Three-Input-Three-Output Air Path Control System of a Heavy-Duty Diesel Engine

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Abstract: In this paper, the control requirement of the air path system of a Heavy Duty (HD) diesel engine which was equipped with a High Pressure (HP) Exhaust Gas Recirculation (EGR), a Variable-Geometry Turbocharger (VGT), and an Electric Turbocharge Assist (ETA) is discussed. A Three-Input-Three-Output (3I3O) multivariable control structure is proposed. The engine dynamic model required for controller design was obtained using system identification and the controller was tuned by solving an $H\infty$ optimization problem. The engine experimental test results show that this 3I3O closed-loop control system has excellent tracking performance, disturbance rejection performance, and gain scheduling capability. The control system has been demonstrated to work with a practical ETA device to make a substantial improvement to engine transient performance.

Keywords: Engine Control, Diesel Engine, MIMO, Closed-Loop Control, Static Decoupling, System Identification, PI Controller.

1. INTRODUCTION

Modern diesel engines make use of turbocharger technology to achieve increased mechanical power output, improved efficiency of combustion, lowered emissions levels and hence a downsized engine and improved fuel economy. Furthermore, the Variable-Geometry Turbocharger (VGT) is able to create enough boost at engine low speed meanwhile to limit engine breathing at high engine speed. More recently, Electrically Assisted Turbocharger (EAT) or Electric Turbocharger Assist (ETA) where an electric motor/generator is added to the turbo shaft has received significant research attention. It is not only able to improve the engine transient response but also has ability to harvest exhaust energy when it is operated at generating mode (Terdich *et al.,* 2013). Simulation work shows that by using ETA, an urban bus can save up to 6.4% fuel consumption together with lower CO_2 emissions for a typical vehicle driving cycle (Millo *et al.,* 2006). Electric Turbocompound (ETC) is an another name for EAT and is often associated with the feedback of recovered energy to the engine or storage device such as shaft motor, supercapacitor, and battery (Hopman *et al.,* 2005; Algrain*,* 2005; Millo *et al.,* 2006; Arise *et al.,* 2014). The other attractive benefit of ETC is that it is no longer necessary to use a wastegate or a VGT (Hopman *et al.,* 2005; Millo *et al.,* 2006). However, not much practical research work or comparison work has been carried out on this topic.

In the study presented in this paper, the ETA device is fitted with a VGT and this enables the comparison of ETA and VGT response and interaction. The motor/generator used in the ETA is a switched reluctance electrical machine and the integration information of this electrical machine with the VGT and its experimental performance testing results can be found in reference (Winward *et al.,* unpublished). By adding ETA into the modern diesel engine air path system which consists of Exhaust Gas Recirculation (EGR) and VGT devices, it creates a significant challenge to the conception of the air path control system. To the authors' knowledge, so far, only one paper was found to address the closed-loop control of ETC which used boost pressure as the measured and controlled variable. In this paper, a three-input-three-output (3I3O) multivariable control system has been developed and tested on a Heavy Duty (HD) diesel engine under laboratory conditions. By implementing this control structure, the system level minimization of fuel consumption and exhaust emissions can be readily further carried out.

The rest of this paper is organized as follows. The control requirement involved in air system with ETA device is discussed in Section 2. Section 3 presents the methodology used in this study to design the Multi-Input-Multi-Output (MIMO) controller. Experimental engine test results of this MIMO control system are shown in Section 4 and then followed by the conclusion in Section 5.

2. CONTROL PROBLEM

2.1 System Description

The test engine used in this study is a HD diesel engine. It is equipped with a High Pressure (HP) EGR device and a VGT device. The VGT turbo system was modified to be integrated with a Switched Reluctance (SR) electric machine for ETA. The system level schematic is shown in Fig. 1. There are three control inputs in the air system which are highlighted in yellow in Fig. 1 : VGT vane position, EGR valve opening, and ETA torque demand. There are five measured engine variables closely related to the engine air system which are: intake Mass Air Flow (MAF), Manifold Air Pressure (MAP), EGR MAF, Exhaust Pressure (EXP), and Turbo Shaft Speed (TSS). These five engine variables are highlighted in blue in Fig. 1. The exhaust temperature is not considered as a potential controlled variable here mainly because it has slower dynamics compared to the above five variables.

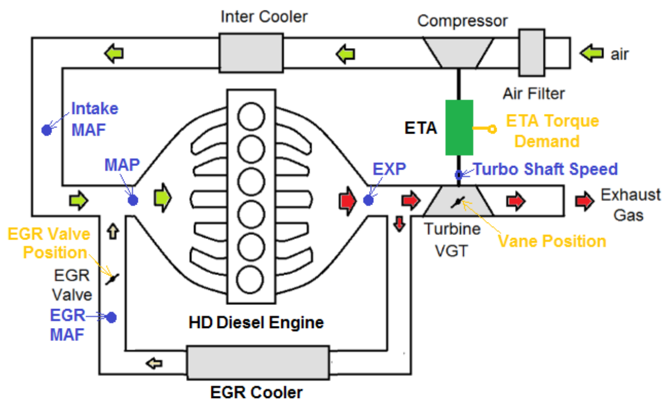

Fig. 1. Schematic of the test diesel engine equipped with HP EGR, VGT and ETA. Blue points and blue names: measured engine variables; Yellow words: manipulated control inputs.

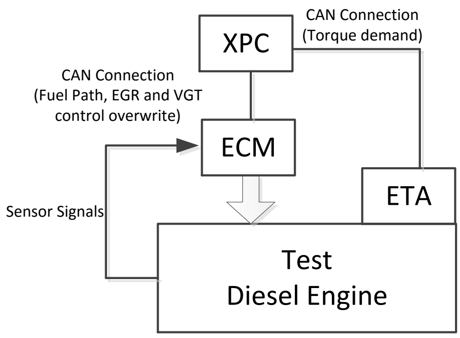

Fig. 2. Schematic of the environment for the implementation of engine control system.

The implementation environment for the 3I3O air path control system is shown in Fig. 2. The 3I3O controller is implemented using XPC hardware with a Simulink model.

2.2 The Impact of ETA on Fuel Consumption

Based on the engine test data, several figures were plotted to review the impact of ETA on engine fuel consumption which will help with the selection of controlled variables and high level system optimization. Fig. 3 (a) shows the behaviour of ΔP defined as EXP-MAP at the engine steady state operating point: 1800rpm, 400Nm with the EGR valve closed. ΔP falls slightly when the ETA changes from generating mode to motoring mode at low VGT vane position (open) and slightly increases at high VGT vane positions (towards close). This could be related to the increase of compressor's efficiency with the more open VGT vane position. Fig. 3(b) shows that fuel rate is strongly correlated to ΔP when the EGR valve is closed. It increases as ΔP increases.

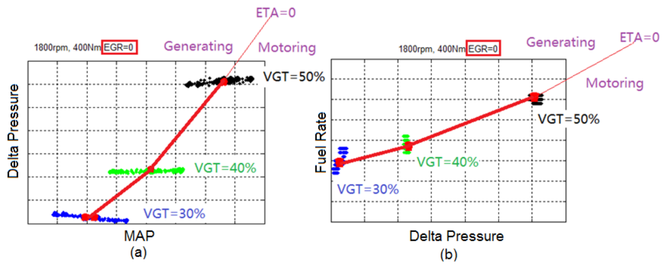

Fig. 3. (a) Delta pressure and MAP change with ETA and VGT inputs at EGR valve closed; (b) The relationship between fuel rate and delta pressure.

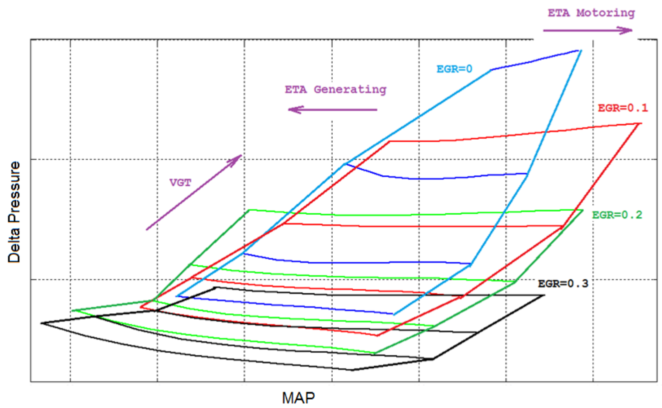

Fig. 4. The relationship between delta pressure and MAP under different combinations of VGT, EGR and ETA control input conditions.

Fig. 4 shows at one fixed operating point, the relationship between delta pressure and MAP changes with EGR valve position. It shows that at lower EGR valve open position, the area formed by delta pressure and MAP under the feasible combinations of VGT and ETA input condition decreases with an increasing EGR valve open position. Fig. 5 shows the relationship between fuel rate and ΔP for one engine steady state operating point under different combinations of VGT, EGR and ETA control input conditions. The area created by different combinations of VGT and ETA input at fixed EGR valve position evolves from long thin triangular shape at EGR valve closed to tall nearly rectangular shape on the left when the EGR valve is wide open. For simplicity, all these achievable areas of fuel rate against ΔP obtained by manipulating the three control inputs can be represented as a triangle with three points are obtained from three inputs conditions: [VGT_{max}, ETA_{motor_max}, EGR_{min}]; [VGT_{min}, $ETA_{generate\_max}$, EGR_{max}]; [VGT_{min}, ETA_{motor_max}, EGR_{max}]. This triangular shape for each of six different engine operating points is plotted in Fig. 6.

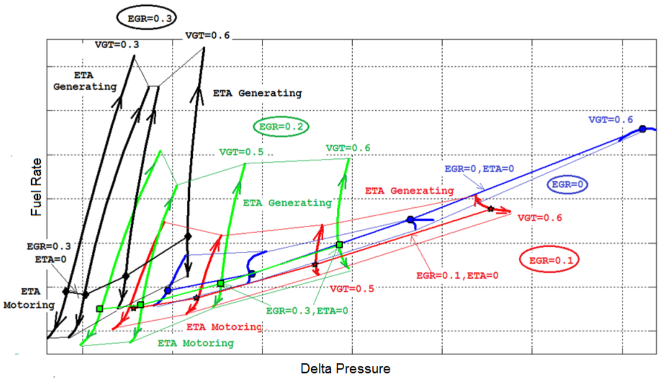

Fig. 5. The relationship between fuel rate and delta pressure under different combinations of VGT, EGR and ETA control input conditions.

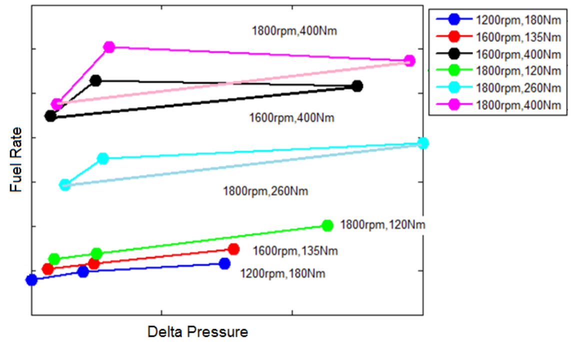

Fig. 6. Triangular shapes in fuel rate against delta pressure plot for six different engine operating points.

It can be seen in Fig. 6 that the triangle of feasible area of fuel rate against delta pressure becomes taller at engine higher speed and load. The triangular shape degenerates to a straight line at engine low load. This phenomenon implies that at engine high load, fuel rate is more sensitive to ETA and EGR input change. Generally it can be said that the fuel rate is correlated to ΔP. By controlling ΔP, the fuel consumption can be properly controlled. If the boost pressure MAP is chosen as one of the controlled variables, EXP could be another one as the control of MAP and EXP together is equivalent to the control of MAP and delta pressure together. By doing this, ETA can be controlled related to the intention of control engine fuel consumptions. On the other side, the benefit from ETA for improving engine acceleration performance can be kept by setting a proper MAP reference during engine acceleration transients.

2.3 Selection of Controlled Variables

A square 3I3O control structure is used in this study because this design follows the physical structure of the gas path and such a squarestructure is well supported by control design techniques . The three controlled variables were selected from above five candidate measured engine variables. There are several methods can be applied in the selection of the controlled variables such as minimum singular value rule, exact local method, optimal linear combination of variables, gradient function, input sensitivity etc. (Alstad, 2005). The available potential controlled variable in this study are relatively few and according to the discussion in the previous subsection, MAP and EXP should be chosen as the two controlled variables for indirectly controlling the engine fuel consumption. There is a strongly correlated relationship between MAP and TSS (Fig. 7), leaving only two options for 3I3O control structure (Fig. 8). In Fig. 7, the right plot shows the nine combinations of ETA and VGT control inputs, the left plot shows the corresponding measured TSS and MAP values to these nine points.

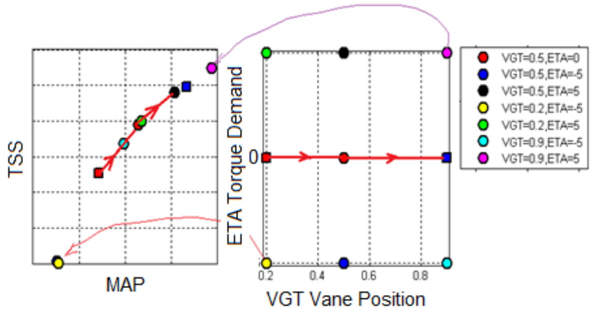

Fig. 7. Correlation between TSS and MAP at fixed engine operating point and fixed EGR valve open position under different VGT vane position and ETA torque demand conditions

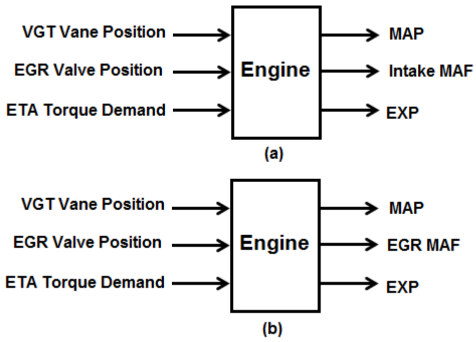

Fig. 8. Two options for 3I3O control structure

These two control structures have the same three inputs and the same two outputs except that intake MAF is chosen as the third controlled variable in the first control structure and EGR MAF is used as the third controlled variable in the second control structure. Both control structures have been developed and tested in this study. Similar control performances have been achieved for both. According to authors' experience, the second one (b) in Fig. 7 has advantage over the first one (a) in easier set-point design. However, for the second control structure (a) in Fig. 8, a reliable and accurate EGR MAF model is needed. The EGR MAF modelling work related to this study is reported in a paper (Yang *et al*. 2016). The control work discussed in this paper only focuses on the second control structure.

2.4 Control Strategy

The majority of control work on diesel engine air path to be found in the literature are about Two-Input-Two-Output (2I2O) multivariable control design. This is because historically there are only two control inputs – respectively the EGR valve open position and VGT vane position. Since there is strong coupling effect between these two inputs, multivariable controller design methods were usually used and were claimed to have better control performance over a decentralized control strategy. The multivariable controller design methods could be Control Lyapunov Functions, Robust Control, Nonlinear Internal Model Control, Predictive Control etc. (Collin, 2011).

Considering the simplicity of implementing the MIMO controller in XPC and without losing the advantages of multivariable control, a decoupled 3I3O Proportional-Integral (PI) multivariable controller has been used in this study (Fig. 9). The decoupler structure is shown in Fig. 10. This decoupler is a constant network without dynamics. It can be represented in a matrix form shown in (1).

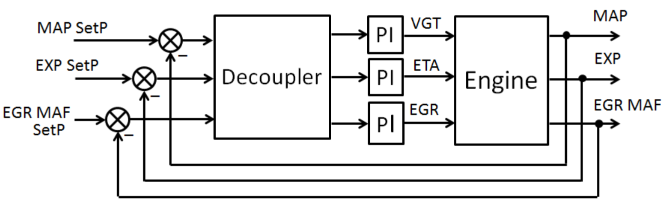

Fig. 9. Decoupled 3I3O PI Control

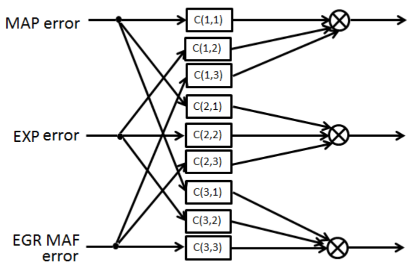

Fig. 10. Decoupler structure

$$C_d = \begin{bmatrix} c(1,1) & c(1,2) & c(1,3) \\ c(2,1) & c(2,2) & c(2,3) \\ c(3,1) & c(3,2) & c(3,3) \end{bmatrix} \quad (1)$$

The three PI controllers have the forms as:

$$C_1(s) = K_{p,1} + \frac{K_{i,1}}{s} \quad (2)$$

$$C_2(s) = K_{p,2} + \frac{K_{i,2}}{s} \quad (3)$$

$$C_3(s) = K_{p,3} + \frac{K_{i,3}}{s} \quad (4)$$

The complete controller would have the form:

$$C = C_d \times \begin{bmatrix} C_1(s) \\ C_2(s) \\ C_3(s) \end{bmatrix} \quad (5)$$

The matrix C_d, the three K_p, and the three K_i values are controller parameters need to be tuned based on the engine dynamic model and control system specifications.

The authors also have studied the usage of a MIMO controller which consists of 3×3 PI controllers (Zhao, 2016). Compared to that work, the controller used here has less parameters and without diverge problem of integration part of the PI controllers.

3. MULTI-INPUT-MULTI-OUTPUT CONTROL DESIGN METHODOLGY

3.1 Control-Oriented Model

There are normally two ways to obtain the control-oriented engine model for controller tuning. One is to develop a nonlinear Mean Value Engine Model (MVEM) and then linearize it at the interested engine operating points of interest. However, the development of MVEM needs profound engine modelling knowledge and relatively long development time. The alternative way is using system identification technology to obtain the linear dynamic model at an engine steady state operating point. The tuned controller using this model can work within a certain area around this engine operating point. Consider the nonlinear dynamics related to engine operating point, a gain-scheduling control strategy is needed to cover a wider engine operating range. By using this method, the controller can be developed much more quickly than using the first method. However, the efficient segmentation of the engine operating range is a very interesting research topic. However, it is out of the scope of this paper. Because of the constraint of time, this paper only focuses on the demonstration of the controller working with step (block) load changes at a fixed engine speed. Six steady engine operating points were equally selected from 100Nm to 800Nm at 1800rpm to obtain linear 3I3O engine dynamic models for tuning the corresponding six controllers.

There are also nonlinear dynamics from the three inputs to the three outputs at engine steady state conditions. For example, the response gains for MAP and EXP to VGT vane position decrease when the EGR valve opens wider. The response gains for MAP and EXP to ETA positive torque demand input are higher than those to ETA negative torque demand input. However, by using linear system identification method, these nonlinear dynamics are ignored and a mean dynamic model is obtained among the perturbation test data. The perturbation signal could be random signals for three inputs within their constraints or single different value step changes for each input at different combinations of the other two inputs' values. The step input perturbation testing was used in this study and the experimental engine control results show that the dynamic models identified from this step perturbation testing data are good enough for controller design. The dynamic model could be State Space (SS) model or a 3×3 Transfer Function (TF) matrix.

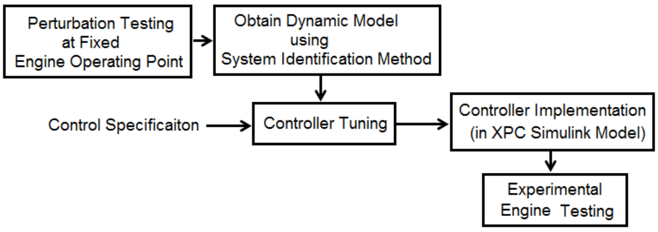

Fig. 11. The work flow chart of the control study

The work flow chart of the 3I3O air path control study is shown in Fig. 11. Within this control framework, if the engine control test results are not good enough due to, for example, oscillation or slow response, the re-design of the controller could proceed by (1) adjusting the control specification; (2) identifying higher order dynamic model or (3) repeating the perturbation testing using different perturbation signals. The experience of design is that by selecting a first order TF matrix dynamic model and the crossover frequency between 0.3Hz to 3Hz, the controllers tuned worked well after one tuning session, indicating an acceptable level of control robustness.

3.2 Robust Control Design

The *looptune* MATLAB function (Robust Control Toolbox 4.1) was applied in the tuning of the controller described in section 2.4 in this paper. It formulates and solves a H_∞ optimization problem (Gahinet *et al*., 2011). As being a simple start, only one control specification was defined which is the crossover frequency band. The engine test results show that using this single design parameter can give good feedback control performance.

3.3 Gain-Scheduling

In order to do transient tests across a wide range of block loads, gain scheduling for both the controller and set points need to be implemented. The schematic of gain scheduling control system is shown in Fig. 12.

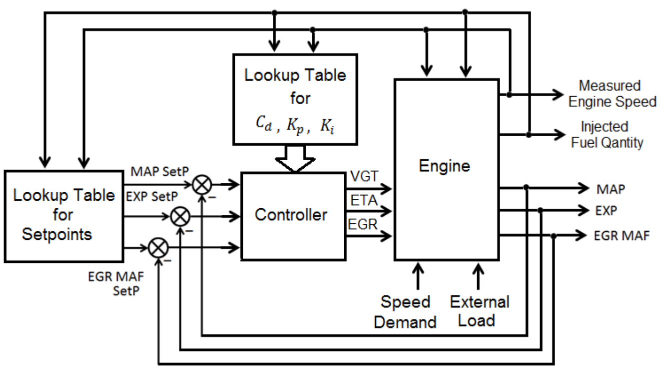

Fig. 12. Gainscheduling for engine transient testing

At 1800rpm with a load change from 100Nm to 800Nm, six engine operating points were selected to get six controllers. The gain scheduling method used a lookup table based on these six controllers and linear interpolation was carried out when the engine was running at the operating points other than the six chosen operating points. The engine operating points were determined using two inputs which are engine speed and injected fuel quantity for each cycle. The same method was utilized to determine the setpoints for the three controlled variables. The set point policy was only designed for engine steady state operating point. It can be expanded to include the requirements for engine transient process to further improve engine transient performance. The gain scheduling of controller can also be done during the controller tuning stage which will improve the smoothness of control performance during engine operation under transient conditions.

4. ENGINE EXPERIMENTAL TEST RESULTS

4.1 Setpoint Tracking Performance

First, the setpont tracking performance was tested on the test engine. It was tested at several engine operating points. They have similar tracking performance. Fig. 13 shows the tracking performance when the engine was running at 1800rpm and 260Nm. It can be seen that the tracking performances for three controlled variables are satisfactory.

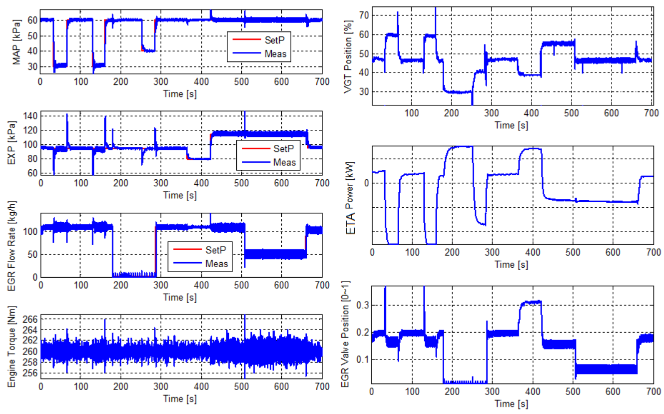

Fig. 13. Engine experimental control testing results: tracking performance of the 3I3O air path control.

At the beginning, only the MAP setpoint was subjected to a step change between 30 kPa and 60 kPa. The other two setpoints were kept unchanged. The three inputs were automatically changed by the controller to make the measured MAP follow the MAP setpoint change. When MAP setpoint drops from 60 kPa to 30 kPa, VGT vane position was increased, EAT was pushed from motoring mode into generating mode, meanwhile the EGR valve was closed a little. The changes of these three inputs worked together to achieve low boost pressure. When the EGR flow rate setpoint was subject to a step change from around 100 kg/h to 0 kg/h at about 180 s, the EGR valve was forced to be closed which was a correct action from the controller. When the EXP setpoint was subject to a step change at about 360 s, the controller decreased the VGT vane position and open the EGR valve wider to achieve lower EXP, meanwhile increased ETA motoring work in order to maintain the same MAP value. The 3I3O controller was demonstrably satisfying the control requirement amongst the three controls.

4.2 Disturbance Rejection Performance

Two types of the disturbance rejection performance of the control system were tested on the test engine. One is the rejection performance of the 3I3O control system to engine torque disturbance input (Fig. 14). The other is the performance to speed disturbance input (Fig. 15). Fig. 14 shows that under the torque disturbance signal changing from 120 Nm to 400 Nm, all three controlled variables were controlled around their constant setpoint values. When the engine torque was increased, VGT vane position was reduced by the controller and ETA was set to a higher generating state to compensate the increasing trend of MAP and EXP because of increased engine load. Fig. 15 shows that when engine speed was increased from 1700 rpm to 1900 rpm over about 50s, similar to the control response to the increase of engine load, the controller also reduced VGT vane position and took the ETA to a higher generating level to compensate the increase trend of MAP and EXP because of increased engine speed.

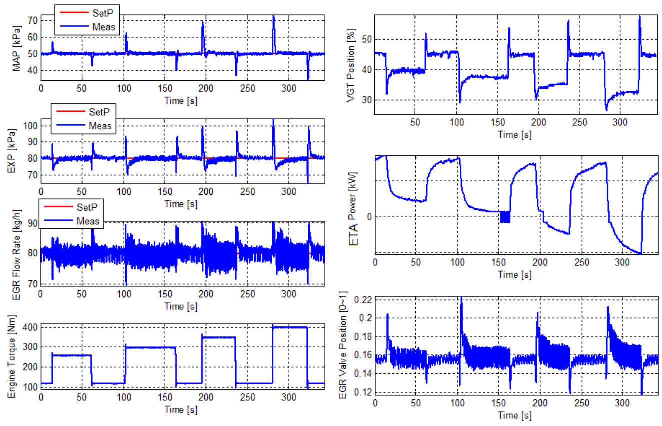

Fig. 14. Engine experimental control testing results: disturbance rejection performance of the 3I3O air path control: engine torque is disturbance input.

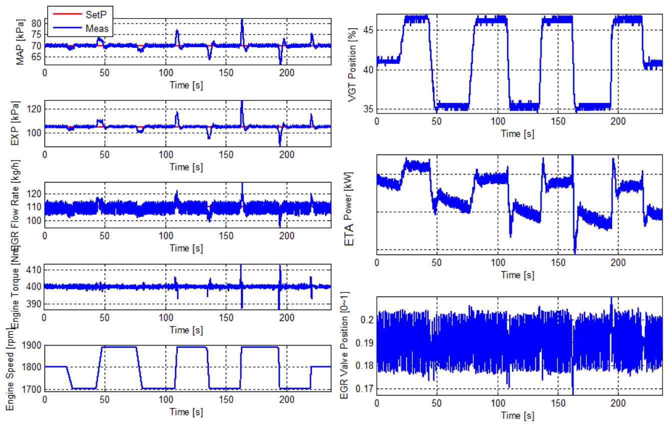

Fig. 15. Engine experimental control testing results: disturbance rejection performance of the 3I3O air path control: engine speed is the disturbance input.

4.3 Gain scheduling Performance

The gain scheduling performance was tested during engine block load tests. Engine speed is held constant at 1800 rpm, with a ramp of engine load from 120 Nm to 800 Nm and then ramp back at a different rate. In the engine torque plot in Fig. 16, from left to right, the torque ramp rates are 10 s, 5 s, 2 s, and 1 s respectively. It can be seen that the gain scheduling controller is able to control the three controlled variables to their corresponding setpoint values. During the fastest torque ramp up change, the ETA was controlled to work in motoring mode and its response is faster than the response of VGT vane position. This implies that the 3I3O controller can automatically take advantage of the fast response feature of ETA to meet the fast MAP setpoint change. Based on this low level 3I3O control system, the high level optimization of engine performance and minimization of engine fuel consumption can be implemented by online adjustment of the setpoints based on an optimization algorithm

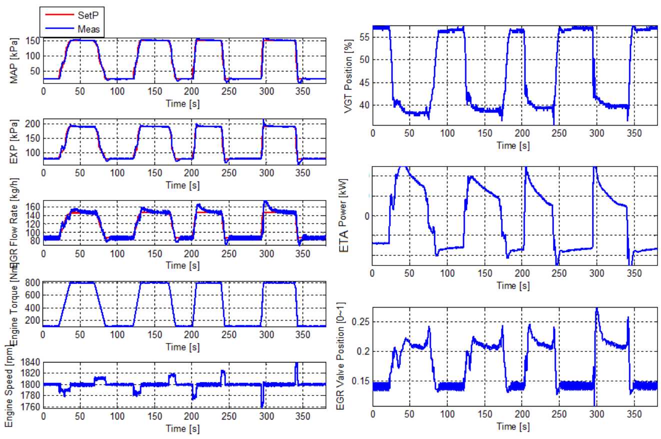

Fig. 16. Engine experimental control testing results: gainscheduling performance of the 3I3O air path control: engine speed is controlled by the speed governor at 1800rpm, engine load ramp from 120Nm to 800Nm.

5. CONCLUSION

This paper presents a practical MIMO control solution for 3I3O control problem in the air path system of a HD diesel engine. Based on the analysis of experimental test results of a HD diesel engine equipped with three air system devices which are a VGT, an EGR, and an ETA, three controlled variables were selected. These three selected controlled variables are MAP, EXP, and EGR flow rate. The three manipulated control inputs are VGT vane position, EGR valve open position, and ETA torque demand. System identification was applied to obtain the 3I3O engine dynamic model for controller tuning. The perturbation signals used are simple step change signals. The controller was tuned by solving a H_∞ optimization problem. Engine test results show this control system not only has good tracking, disturbance rejection, and gainscheduling performance, it also has ability to optimally use the three devices together to improve engine performance and fuel economy.

Future work can be carried out on the study of efficient segmenting of engine operating range; gainscheduling design in controller tuning stage; system level online optimization for providing the setpoint values.

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