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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∞ 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.

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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.

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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.

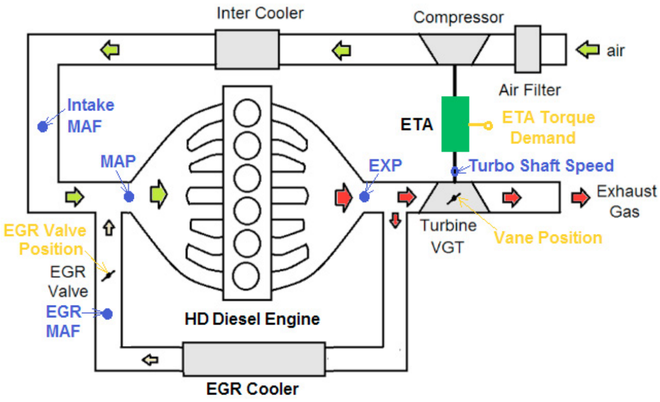

Fig. 1. Schematic of the test diesel engine equipped with HP EGR, VGT and ETA. Blue points and blue names: measured engine variables; Yellow words: manipulated control inputs.

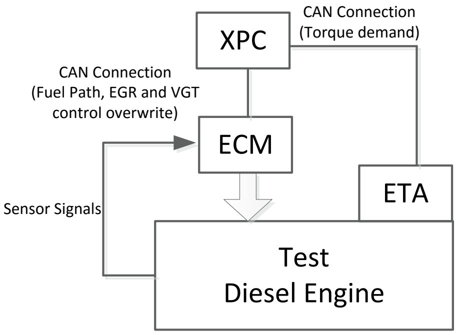

Fig. 2. Schematic of the environment for the implementation of engine control system.

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.

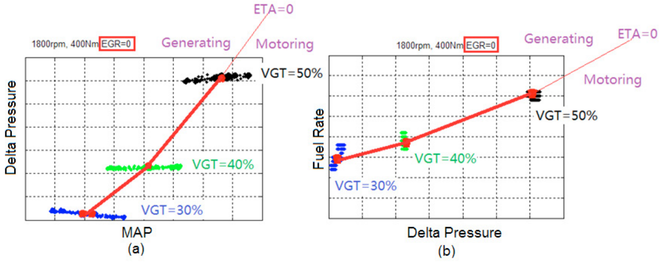

Fig. 3. (a) Delta pressure and MAP change with ETA and VGT inputs at EGR valve closed; (b) The relationship between fuel rate and delta pressure.

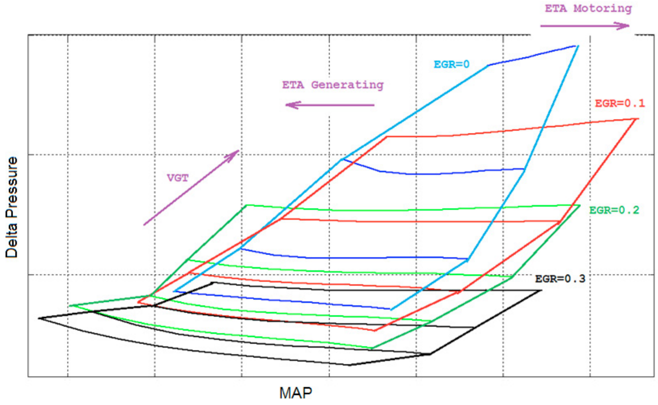

Fig. 4. The relationship between delta pressure and MAP under different combinations of VGT, EGR and ETA control input conditions.

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