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RESEARCH ARTICLE

Experimental Investigations on Control Strategy of Regulated Two-Stage Turbocharging System for Diesel Engine Under Transient Process

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ABSTRACT The regulated two-stage (RTS) turbocharging system is considered to be one of most effective measures to meet the requirements of the higher power density and the higher speed of automobile and marine diesel engines. However, the turbocharger matching and boost pressure control becomes significantly complex due to the engine operating conditions changed frequently. The engine test bench was built up to investigate the effects of several control strategies on the dynamic performance of the diesel engine with the RTS system. For the transient state four different control strategies, the open-loop control, the conventional PID control, the variable-parameter PID control, and the fuzzy control were employed. The experimental results show that the designed fuzzy control strategy has the best dynamic performance and the stability for both the transient loading process with constant speed and the transient marine operating conditions. Under the transient loading process and constant speed, the response time of the fuzzy control strategy is 0.3 s faster than that of the variable-parameter PID control, and 2.8 s faster than that of the open-loop control strategy. Under the transient marine operating conditions, the response time of the fuzzy control strategy is reduced by 0.9 s than that of the variable-parameter PID control, and 5.2 s reduced than that of the open-loop control strategy.

INDEX TERMS Control strategy, diesel engine, dynamic performance, regulated two-stage turbocharging system.

I. INTRODUCTION

To achieve more power output and meet the downsizing requirement, the regulated two-stage (RTS) turbocharging system was introduced as an effective measure to improve the steady and transient performance of the automobile and marine diesel engines. Through employing RTS system, the diesel engine could achieve much higher pressure ratio and wider flow range [1], [2], [3], [4], [5].

For the automobile application, the turbocharging system was designed to increase the low-speed torque and broaden the steady operation range. Therefore, in order to achieve more torque output of engine and to maximize the boost pressure, the RTS system was employed and its high-pressure turbocharger and low pressure one was operated in series mode [6], [7], [8], [9]. Buchwald *et al.* [10] adopted two-stage turbocharging system in a 4-cylinders diesel engine with EGR (Exhaust Gas Recirculation) system. The results of their researches showed that, by using the RTS system, the engine could obtain much higher torque output in the low-speed operation, while the boost pressure was steadily kept in a high level in medium- and high-speed operation conditions. Steinparzer [6], Choi [4], Langen [7], and Mattarelli [11] have also reached similar results in their investigations on diesel engines used for passenger vehicle.

For the marine application, the engine emission problem is becoming more urgent according to the stringent emission regulation. Therefore, new technology, such as the

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Miller cycle and EGR, were gradually used for reducing the in-cylinder temperature and optimizing the NOx emissions. However, the use of these solutions would increase the residual gas quantity in the cylinders, which would reduce the intake fresh air quantity. In such a situation, the application of RTS system would obtain sufficient mass flow of fresh air and maintain the same level of engine power output, which compared with the power output of engine without employing Miller cycle and EGR measures. Wik *et al.* [12] investigated the combination effects of Miller cycle and two-stage turbocharging system on a medium-speed diesel engine. Their results presented that, the combination of extreme miller and two-stage turbocharging could reduce the engine NOx emission by 50%, while the power output had no change compared to the engine with non-miller and one-turbocharging. Bernasconi *et al.* [13] conducted a research on diesel engine with EGR and two-stage turbocharging. In their investigation, the NOx emission was effectively reduced and met requirement of the Tier 4 regulation. Meanwhile, the engine operating range was obviously broaden when compared with the engine using one-stage turbocharging system. Mallamo *et al.* [14] had got the similar results in their researches on a heavy vehicle diesel engine using simulation method. Their results showed that, by using miller and RTS system, the power output of engine could be further promoted, and fuel consumption and NOx could be effectively reduced.

Under different operation conditions of diesel engine, either steady-state or transient process, the turbocharging system needed to provide the suitable boost pressure to meet the engine performance requirement. During the engine running with turbocharger, the boost pressure was significantly affected by the engine speed and torque. The boost pressure fluctuated according to the engine speed and torque changed. And such fluctuation in boost pressure presented serious nonlinear and time-varying features. Due to the nonlinear features, the boost pressure was uncertain during transient operation process of engine, which might deteriorate the engine performance. For RTS system, such nonlinear features under transient process became more serious. In order to improve transient performance of RTS system, usually, a bypass valve for high pressure turbine was employed to control the boost pressure. A suitable control strategy for the bypass valve might achieve desired transient response in boost pressure during transient operation. Therefore, the research on control strategy of turbine bypass valve is significant for the design of the RTS turbocharging system.

A suitable control strategy should not only meet the boost pressure requirement under steady-state, but also achieve a short transition time delay under transient operation conditions. By properly controlling the turbine bypass valve, the boost pressure could rapidly converge to a newly demand point when engine operation condition was changed. The shorter response time of boost pressure could effectively avoid the excessive overshoot and oscillation in boost pressure during the transient operation condition of engine. Many researchers have proposed different control strategies for turbocharging system to promote the transient performance of diesel engines. Eriksson *et al.* [15] investigated the gas path control in a turbocharging diesel engine. In their work, a control strategy, which combined the feed-forward control and the feedback loop, was adopted to adjust the opening of waste-gate valve according to boost pressure. Amstutz *et al.* [16] using excess air coefficient as the feedback parameter to control the opening of EGR valve, which would have effects on the turbocharging system of diesel engine. In those investigations, the PID controller with constant parameters was adopted. Although such control strategies could achieve good performance under a certain steady operating condition, the engine performance might deteriorate under transient process due to the nonlinear features of turbocharging system. Hualei Li *et al.* [17] designed a closed-loop strategy to control boost pressure of a diesel Engines with regulated two-stage turbocharging system. And they have compared the transient loading characteristics between the open-loop control strategy and the closed-loop control strategy with different control parameters. Their investigation showed that a PI controller with the variable parameters produced better transient characteristic than that with the constant parameters. Georg Tinschmann *et al.* [18] had researched the transient loading performance of regulated two-stage turbocharging system for MAN 6L diesel engine. In their investigation, though controlling the RTS system, a diesel engine which using VVT and Miller cycle, could achieve good performance under both low-speed and high-speed operating condition. And the transient performance was also effectively improved.

In those researches mentioned above, all the control strategies were based on PID controller which with constant or adjustable parameters. Many investigation [19], [20], [21] presented that, in the RTS system applications, the control parameters of PID controller should change with the operating conditions, and the online calibration of these parameters was needed to improve the regulation ability on boost pressure. However, the calibration process of control parameters depended on a lot of calculations and experiments, which would cause huge capital and labor costs.

Due to the nonlinear features of engine, fuzzy control was introduced in engine control in the last decades [22], [23], [24], [25], [26]. Fuzzy control method was mostly depended on experience of experts. And the negative effects of nonlinear features on system control might be minimized by adopting fuzzy control. Xia and Zhang [26] employed the fuzzy optimization method in RTS turbocharging system of a diesel engine under high altitude condition. Their investigation was performed on a GT-MATLAB co-simulation platform. And the results showed that the engine performance could be improved significantly by using such a fuzzy method. However, they did not conduct any experiments to test their conclusions achieved by simulation.

In this study, an experimental investigation on control strategies of regulated two-stage turbocharging system is carried out. And a test bench is built up to study the transient

TABLE 1. Main parameters of WP7 diesel engine with RTS system.

Parameters	Value
Manufacturer	Weichai Power Co., Ltd.
Rated speed (r/min)/Rated power(kW)	2200 /220
Maximum torque speed (r/min)/Maximum torque (N·m)	1500/1160
Bore (mm)/Stroke (mm)	108/130
Connecting rod length (mm)	209.7
Compression ratio	18:1
High pressure turbine/compressor	S200G/70/21ACAKM
Low pressure turbine/compressor	S300G/3571NRAKB

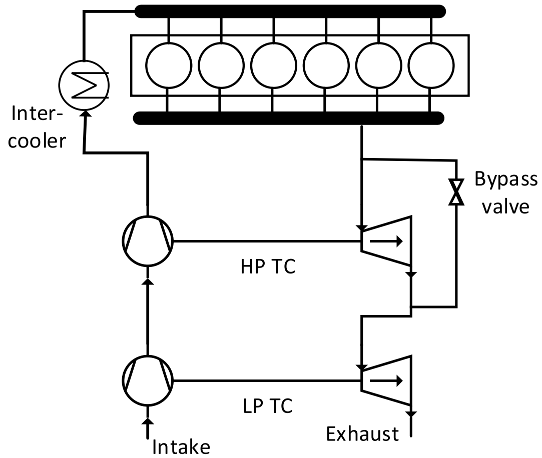

FIGURE 1. Schematic diagram of RTS system.

performance under different control strategies. In order to overcome the shortcomings of the open-loop and PID control strategies, a fuzzy control strategy is adopted to improve the transient characteristics of diesel engine with RTS turbocharging system. Based on the test bench, four control strategies are investigated, and the experimental results during the transient loading process are compared under automobile operating conditions and marine propelling conditions.

II. TEST BENCH OF DIESEL ENGINE WITH RTS SYSTEM

In this study, a WP7 [27] diesel engine is selected as the base engine. The main parameters are shown in Table 1.

For this diesel engine, a regulated two-stage turbocharging system is re-matched to increase the boost pressure and improve the low-speed performance. Two new turbochargers which provided by Borg Warner Company were used as high- and low-pressure turbochargers instead of the original single-stage turbocharging system.

Fig. 1 shows the schematic diagram of RTS system used in experiment. And Fig. 2 is the picture of the test bench. In the set-up of such an RTS system, a straight pipe, which length is as short as possible, is used to connect the high-pressure turbine (HPT) and low-pressure Turbine (LPT). With such connecting design, it can reduce the energy loss of exhaust

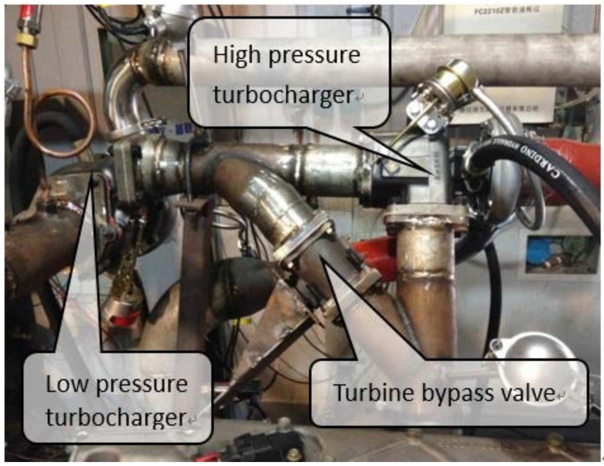

FIGURE 2. Layout of regulated two-stage turbocharging system.

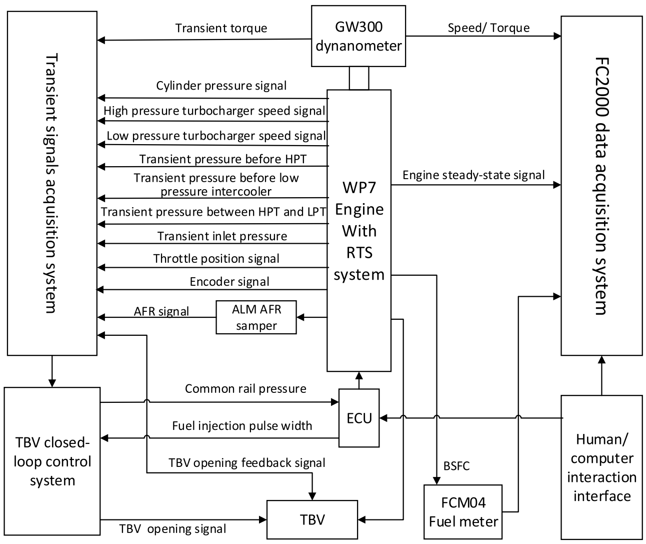

FIGURE 3. Measurement and control system of test bench for WP7 diesel engine with RTS system.

gas and improve the utilization efficiency of exhaust energy. To decrease the flow losses, the separation angle between the exhaust pipe and the branch pipe of turbine bypass valve is designed at the angel of 45 degree. Such a separation angle is beneficial to the exhaust gas flow in the three-way pipe junction. The high-pressure turbine is set up in parallel with a butterfly valve, which is used as the turbine bypass valve to regulate boost pressure. The opening of turbine bypass valve can be continuously adjusted through controlling an electronic motor with angular position feedback potentiometer.

Fig. 3 shows measurement and control system of the test bench for WP7 diesel engine with RTS system. The test bench is built up to study the operating performance of the engine with RTS system. It includes three main components: WP7 diesel engine with RTS system, valve control system, and

TABLE 2. Experiment instruments.

Instrument and equipment	Precision
GWD300 eddy current dynamometer	±0.4% torque; ±1 r/min speed
FCM fuel consumption measuring instrument	±0.5%
Micro-Epsilon turbocharger speed sensor	±0.1%
HM90 intake and exhaust pressure transmitter	±0.1%
K type thermocouple temperature sensor	±(0.15+0.002*|t|)

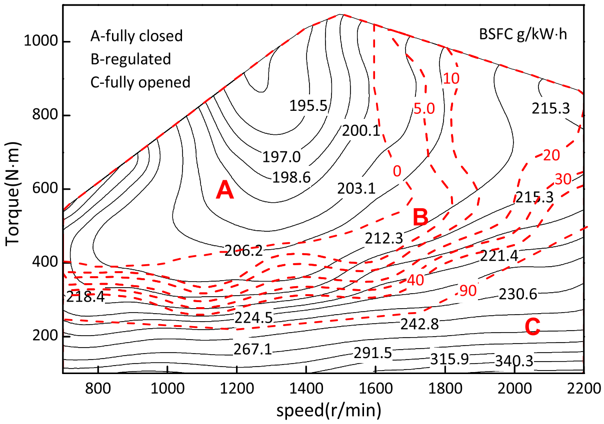

FIGURE 4. Economic control strategy and corresponding BSFC performance.

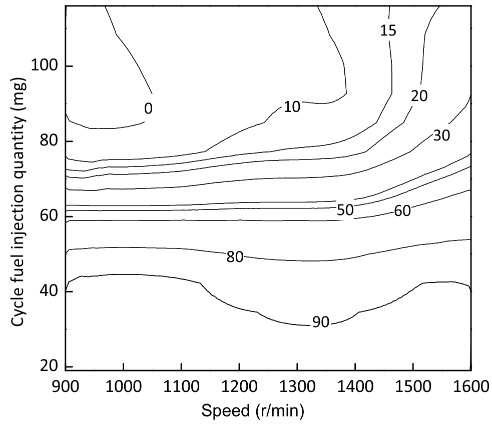

FIGURE 5. TBV opening map of economic control strategy.

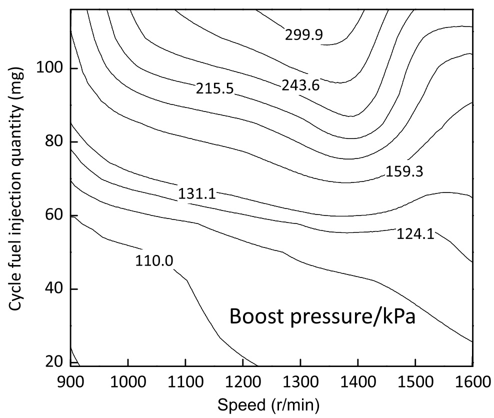

FIGURE 6. Boost pressure map of economic control strategy.

steady and transient signal acquisition systems. The experiment instruments used in experiments are listed in Table 2.

III. RTS SYSTEM CONTROL STRATEGY

Based on the test bench of WP7 diesel engine with the RTS system, the steady-state experiment is carried out. In the experiments, the engine speed is adjusted at intervals of 100 rpm from 700 rpm to 2200 rpm. At each speed point, the engine torque is changed at intervals of 100N·m, and the opening degree of turbine bypass valve is regulated from 0 degree (totally closed) to 90 degree (fully open) at intervals of 5 degree. For the purpose of improving the fuel efficiency, the steady control strategy, named as economic control strategy, is determined according to the opening degrees that makes the engine achieving the minimum BSFC (Brake specific fuel consumption) value within the whole operating range.

Fig. 4 shows the economic control strategy of turbine bypass valve (TBV) and corresponding BSFC performance. As showed in Fig. 3, the entire operating range is divided into three parts, Area A, Area B, and Area C. For the low-medium speeds and high loads (Area A), the engine needs a large mass flow rate of intake air to achieve good combustion performance. Therefore, in this area, the TBV needs to be totally closed, which makes the RTS system operated as an ordinary two-stage turbocharging system to maximize the intake air flow quantity. For the low loads at different speeds (Area C), due to the relatively small quantity of cycle fuel injection, the excess air coefficient is much larger than that is required for in-cylinder combustion. With the small TBV opening in area C, in-cylinder combustion cannot be further improved by the increased air supply. Contrarily, the small TBV opening would lead to the increase of the exhaust back pressure of engine which increases pumping loss and fuel consumption. Therefore, the TBV should be fully opened to reduce the pumping loss and decrease the BSFC level in area C. For the medium speeds, medium loads, and high loads at high speeds (Area B), the TBV opening should be regulated based on the changing of fuel injection quantity and engine speed to provide the suitable intake air and meet the requirements of excess air coefficient.

Respectively, Fig. 5 and Fig. 6 present the economic TBV opening and corresponding boost pressure according to engine speed and cycle fuel injection quantity. During steady-state operation, once the operating conditions change from a steady-state to a new operating point, the control system would obtain the TBV opening at the new operating point by looking up the feed-forward MAP table according to the signals of engine speed and cycle fuel injection quantity, and adjust the TBV opening to the new target position.

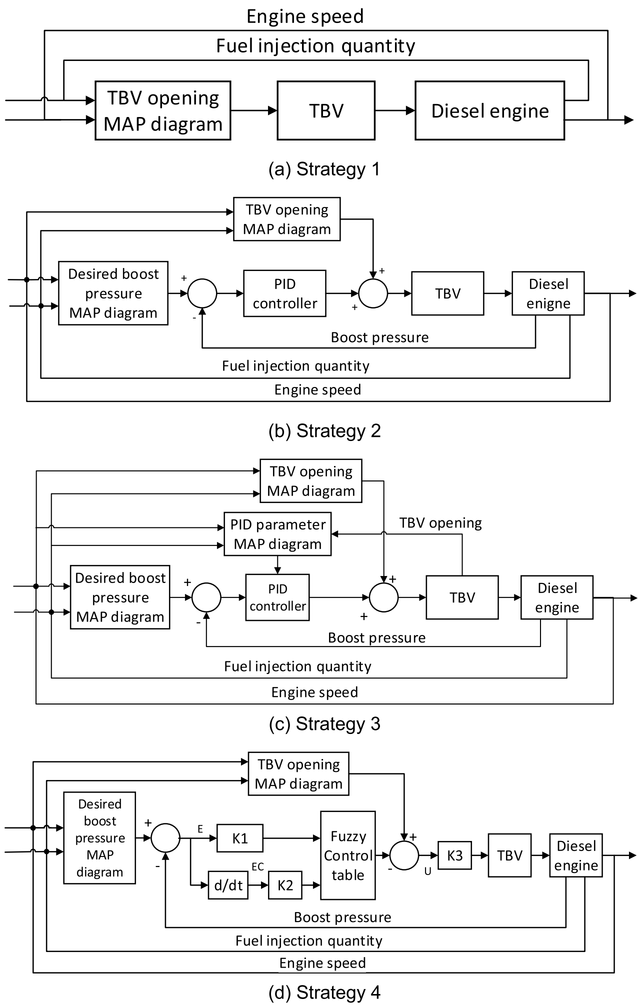

FIGURE 7. Four control strategies designed for transient loading process.

By using such an economic control strategy, under steady-state conditions, the engine can obtain the optimal performance in the whole operating range. However, it is very difficult to achieve suitable transient performance based on the steady-state control strategies. Therefore, transient control strategies should be adopted to ensure quick establishment of boost pressure during transient accelerating and loading processes.

Four strategies have been adopted to control the TBV opening during transient process in this investigation. The schematics of these four control strategies is showed in Fig. 7. All these control strategies are based on the TBV opening and corresponding boost pressure MAP which resulted from steady-state experiments. The investigations on these four control strategies are carried out under the transient loading conditions of vehicle operation and marine propulsion. The feature of each strategy is listed in Table 3. As shown in the table, the strategy 1 is an open-loop control strategy, and all the other three are closed-loop strategies with feedback loops.

TABLE 3. Main Features of four control strategies.

Control strategies	Control loop	TBV opening MAP	Boost pressure MAP	PID parameter	Fuzzy control
Strategy 1	open	Yes	No	—	NO
Strategy 2	closed	Yes	Yes	constant	NO
Strategy 3	closed	Yes	Yes	variable	NO
Strategy 4	closed	Yes	Yes	—	Yes

As an open-loop control strategy, Strategy 1 acquires the suitable output parameters (such as TBV opening) based on the MAP table looked up. The real-time control accuracy and response characteristics of the control system mainly depended on precision of the MAP table. For Strategy 1, the TBV opening is determined by looking up the TBV opening MAP table according to the real-time speed and fuel injection quantity of the engine. The TBV opening value resulted from looking up MAP table is directly used to control turbine bypass valve by TBV control system. And then the boost pressure would change according to the TBV opening and engine state.

For Strategy 2, 3 and 4, the control accuracy can be effectively improved due to the addition of the feedback loops. In Strategy 2, a PID (Proportion Integration Differentiation) controller with constant parameters is adopted. In this strategy, the desirable boost pressure and the TBV opening is achieved according to the real-time speed and fuel injection quantity, and the actual TBV opening is adjusted by a PID controller to adapt to the difference between the desirable boost pressure and the actual boost pressure feedbacked through the closed-loop. Here, the PID controller has a zero D gain due to the highly nonlinear features of RTS system. For such a nonlinear noisy system, introduction of D gain would result in increased complexity and noise susceptibility, and reduce gain margin of the controller [28]. And such a similar PI controller has been widely used in engine control [29].

In strategy 2, the parameter Kp and Ki of the PID controller was determined through simulation method. A detail model of the engine was established in GT-POWER, and the operating conditions used for simulation are similar to the experiments. A DOE analysis was conducted through combination of GT-POWER and ISIGHT software. And Latin Square Design method was used in DOE analysis. According to the simulation results, the constant parameter Kp and Ki for Strategy 2 is respectively set as 16 and 0.8 in this investigation.

For Strategy 3, as shown in Fig. 7, the difference compared to Strategy 2 is that variable parameters for PID controller were adopted. In Strategy 3, the parameter Kp and Ki of the PID controller can be adjusted according to the inputs of the real-time engine speed, fuel injection quantity and TBV opening. According to the simulation results, the transfer function from TBV opening to boost pressure can be simplified and treated as a first-order inertia system. The MAP of parameter

TABLE 4. Fuzzy rule of boost pressure for Strategy 4.

EC / U / E	NB	NM	NS	ZO	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	NS
NM	NB	NB	NB	NB	NM	NS	ZO
NS	NM	NM	NM	NS	ZO	ZO	PS
ZO	NM	NM	NS	ZO	PS	PM	PM
PS	NS	ZO	ZO	PS	PM	PM	PM
PM	ZO	PS	PM	PB	PB	PB	PB
PB	PS	PS	PM	PB	PB	PB	PB

Kp and Ki is determined according to the system transfer function. Through analyzing the simulation results, the Kp of Strategy 3 was set as 1/2 times the reciprocal of the system gain, while the Ki was the same as the system time constant. Here, for Strategy 3, according to the simulation analysis, the variation range of parameter Kp was from 5 to 50, and Ki was from 0.5 to 2.

For Strategy 4, the universe of discourse for the boost pressure error E and for the change rate EC of boost pressure was determined according to the speed and fuel injection quantity based on the analysis of experimental results. The fuzzy rule of boost pressure for Strategy 4 is listed in Table 4. Here, NB means big negative, NM means medium negative, NS means small negative, ZO means Zero, PS means small positive, PM means medium positive, and PB means big positive. The controller output U is determined by the sum of the look-up results from fuzzy control table and the TBV opening MAP diagram. And then the TBV opening value calculated is used to adjust the TBV opening by the TBV control system. There are 49 rules are presented in Table 4. All these rules are synthesized in the form like below.

$$\text{if } E = NB \text{ and } EC = NB \text{ then } U = NB$$

These four control strategies were digitalized and coded with C language. In order to guarantee the real-time performance, the codes were deployed on a micro control unit (MCU), which used as the TBV opening controller. Then the TBV is controlled with the four control strategies, and the stability and transient response characteristics are investigated based on the test bench of WP7 engine with RTS system.

IV. RESULTS AND DISCUSS

Experiments were conducted to investigate the stability and transient response characteristics of the four strategies. The following is comparison of the test results of these four strategies.

A. STABILITY COMPARISON OF FOUR CONTROL STRATEGIES

In order to investigate stability of the four strategies, experiments were conducted under a specified operating condition of engine, and a boost pressure disturbance was introduced by changing the opening of a butterfly valve installed upstream

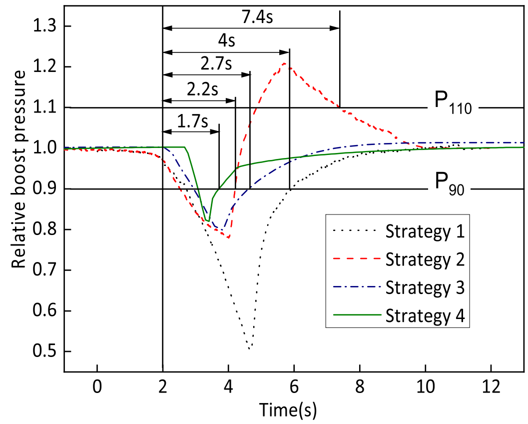

FIGURE 8. Boost pressure of four strategies during disturbance process.

of intake pipe. Here, the operating condition was maintained at the speed of 1500rpm and the cycle injection quantity of 116mg. During experiments, as the corresponding boost pressure was decreased due to disturbance introduction, the four strategies would take effect to adjust TBV opening to recover the boost pressure. The stability comparison of four control strategies was carried out to evaluate the anti-jamming and recovering ability of boost pressure under the steady-state operating conditions.

The boost pressure variations during disturbance process were presented in Fig. 8. As shown in the figure, for all test cases, an intake flow disturbance took place at 2 second due to the reduction of the butterfly opening, which resulted in a quick reduction of boost pressure because of the throttling effect of butterfly valve.

In Fig. 8, it can be seen that, due to the intake flow disturbance, boost pressures for all test cases dropped firstly and then gradually recovered to the target level. In the figure, the transition times of the pressure fluctuation for every case were compared. Here, the transition time was defined as an interval from the occurring of disturbance to the moment at which the pressure recovered to the 0.9 or 1.1 times of target value before it achieved stable state. As shown in Fig. 8, the transition time of the strategy 4 was the shortest one, while the strategy 2 had the longest transition time. For the case of strategy 2, although pressure recovered to the level of P90 at 2.2 s after disturbance occurred, its transition process was finished at 7.4 s due to the subsequent pressure oscillation with an overshooting which about 1.2 times of target level. By compared analysis, the transition time of strategy 2 was about 4.3 times of the transition time of strategy 4, which was about 1.7 s. As presented in Fig. 8, the transition times for strategy 3 and strategy 1 were 2.7 s and 4 s, respectively.

Fig. 9 presented mean value and variation range of boost pressure for all strategies during disturbance process. Here, the mean values were calculated using the data from 2s to 10s, which included the whole transition process for all cases. As shown in Fig. 9, the Strategy 1, which using open-loop control method, achieved the lowest mean pressure and the

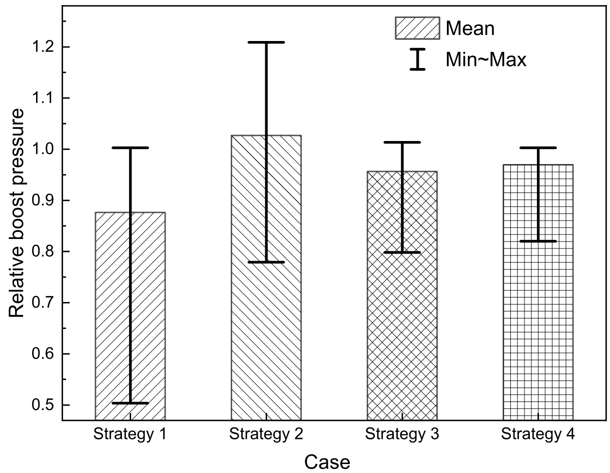

FIGURE 9. Mean value and variation range of boost pressure for all strategies during disturbance process.

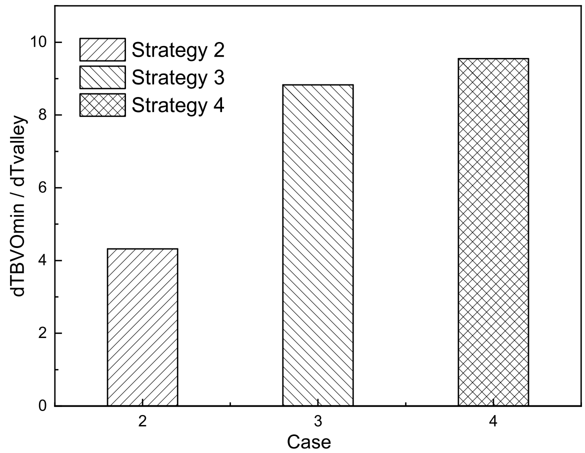

FIGURE 11. dTBVOmin / dTvalley for Strategy 2, 3 and 4.

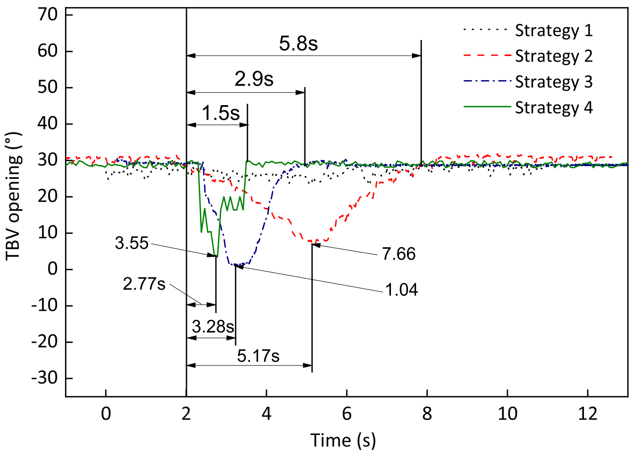

FIGURE 10. TBV opening of four strategies during the boost pressure disturbance process.

widest variation range. For strategy 2, the case using PID control method with constant parameters, although a highest mean pressure was achieved, it had a highest overshooting in boost pressure, which was about 1.2 times of the target level. As presented in Fig. 9, the mean value and variation range of boost pressure for strategy 3 and strategy 4 were similar. Their mean pressures close to the target value, and their pressure variation range were obviously narrower than that of strategy 1 and strategy 2. For strategy 4, which using the fuzzy control method, it achieved the narrowest pressure variation range, which was smaller by about 2.7 times when compared to the results of strategy 1.

Fig. 10 presented the results of TBV opening during the boost pressure disturbance process. As shown in Fig. 10, for the cases of strategy 2, strategy 3 and strategy 4, all these TBV opening firstly reduced due to the disturbance occurred, and then gradually recovered to a stable level. But for the case of strategy 1, its TBV opening nearly maintained at the original opening level due to the open-loop control method, which determined the TBV opening depended on engine speed and fuel injection quantity.

As shown in Fig. 10, the changes of the TBV opening for strategy 2, strategy 3 and strategy 4 were obviously different due to the different control method. It can be seen from Fig. 10 that the action durations of these three strategies is 5.8 s, 2.9 s and 1.5 s respectively. Therefore, through using the strategy 4, the TBV action durations could be significantly reduced. As the experiment results shown that the action durations for strategy 4 was shorter by about 3.9 times compared to that of strategy 2.

From Fig. 10, it could also be seen that, by compared the change rate of TBV opening at the beginning of disturbance occurring, the TBV opening of strategy 4 decreased the fastest, then Strategy 3, and Strategy 2 had the slowest reduction rate. In order to further analyze the response of TBV under Strategy 2, Strategy 3, and Strategy 4, the ratio, dTBVOmin / dTvalley was introduced. Here, dTBVOmin referred to the difference between the normal TBV opening before disturbance occurring and the minimum opening during disturbance process for each strategy. And dTvalley referred to the interval between disturbance occurring and the moment at which the minimum TBV opening achieved for each strategy. Fig. 11 presented the results of dTBVOmin / dTvalley for strategy 2, strategy 3 and strategy 4. As shown in Fig. 11, strategy 4 achieved the maximum level of dTBVOmin / dTvalley at 9.57, and strategy 2 obtained the minimum level at 4.3. The results of dTBVOmin / dTvalley for strategy 3 was about 8.84, which was obviously lower than that of strategy 4. Therefore, it could be concluded that, for the RTS turbocharging system control, the strategy 4 using fuzzy control method could achieved a faster response speed when compare to the other strategies adopted in this investigation during the transient process.

According to the analysis results for boost pressure response and change process of TBV opening during disturbance process, when compared with other strategies, the strategy 4 using fuzzy control method had significant advantages in RTS turbocharging system control. The fuzzy control method could achieve the shortest transition duration and the fastest response speed during transient process. And more stable control characteristics could be obtained by adopting the fuzzy control method.

B. COMPARISON OF RESPONSE CHARACTERISTICS UNDER TRANSIENT CONDITIONS

In this section, response characteristics of these four strategies under transient loading processes were analyzed. Two typical loading processes, representatives for automobile operating conditions and propelling conditions, were investigated.

The transient loading processes for automobile operating conditions and propelling conditions take a very important part in the transient operating conditions. These transient conditions are very complicated due to the nonlinear relationships for the multiple control variables, such as the relationship between the response parameters of boost pressure and engine speed and the control variables such as TBV opening and fuel injection. The response of boost pressure significantly affected the combustion process. Analyses of the boost pressure response could reflect the transient characteristics of RTS turbocharging system under different control strategies. Therefore, the transient boost pressure response characteristics are compared between these four control strategies under the two typical loading processes.

Firstly, experiments under the transient loading process for automobile operating conditions was conducted. In this transient process, the engine speed was maintained at a constant level of 1500r/min by controlling the dynamometer. The cycle fuel injection quantity at beginning of the transient process was 75mg, and 103mg at the ending. The experimental results were presented in Fig. 12.

As shown in Fig. 12. (a), the transition duration for the cycle fuel injection was from 1s to 6.8s. In the transition duration, the cycle fuel injection linear increased from 75mg to 103mg. During the transition process, a speed overshooting of about 44r/min occurred due to the increase of cycle fuel injection quantity, which resulted in the increase of engine torque.

According to Fig. 12, for all strategy cases, the response speed of boost pressure is similar before the time of 4 second. When the time is over 4 second, the difference between the actual boost pressure and the desired boost pressure is gradually increased. The response speed of boost pressure for Strategy 1 is much slower than other control strategies. The difference of response time is 2.8 second compared to Strategy 2 and Strategy 3, and 2.5 second compared to Strategy 4 respectively (seen in Fig. 12. (c)).

As shown in Fig. 12. (d), Strategy 4 closes the TBV with the control of the digitized fuzzy rule based on the error of boost pressure and the error change rate. Strategy 2 and Strategy 3 also regulate the TBV gradually with the control of PI controller, in which the proportional and integral parameters were obtained by looking up the PID parameters MAP diagram. However, their response actions are much slower than that of Strategy 4 and the corresponding response of boost pressure shows a delay of 0.3 second compared with Strategy 4. For Strategy 1, the TBV opening is regulated with the change of the operating conditions, and its response speed of boost pressure is not obviously delayed before the time of 4 second when compared to the other strategies.

By observing Fig. 12, it could be seen that, during the transient loading process at constant speed, the speed and fuel injection quantity rose up to the maximum value at 6 second, and then the speed gradually returned to the initial value (shown in Fig. 12. (a)). According to the TBV opening results, for Strategy 2 and Strategy 3, the TBV is also closed at 5 second, and then open gradually. For strategy 3, which used PID control method with variable parameters, its TBV opening achieved the steady state at 10s, and its boost pressure simultaneously entered the steady state with the desired pressure value. But for strategy 2, which adopted a PID control method with constant parameters, a severe oscillation was occurred in the TBV opening change after about 8 second. And the corresponding oscillation was occurred in the boost pressure of strategy 2. In the case of Strategy 4, the TBV was also adjusted to the desired opening at 10 second. This is mainly because that, at the moment, the difference error between boost pressure of strategy 4 and the target pressure is positive, and it shows an increase tendency. As shown in Fig. 12, although the pressure of strategy 4 had an overshoot of 5 percent, its control effects were much better than that of the other control strategies.

From Fig. 12, it also could be seen that, in the cases of Strategy 2 and Strategy 3, the transient response characteristics were extremely similar before 10s. However, in the phase after 10s, the results of strategy 2 shows a huge fluctuation in the TBV opening and boost pressure, which could not achieve the steady state with desired target value.

According to Fig. 12. (b), in cases of Strategy 3 and Strategy 4, the torque was maintained at a constant value after 10 second. This is because the boost pressure and fuel injection quantity are constant during this phase, which would result in a steadier combustion process in the engine. The torque of Strategy 2 shows an oscillation trend due to the fluctuation in its boost pressure in the phase after 10s. For Strategy 1, its torque shows an obvious delay trend, which correspond to the delay of its boost pressure.

The experimental results under the transient loading process for marine propelling conditions was presented in Fig. 13.

As shown in Fig. 13. (a), under such propelling conditions, the engine load is increased from 25% to 75%. And the corresponding engine speed is increased from 945r/min to 1363r/min, which was controlled by a dynamometer. The speed and the fuel injection quantity are increased from 2.5 second, and reached a new steady state at about 7.5 second.

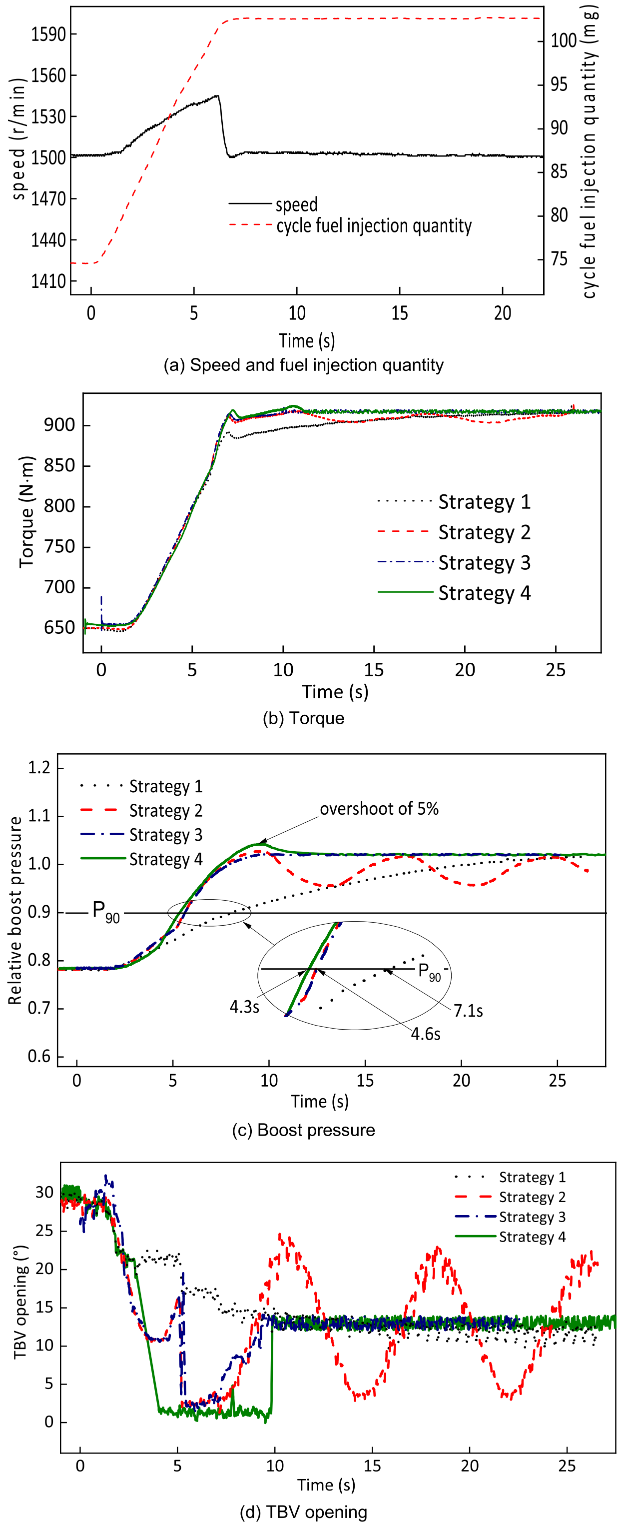

FIGURE 12. **Comparison of four control strategies at transient loading process and constant speeds.**

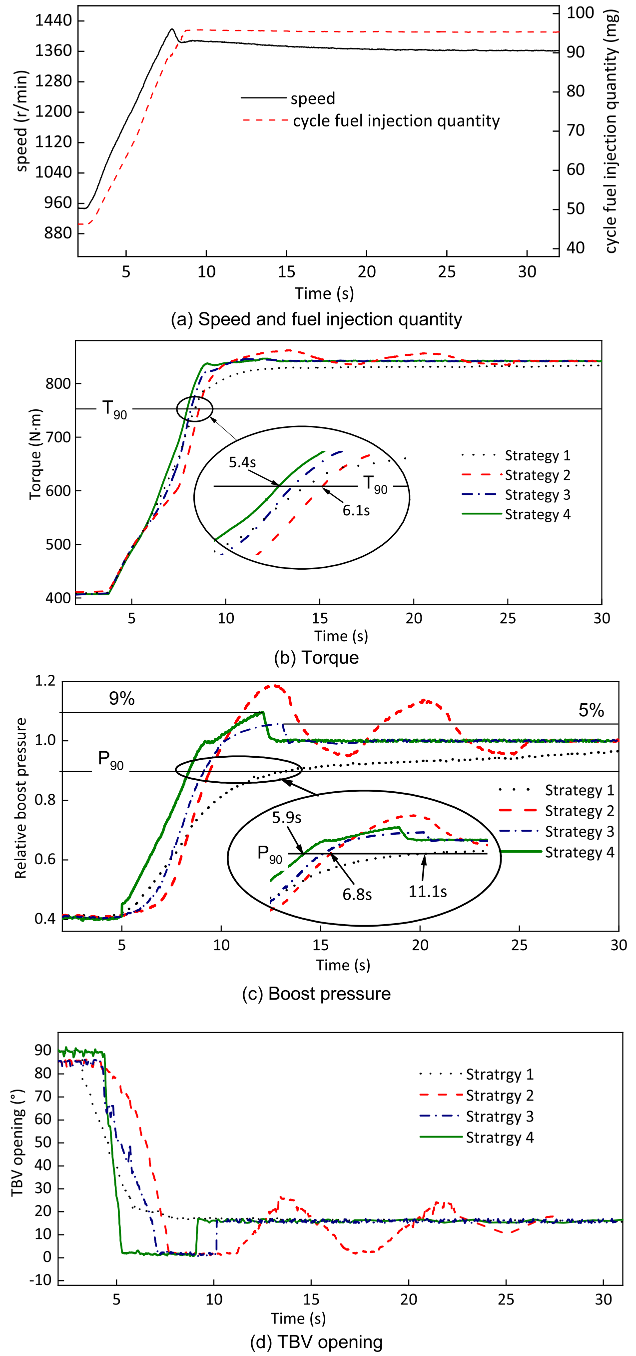

FIGURE 13. **Comparison of four control strategies for the transient marine propelling characteristics.**

According to the results of TBV opening, which shown in Fig. 13. (d), the TBV opening of strategy 1 was linearly decreased at first, and then became stable as the engine speed and the fuel injection quantity stabilized at about 7.5 second. The closing action of TBV for strategy 1 closely followed the change of speed and fuel injection quantity, which was because the TBV opening was determined according to the MAP depended on engine speed and cycle fuel injection quantity. The beginning of TBV action for the other three strategies was of about 1.5s delay compared to that of strategy 1. But as the transition process proceeding, all the TBV opening of strategy 2, strategy 3 and strategy 4 became fully closed, which never occurred for strategy 1.

As shown in the Fig. 13, these three control strategies, strategy 2, strategy 3 and strategy 4, began to regulate the

TBV almost at the same time, which was according to the difference of boost pressure. However, their change rates were different for the different TBV control methods. Strategy 4 changed the TBV opening from fully opened to fully closed in 0.5 second at the time of 5 second (seen in Fig. 13. (d)), and the adjusted velocity was much faster than that of strategy 2 and strategy 3. For these three strategies, the TBV opening is determined by the difference of actual pressure and desired boost pressure and the feed-forward value of TBV opening. But at the begin of TBV action for these three strategies, engine speed and cycle fuel injection quantity rose up to 1100r/min and 60mg respectively, and the actual boost pressure still unchanged at this moment. Therefore, a sharply decrease in TBV opening occurred at this moment for all these three cases. As the results shown in the figure, the response time strategy 4 was about 5.9 second when the boost pressure rises up to 90% of the final steady value (Fig. 13. (c)), while that was about 6.8 second for strategy 2 and strategy 3. Strategy 1 was of about 11 second in response, which was much longer than that of the other three strategies.

For Strategy 3, although the beginning of TBV action was at the same time as Strategy 4, its TBV action speed was a little slower than that of Strategy 4, but much faster than that of strategy 2. Strategy 3 could reduce the TBV opening quickly due to the corresponding control parameter P and I are very large under conditions with the low speed, the small fuel injection quantity and the fully open TBV. The regulation rate of TBV opening for Strategy 2 was relatively slow due to a small difference of boost pressure, which was due to the constant PI control parameters independent of the operating conditions. When the difference of boost pressure is gradually decreased at 10 second and changes to positive, Strategy 3 opens the TBV quickly and regulates the PI control parameters. The boost pressure of Strategy 3 shows an overshoot of 5% which is much smaller than that of Strategy 4 due to the short duration time of the fully closed TBV. But Strategy 3 recovers the boost pressure to the desired value to achieve a certain steady operating condition at 12.5 second. Although the boost pressure of Strategy 4 shows an overshoot of 9%, it appears a relatively quick response rate (Fig. 13. (c)).

It could be seen in Fig. 13, the transient response characteristics of Strategy 4 shows much better than other three control strategies during the transient process of engine torque. The response time of Strategy 4 is advanced of 0.7 second compared with that of Strategy 2. For all the cases, engine was operated with the same fuel injection quantity. Therefore, the transient response of boost pressure was of most importance in analysis of transient characteristics. The comparison results shown that Strategy 4 has the unique advantage on improving the transient loading performance.

V. CONCLUSION

The dynamic characteristics of the WP7 diesel engine with the regulated two-stage turbocharging system using different control strategies are investigated on the test bench. According to the analysis on the experimental results, the following conclusions can be made.

(1) The fuzzy control has shown the best control performance for the transient loading process at constant speed. The response time with the use of fuzzy control is reduced by 0.3 second compared with that of the variable parameters of PID controller, and is reduced by 2.8 second compared with that of open-loop control strategy.

(2) Under the transient marine propelling conditions, the response time of the fuzzy control is reduced by 0.9 second compared with that of the variable parameters of PID controller, and is reduced by 5.2 second compared with that of open-loop control strategy.

(3) According to the stability analysis of different control strategies, the fuzzy control method could achieve the shortest transition duration, and its recovering time of boost pressure is two fifths of the open-loop control strategy. More stable control characteristics could be obtained by adopting the fuzzy control method.

(4) The fuzzy control method could achieve the fastest response speed during transient process. Strategy 4 achieved the maximum level of dTBVOmin / dTvalley at 9.57, which was about 2.2 times of the result of strategy 2.

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