regulations on ship discharge are becoming more and more strict. Diesel engine miniaturization can effectively improve the economy of diesel engines and reduce emissions, but when the Marine diesel engine miniaturization, its exhaust capacity will be reduced accordingly, which will lead to the reduction of the performance and work efficiency of the ship. In order to solve a series of problems caused by the miniaturization of Marine diesel engines, the most direct way is to install a supercharger for diesel engines to increase the intake of air and fuel combustion more fully, so as to greatly improve the working efficiency and performance of diesel engines. However, when the diesel engine is running under low operating conditions, the compressor surge is easy to occur, which affects the performance and economy of the diesel engine. This matching contradiction can be solved by adopting successive supercharging technique. In the 1970s, the German MTU company carried out research on the sequential pressurization system [1-2].

Successive turbocharging system is usually composed of two or more superchargers. The number of superchargers put into use is determined according to the demand of the engine for air intake under different operating conditions [3]. In order to study the sequential turbocharing switching process, controlled cutting when the compressor at different delay time, the work efficiency and performance of diesel engine and compressor and controlled the influence of the compressor, in the process of simulation, to record the change of the controlled the speed of the compressor and compressor, research and analysis of the law, get sequential turbocharing switching process, Optimum cutting

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time of controlled compressor. The determination of air valve switch delay time is the key to the sequential turbocharing switching process [4], if in the process of subsequently switch, controlled compressor not at the right time, will cause the compressor surge phenomena occur, in order to improve the compressor matching with diesel engine [5], looking for the right switch delay time, this paper studies the diesel engine at low load, Under medium load and high load conditions, the influence of different switching delay time on the sequential pressurization switching process is analyzed and the law is obtained.

2. Sequential turbocharging system

2.1 Working principle

The sequential supercharging system is composed of a diesel engine, a basic compressor and one or more controlled compressors. The cutting in or cutting out of the controlled compressor is controlled by the opening and closing of the gas valve, and the switching time of the controlled compressor is controlled by the delay of the opening and closing time of the air valve. Successive turbocharging technology can effectively solve the problems of low efficiency and poor performance of diesel engines under low operating conditions. When the working condition of diesel engine at low running state, the working conditions of diesel engine don't need many sets of compressor to the gas supply, through the corresponding valve closed sequential turbocharing system, control of controlled blower cut out sequential turbocharing system, make the diesel engine exhaust all flow into basic compressor, the efficiency of exhaust gas energy use, thus greatly improving the inlet pressure in the cylinder, The fuel combustion is sufficient and the working efficiency and performance of diesel engine under low working conditions are effectively improved. When the load increases, the diesel engine diesel combustion produces a large amount of waste gas, on the one hand, on the other hand the fuel combustion also greatly increase the demand for air inflow, basic compressor can meet the job requirements of diesel engine, in order to ensure full combustion and diesel engine under the working condition of high work efficiency, the need to open the corresponding valve, controlled compressor running, To provide sufficient compressed air for diesel combustion [6].

In the switching process of successive pressurization system, the different switching delay time of air valve is one of the important factors affecting the switching process. When the diesel engine load increases, it is necessary to open the gas valve of the successive pressurization system. At this time, the turbine of the controlled compressor is put into work. If the air valve is opened too early, the compressed air will flow back to the exhaust pipe of the controlled compressor, which leads to the surge phenomenon of the controlled compressor. If the air valve is opened too late, the compressed air will flow back to the exhaust line of the base compressor and cause surge of the base compressor. In order to ensure the normal operation of diesel engine, basic compressor and controlled compressor, it is necessary to open the air valve when the turbine of the controlled compressor is put into operation and its speed is slightly higher than that of the basic compressor.

2.2 Delay switching control

The simulation model of successive pressurization system is established in this paper. The compressed air needed for fuel combustion in the cylinder of diesel engine is supplied by the compressor, and the exhaust gas generated by combustion flows into the turbine to drive the turbine to rotate and make it work. Different working conditions of diesel engine can be simulated by adjusting different speed of diesel engine. The valve opening and closing states of successive supercharged diesel engines are also different under different working conditions: (1) when the diesel engine is operating under low load condition, the gas valve, bypass valve and air valve are all in closed state, and only the basic compressor works under this working condition (1TC); (2) When the diesel engine is running under medium load condition, the gas valve, bypass valve and air valve are all in open state, and the basic compressor, controlled compressor and bypass system are all in working state (2TC+CAB); (3) When the diesel engine runs under high load condition, the bypass

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valve is in the closed state, the gas valve and the air valve are in the open state, and the basic compressor and the controlled compressor are in the working state under this condition (2TC) .

The successive pressurization system model was established through MATLAB/ Simulink, as shown in Fig.2. The model mainly includes basic compressor model, turbine model, controlled compressor model, bypass valve model, gas valve model, air valve model, cylinder model and so on.

When the input parameter of crankshaft speed is NS =400rpm, the diesel engine runs under low load condition and stabilizes at 1tC after a certain period of time. Since the gas valve, bypass valve and air valve are all in closed state under this working condition, their values are all 0. Adjust the crankshaft speed ns = 900 RPM, the diesel engine running under medium load conditions at this time, open the inlet pipe gas valve, controlled operation of the turbine compressor, since there is no open air valve, flow controlled flow of air compressor is 0, after a certain time delay, stay turbine speed increases to the corresponding value and open air valve and bypass valve, The controlled compressor starts to operate. At this time, the basic compressor, controlled compressor and bypass system are all in working state, so that the diesel engine is stabilized at 2TC+CAB state. When the crank speed is adjusted as ns=1000rpm, the diesel engine is running under the condition of high load, and the gas valve in the intake pipe is opened to enable the turbine of the controlled compressor to operate. After a certain time delay, the air valve is opened when the turbine speed rises to a corresponding value, and the controlled compressor starts to operate, and the bypass valve is closed. At this time, the basic compressor and controlled compressor are in the working state, and the bypass system is in the closed state, so that the diesel engine is stable at 2TC state. By opening and closing the gas valve, the working state of the turbine of the controlled compressor can be controlled. By opening and closing the air valve at different time delays, different switching delay states of the successive pressurization system can be obtained. The switching delay of the air valve is the key factor affecting the entry system of the controlled compressor. The influence of opening the air valve at different time on the switching process of the sequential pressurization system is studied in this paper.

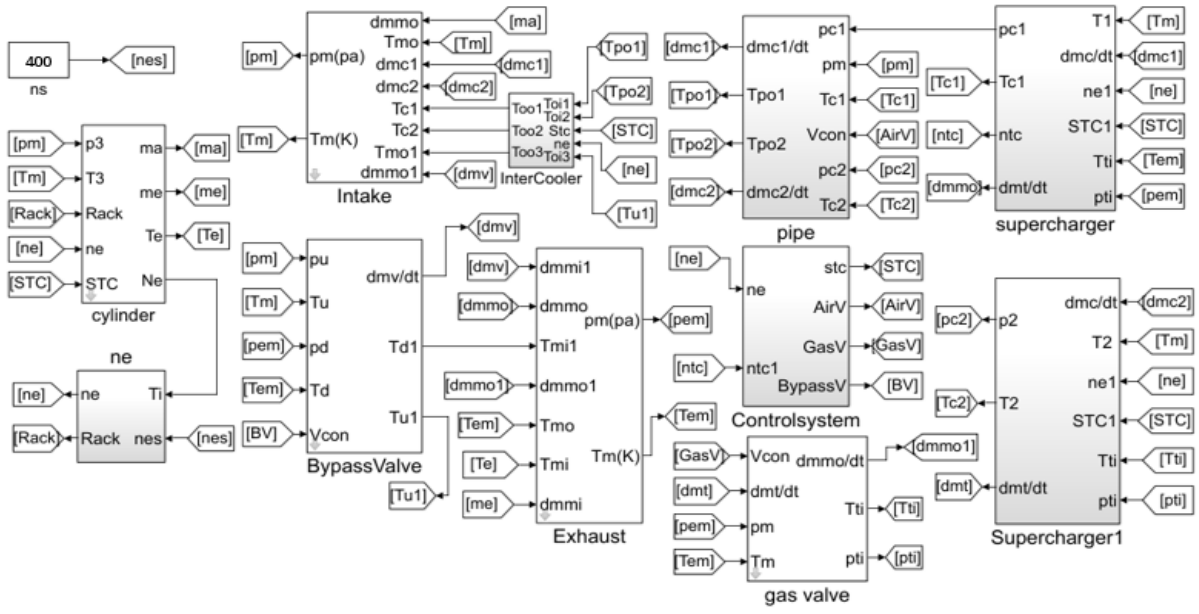

Fig. 2 Block diagram of MATLAB/Simulink simulation model of sequential pressurization system

3. Simulation model of successive turbocharged diesel engine system

3.1 Compressor model

In the simulation of successive pressurization system, the compressor may surge due to the influence of the switching delay process. In order to obtain the correct simulation results, a polynomial fitting

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method should be adopted to expand the characteristic curves of the compressor in the surge zone and negative flow zone [7-8], as shown in Figure 3.

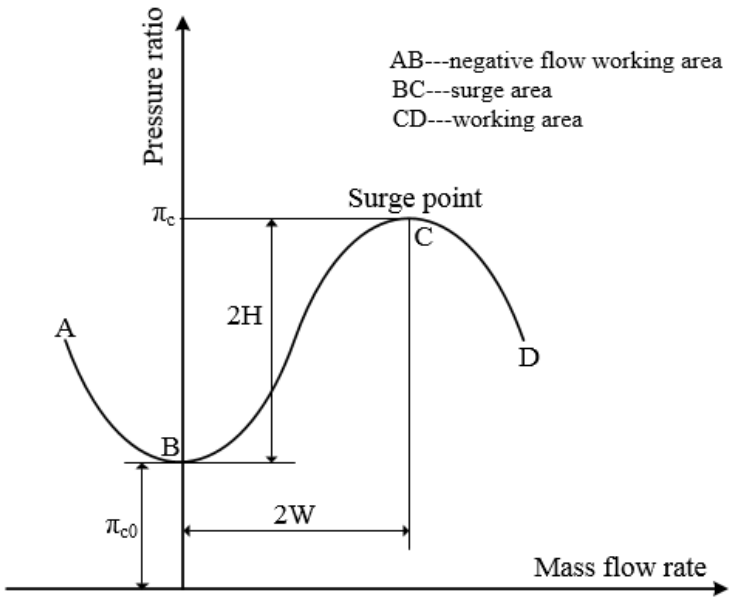

Fig. 3 Extended compressor characteristic curve

In Fig.3, segment CD represents the normal operating range of the compressor, segment BC represents the surge operating range of the compressor, and segment AB represents the negative flow operating range of the compressor.

Cubic curve fitting method is adopted to describe the operating characteristic curve of the compressor in the surge zone:

$$\pi_c = \pi_{c0} + H[1 + 1.5\left(\frac{\dot{m}_c}{W} - 1\right) - 0.5\left(\frac{\dot{m}_c}{W} - 1\right)^3] \tag{1}$$

The conic curve fitting method is adopted to describe the operating characteristic curve of the compressor in the negative flow area:

$$\pi_c = \pi_{c0} + 0.5H\dot{m}_C^2 W^{-2} \tag{2}$$

Type: $\dot{m}_c$——Compressor mass flow rate;

π_{c0}——The pressure ratio of a compressor at zero flow.

The pressure ratio of the compressor at zero flow can be obtained by the energy conservation method:

$$\pi_{c0} = \left[1 + \frac{k-1}{2kRT_1}\omega^2({r_2}^2 - {r_1}^2)\right]^{\frac{k}{k-1}} \tag{3}$$

Type: r_1——Compressor impeller inlet diameter;

r_2——Compressor impeller outlet diameter;

ω——Compressor angular velocity;

T_1——Compressor inlet temperature;

R——Gas constant

k——Specific heat ratio.

The torque of the compressor can be obtained by the energy equation:

$$M_c = \frac{30kR\dot{m}_cT_1}{\pi n_c(k-1)\eta_c}[{\pi_c}^{(k-1)/k} - 1] \tag{4}$$

Type: η_c——Compressor efficiency.

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3.2 Compressor rotating shaft model

In the sequential supercharging system, the operation of the compressor is driven by the turbine, so the compressor speed can be obtained by the following formula:

$$n_c = \frac{30}{\pi I_c}[M_T - M_c] \tag{5}$$

Type: n_c——Compressor speed;

I_c——Compressor moment of inertia;

M_T——Turbine torque;

M_c——Compressor torque.

3.3 The valve model

During the switching process of successive pressurization system, the valve can be equivalent to a throttle hole [9].When the gas flow is subsonic, the valve flow rate is:

$$\dot{m}_v = AP_0\sqrt{\frac{2k}{(k-1)R_0T_0}\left[\left(\frac{P_1}{P_0}\right)^{2/k} - \left(\frac{P_1}{P_0}\right)^{(k+1)/k}\right]} \tag{6}$$

When the gas flow is supersonic, the flow rate of the valve is:

$$\dot{m}_v = AP_0\sqrt{\frac{2k}{R_0T_0}\left(\frac{k+1}{2}\right)^{(k+1)/(k-1)}} \tag{7}$$

Type: A——Valve effective flow area;

P_0——Gas pressure in front of the valve;

P_1——Gas pressure behind the valve;

T_0——Gas temperature in front of valve;

R_0——The gas constant in front of the valve;

k——heat capacity ratio.

3.4 The turbine model

During the switching process of successive pressurization system, the turbine is always in normal working state. The turbine can be simplified as a throttle nozzle, and the turbine flow rate can be obtained by thermodynamic law as follows:

$$\dot{m}_T = \mu_T F P_{\mathrm{TI}}\sqrt{\frac{2k}{(k-1)RT_T}\left[\left(\frac{P_{TI}}{P_{TO}}\right)\right]^{2/\mathrm{k}} - \left[\left(\frac{P_{TI}}{P_{TO}}\right)\right]^{(k+1)/\mathrm{k}}} \tag{8}$$

Type: P_{TI}——Turbine inlet pressure;

P_{TO}——Turbine outlet pressure;

μ_T——Turbine flow coefficient;

F——Turbine equivalent flow area.

Turbine torque is:

$$M_T = \frac{30k\dot{m}_T T_T R\eta_T}{\pi n_T(k-1)}\left[1 - \left(\frac{P_{TO}}{P_{TI}}\right)^{(k-1)/k}\right] \tag{9}$$

Type: T_T——Turbine inlet temperature;

η_t——Turbine efficiency;

n_t——Turbine speed.

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4. Analysis of simulation results

4.1 The switching process from 1TC to 2TC has different switching delays

First of all, the operation model makes the diesel engine start to run, and after a period of time, the diesel engine is stabilized at 1TC state. In this state, the diesel engine is in low load condition, and the gas valve, air valve and bypass valve are all in the closed state. Then open the controlled compressor gas valve, controlled compressor turbine began operating work, wait until after a certain time delay, and then open the air valve, the basic compressor and controlled compressor running together, after a period of time diesel engine stability in 2TC state, the state, the diesel engine is in high load condition, the gas valve and air valve is fully open, The bypass valve is in closed condition. When the air valve is opened at different times, the switching delay of the supercharging system from 1TC to 2TC can be obtained successively.

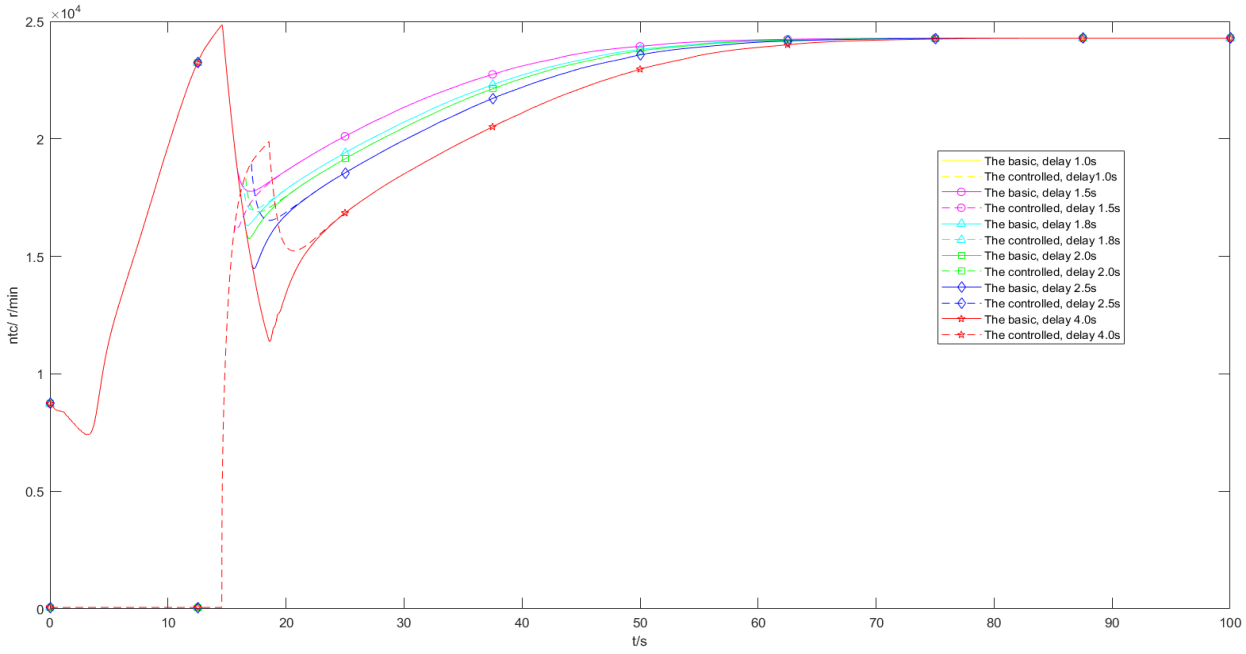

Fig. 4 Compressor speed change curve under different switching delays

It can be seen from the speed change curve analysis of basic compressor and controlled compressor in Fig. 4 that:

1. By analyzing the simulation results of the diesel engine switching from 1TC state to 2TC state, it can be concluded that opening the air valve at different time delays has a great influence on the switching process of the successive pressurization system. Come up from theory analysis, the basic compressor with controlled compressor exhaust pipe connected to the inlet pipe of diesel engine, open the gas valve, controlled work compressor turbine begins to spin, if early to open link in a controlled between the compressor and diesel engine air valve, due to the low controlled compressor rotate speed, the exhaust pipe pressure far less than the pressure of diesel engine intake pipe, Then the compressed air will flow backwards due to the pressure difference, leading to the surge phenomenon of the controlled compressor. On the contrary, if reluctant to open the air valve, controlled the pressure of the compressor exhaust pipe will significantly higher than that of diesel engine intake pipe pressure, once open air valve, can make the diesel engine intake pipe pressure increase, lead to basic compressor exhaust pipe pressure far less than the pressure of diesel engine intake pipe, excessive pressure difference causes air flow back, Thus, the surge of the basic compressor is induced. Therefore, there is a relatively appropriate or "optimal" handover delay time for a particular sequential turbocharged diesel engine [10].

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2. After the air valve is opened at different time delays, the speed of the basic compressor and the controlled compressor will change and finally the speed of the two compressors is basically the same; When the air valve is just opened, "surge" will occur to the compressor due to the influence of switching time delay. When the speed of the basic compressor and the controlled compressor is basically the same, the two compressors operate together without surge.

3. When the air valve is opened with a delay of 1s, the speed difference between the basic compressor and the controlled compressor is 4100rpm; When the delay is 1.5s, the speed difference is 450rpm; When the delay is 1.8s, the speed difference is -1220rpm; When the delay is 2.0s, the speed difference is -2190rpm; When the delay is 2.5s, the speed difference is -4180rpm; When the delay is 4.0s, the speed difference is -8480rpm. To avoid compressor "surge", the air valve must be opened after the turbine of the controlled compressor rotates to a speed slightly greater than that of the base compressor. The analysis shows that when the switching delay is 1.8s, the speed of the controlled compressor is higher than that of the basic compressor and the speed difference is small, and the compressor does not surge. When the switching delay time is 2.5s and 4s, the speed difference between the two compressors is too large and the basic compressor "surge" phenomenon occurs. Therefore, 1.8s is a relatively appropriate switching delay time.

4.2 The switching process from 1TC to 2TC+CAB has different switching delays

First of all, the operation model makes the diesel engine start to run, and after a period of time, the diesel engine is stabilized at 1Tc state. In this state, the diesel engine is in low load condition, and the gas valve, air valve and bypass valve are all in the closed state. Then open the controlled compressor gas valve, controlled compressor turbine began operating work, wait until after a certain time delay, and then open the air valve and by-pass valve, the basic controlled all compressor and by-pass system and the compressor is in working status, after a period of time of diesel engine stability in 2TC+CAB state, the state of diesel engine in a medium load condition. By opening the air valve and the bypass valve at different times, different switching delays of the supercharging system from 1TC to 2TC +CAB can be obtained.

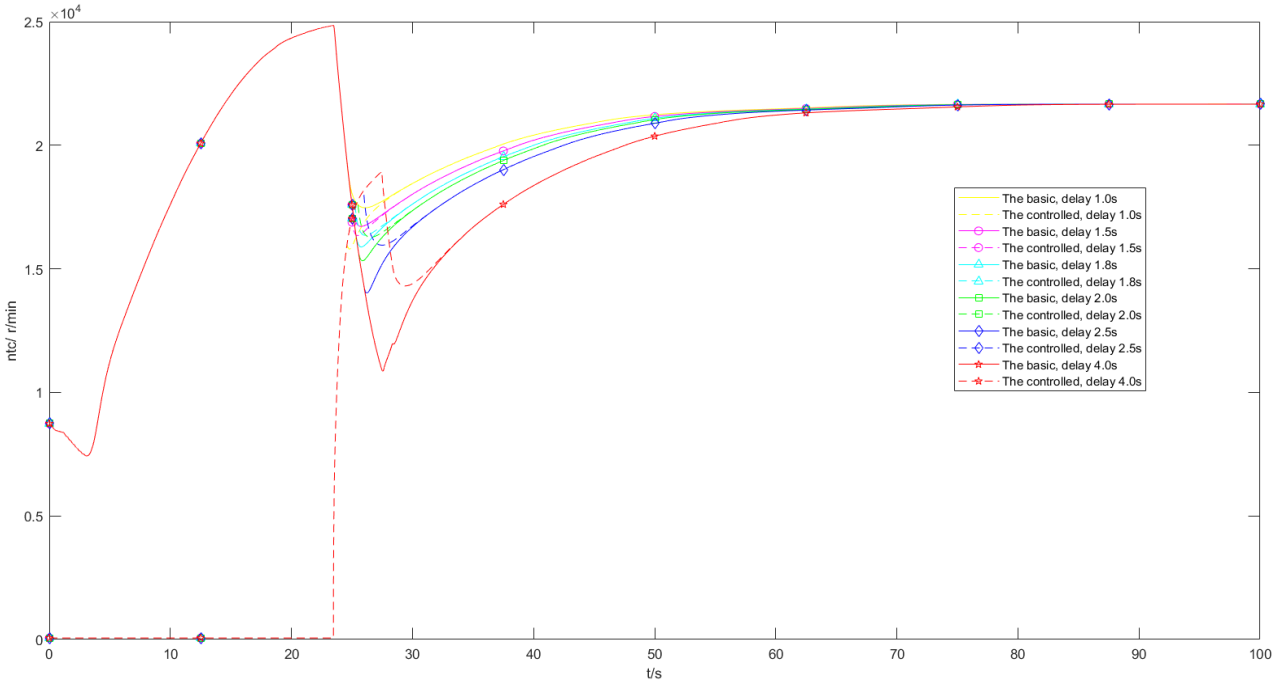

Fig. 5 Variation curve of compressor speed under different switching delay

It can be seen from the speed change curve analysis of basic compressor and controlled compressor in Fig. 5 that:

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1. Analyzing the simulation results of the diesel engine switching from 1TC state to 2TC+CAB state, it can be concluded that the sequential supercharging system switching from 1TC state to 2TC+CAB state is the same as switching from 1TC state to 2TC+CAB state. When the air valve connected between the controlled compressor and the diesel engine is opened too early, the phenomenon of "surge" will occur to the controlled compressor. When the air valve is opened too late, the "surge" phenomenon of the basic compressor will be induced. The appropriate switching delay is to open the air valve when the speed of the controlled compressor is slightly greater than the speed of the basic compressor.

2. When the air valve is opened with a delay of 1s, the speed difference between the basic compressor and the controlled compressor is 4430rpm; When the delay is 1.5s, the speed difference is 800rpm; When the delay is 1.8s, the speed difference is -860rpm; When the delay is 2.0s, the speed difference is -1800rpm; When the delay is 2.5s, the speed difference is -3770rpm; When the delay is 4.0s, the speed difference is -8020rpm. To avoid compressor "surge", the air valve must be opened after the turbine of the controlled compressor rotates to a speed slightly greater than that of the base compressor. When the air valve is opened before 24.96s, the speed of the controlled compressor is lower than that of the basic compressor, and the controlled compressor is prone to "surge". When the air valve is opened after 24.96s, the controlled compressor speeds faster than the basic compressor. The analysis shows that when the switching delay is 1.8s, the speed of the controlled compressor is higher than that of the basic compressor and the speed difference is small, and the compressor does not surge. When the switching delay time is 2.5s and 4s, the speed difference between the two compressors is too large and the basic compressor "surge" phenomenon occurs. Therefore, 1.8s is a relatively appropriate switching delay time.

4.3 The switching process of bypass valve opening and closing with the same switching delay time was compared

In order to compare the influence of the opening and closing of the bypass valve on the handover process with the same handover delay time, the speed changes of the compressor under the conditions of handover delay time of 1.5s and 1.8s were compared when the supercharging system was successively switched from 1TC to 2TC and 1TC to 2TC+CAB. First of all, the running model makes the diesel engine start to run, and after a period of time, it will stabilize at 1TC state. Then, the gas valve is opened to adjust the crank speed of the diesel engine and control the opening and closing of the bypass valve, so that the compressor speed under different states can be obtained.

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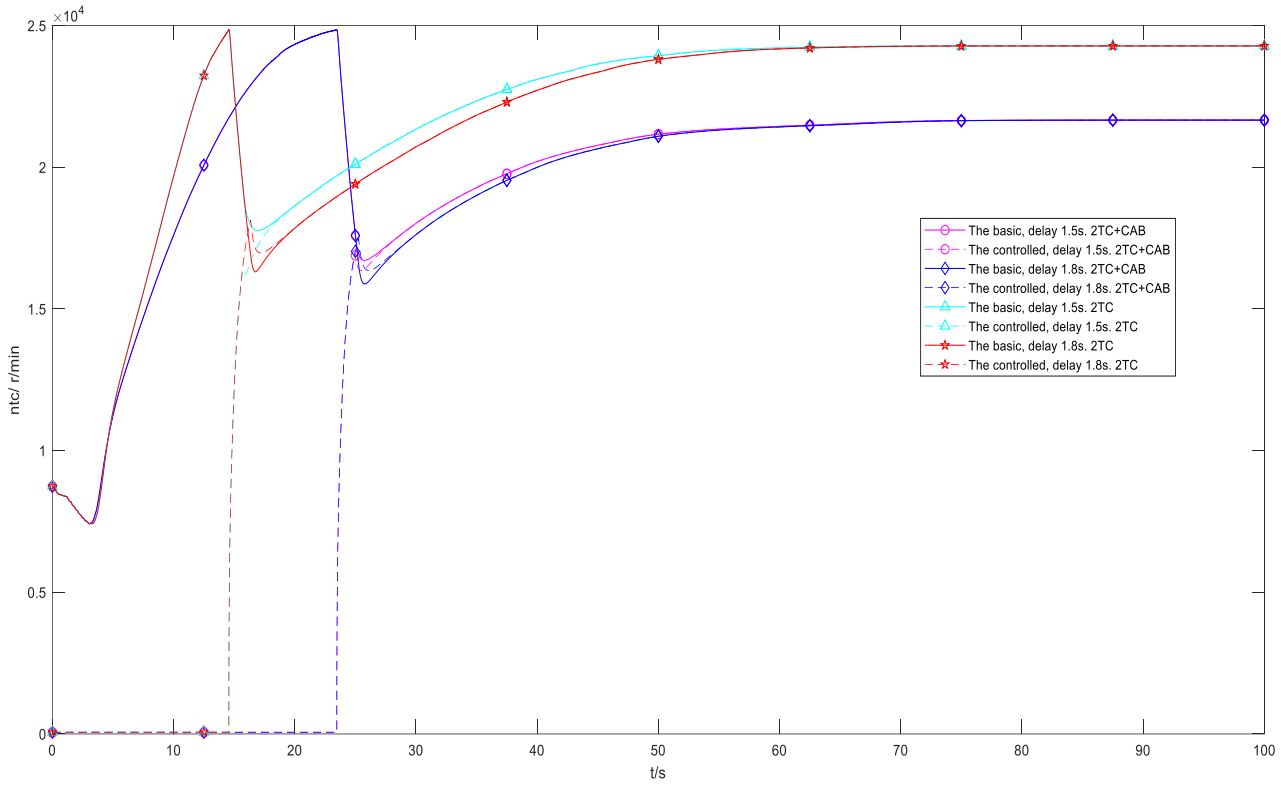

Fig. 6 Compressor speed change curve

From the analysis of compressor speed change curve in Fig. 6, it can be seen that:

When the switching delay time from 1TC to 2TC is 1.5s, the speed difference between the basic compressor and the controlled compressor is 450rpm.The speed difference between the basic compressor and the controlled compressor is 800rpm when the switching delay time of the successive pressurization system from 1TC state to 2TC +CAB state is 1.5s. When the switching delay time of the sequential pressurization system from 1tC to 2tC is 1.8s, the speed difference between the basic compressor and the controlled compressor is -1220rpm. The speed difference between the basic compressor and the controlled compressor is -860r/min when the switching delay time of the sequential pressurization system from 1tC state to 2TC +CAB state is 1.8s. To avoid compressor "surge", it is necessary to open the air valve when the speed of the controlled compressor is slightly greater than the speed of the basic compressor. When the air valve is opened under the delay time of 1.8s, the speed difference between the two compressors is compared under the open and close state of the bypass valve. It can be seen that the speed difference after opening the bypass valve is smaller, which can effectively avoid the basic compressor from running into the surge zone and make the selection range of switching delay time wider.

5. Conclusion

(1) The switching delay time of successive turbocharged system directly affects the working efficiency and performance of successive turbocharged diesel engine. If the appropriate switching delay time is not selected, the performance and efficiency of the diesel engine will be greatly reduced and the compressor "surge" phenomenon will occur. A relatively appropriate switching delay time is to open the gas valve and make the turbine of the controlled compressor rotate until its speed is slightly greater than that of the basic compressor before opening the air valve.

(2) The diesel engine only works with the basic compressor under the low load condition; Under medium load conditions, the basic compressor, controlled compressor and bypass system are all in working state. If the switching delay time is too long, the basic compressor will have a "surge" phenomenon, while if the switching delay time is too short, the controlled compressor will have a

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"surge" phenomenon. Under the condition of high load, the basic compressor and the controlled compressor are in the working state. If the switching delay time is too long, the "surge" phenomenon will occur to the basic compressor, and if the switching delay time is too short, the "surge" phenomenon will occur to the controlled compressor.

(3) As can be seen from the simulation results, the relatively appropriate switching delay time for the sequential pressurization system from 1TC to 2TC state and from 1TC to 2TC +CAB state is 1.8s. Under this switching time, neither the basic compressor nor the controlled compressor has "surge" phenomenon and works normally.

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References

[1] LIU Wei. Study on Two-stage Successive Turbocharging Performance of Marine Medium-speed Diesel Engine under Whole Working Condition [D]. Shanghai Jiao Tong University,2019.

[2] Wang Wei cai. Research on the Performance of Marine Diesel Successive Turbocharging System [D]. Harbin Engineering University,2008.

[3] Zhang Guangxi, Shi Yu mei, Yang Yukui, Liu Xiao mei. Simulation and Analysis of Sequential Turbocharging Matching for Diesel Engine [J]. Internal Combustion Engine & Powerplant, 2019, 36(05): 68-74+80.

[4] Gao Jingbo, Wang Binbin, Xia Qingliang, Gao Zhanbin, Fan Jinyu. Experimental Analysis of Switching Delay Time of Successive Turbocharged Diesel Engine [J]. Journal of Guangzhou Institute of Navigation, 2019, 27(04):1-4.

[5] Duan Daoshen. Research on Performance and Exhaust System Optimization of Successive Turbocharged Diesel Engine [D]. Dalian Jiaotong University,2018.

[6] Ren Yunzheng, Cheng Lun, Yang Ke. Simulation Research on Turbocharging System of 8190 Diesel Engine Based on GT-Power [J]. Automobile Practical Technology,2020(13):152-154.

[7] Zhou Wenjie, Cheng Jianghua, Shi Lei, Xing Weidong, Deng Kangyao. Research on Valve Coupling Control in Successive Turbocharging Switching Process of Diesel Engine [J]. Internal Combustion Engine Range, 2020,41(05):70-76+83.

[8] Qian Yuehua, Cui Yi, Deng Kangyao. Transactions of CSICE, 2010, 28(06):556-563. (in Chinese)

[9] Li Junpeng. Simulation Research on Exhaust System Performance of Marine Successive Turbocharged Diesel Engine [D]. Harbin Engineering University,2015.

[10] Chen Huaqing. Simulation and Analysis of 1Tc/2Tc Switching Process of Marine Successive Turbocharged Diesel Engine [J]. Journal of Thermal Energy and Power Engineering, 2009, 24(02):226-229+268.