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# Gain Scheduled Controller of EGR and VGT Systems with a Model-Based Gain Scheduling Strategy for Diesel Engines

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**Abstract:** This study proposed a gain scheduled controller for exhaust gas recirculation (EGR) and variable geometry turbocharger (VGT) systems with a model-based gain scheduling strategy to manage strong nonlinearity in diesel engines. The feedback controller uses a gain scheduling strategy to obtain appropriate controller gains of the PI controller under various engine operating conditions. The gain scheduling strategy is designed using the proposed static gain model that predicts varying static gains of EGR and VGT plants. The static gain model uses scheduling variables derived from indirect measurements of the EGR mass flow such as the pressure ratio of the intake and exhaust manifolds and the exhaust air-to-fuel ratio. The scheduling variables are effective to reduce a large static gain dispersion caused by various operating conditions of the EGR and VGT actuators. With the predicted static gains of the plant, a Skogestad internal model control (SIMC) method determines PI gains in run-time. The proposed control algorithm is evaluated through engine experiments. The experimental results proved that the integrated absolute error (IAE) and overshoot of the gain scheduled feedback controller are significantly reduced compared to the fixed gain controller.



*Keywords:* Diesel engine, exhaust gas recirculation, variable geometry turbocharger, Skogestad internal model control, Gain scheduling strategy.

## 1. INTRODUCTION

Modern diesel engines are equipped with advanced technologies such as exhaust gas recirculation (EGR) and variable geometry turbo charger (VGT) systems to satisfy stringent emission and energy regulations. The EGR and VGT systems enable the reduction of harmful emissions and fuel consumption by accurately controlling intake air states such as intake pressure and EGR rate. For the successful implementation of the presented technologies, a precise control algorithm design for EGR and VGT systems in diesel engines is a prerequisite.

EGR and VGT systems result in a complicated control task due to nonlinear and coupled behavior. Nonlinearity is derived from turbocharger dynamics, gas flow dynamics, and pulsating gas flow by a reciprocating engine cycle. The turbocharger plays a dominant role due to its nonlinear rotor and fluid dynamics. In addition to nonlinearity, the EGR and VGT systems show strongly cross-coupled behavior because there are two independent physical paths between the intake and exhaust manifolds for each system. The nonlinear and cross-coupled characteristics of the EGR and VGT systems lead to a nonlinear multivariable control problem.

The control problems of EGR and VGT systems in diesel engines were addressed by many researches that applied various control theories (Guzzella and Amstutz, 1998, Rajamani, 2005, Eriksson et al., 2010, Shutty et al., 2011). For the nonlinear multi-input multi-output (MIMO) system, control performances were significantly improved by applying centralized control approaches such as a sliding mode controller (Upadhyay et al., 2002, Utkin et al., 2000), H∞ controller based on linear parameter varying (LPV) model (Xiukun and del Re, 2007), model predictive controller (MPC) (Ortner and del Re, 2007, Saerens et al., 2008), and many others (Mohammadpour et al., 2010, Van Nieuwstadt et al., 2000). Despite of the excellence of the centralized control approaches, calibration of these controllers are non-intuitive and have limited capacity for on-line calibration (Pérez and Sala, 2004, Luján et al., 2007, Jung, 2003). Furthermore, the computational load is considerably high to be embedded in production type ECUs.

Due to the unavoidable issues, most production ECUs control EGR and VGT systems based on a decentralized control approach using a PID controller (Ortner and del Re, 2007). Zentner et al. introduced a cascaded control structure for EGR and VGT plants. The cascaded control structure effectively compensates cross-coupled characteristics using a fast inner loop controller (Zentner et al., 2014). Park et al. and Wang et al. used quantitative feedback theory to obtain robust control gains (Wang et al., 2011, Park et al., 2014). The approaches applied a gain scheduling strategy based on engine operating points (engine speed and fuel injection quantity) to resolve the strong nonlinearity of the EGR and VGT systems. The controller gains were designed through a


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repetitive loop shaping process in each engine operating condition.

Unfortunately, the repetitive loop shaping process requires considerable design efforts. The designed gains based on engine operating points are also vulnerable to operating condition changes in the EGR and VGT actuators due to strong nonlinearity and coupled plant characteristics.

In this study, we proposed a gain scheduled PI control algorithm with a model based gain scheduling strategy in order to manage the strong nonlinearities of the diesel air path. Static gains for the EGR and VGT systems are modelled using a proposed gain scheduling variable derived from the pressure ratio of intake and exhaust manifolds and exhaust air-to-fuel ratio. The proposed static gain models determine appropriate PI gains under various engine operating conditions by applying Skogestad internal model control (SIMC) method (Skogestad, 2004). The proposed gain scheduling strategy provides a systematic design procedure for the EGR and VGT systems while avoiding the repetitive design efforts and reducing elaborate calibration works. Cross-coupled characteristics of the EGR and VGT systems are compensated by designing a simplified decoupler (Hong et al., 2014). The proposed control algorithm for EGR and VGT systems was validated through engine experiments. Step test results showed that the proposed gain scheduling strategy reduced tracking error and overshoot compared to the engine operating point based gain scheduling strategy. The control performance is numerically evaluated by analyzing integrated absolute error (IAE).

This paper is structured as follows. Section II analyses characteristics of the EGR and VGT systems and the static gain models are designed in Section III. Section IV illustrates the gain scheduled PI control algorithm through the SIMC method. The design results of the proposed control algorithm are validated by various test cases of engine experiments in Section IV. Finally, we summarize and conclude this study in Section V.

## 2. ANALYSIS OF THE EGR AND VGT SYSTEMS

### *2.1 Configuration of the target air system*

The target engine is equipped with the EGR and VGT systems. Fig. 1 shows that the exhaust manifold and intake manifold are interconnected by poppet-type EGR valve driven by a DC motor. The lift position of the EGR valve controls the mass flow rate of EGR gas. The VGT system is composed of turbine, compressor, and a smart type vane actuator which includes the vane position controller. The VGT vane position determines the amount of generated turbine power. The generated power boosts the pressure of the intake manifold; in addition, an electronic throttle valve is installed between intercooler and intake manifold to assist the control of the EGR gas flow rate.

**Nomenclature**

| | |
|---|---|
| $a_{1\text{-}3}$ $b_{1\text{-}7}$ | Coefficients of the static gain models for the EGR and VGT systems |
| $AFR_{exh}$ | exhaust air-to-fuel ratio |
| $K_{11}$, $K_{22}$ | static gains for the EGR and VGT systems |
| $K_c$ | control gain of the SIMC based controller |
| $K_P$, $K_I$ | Proportional and integral gains of the PI controller |
| $N_e$ | engine speed (rpm) |
| $P_{int}$ | intake pressure (kPa) |
| $u_{EGR}$ | EGR valve position (%, open) |
| $u_{VGT}$ | VGT vane position (%, close) |
| $T_d$ | time delay (s) |
| $W_f$ | fuel injection quantity (mg/str) |
| $x_{im}$ | burned gas rate in intake manifold (%) |
| $T$ | time constant (s) |
| $\tau_c$ | tuning parameter of the SIMC based controller |
| $\tau_I$ | integral time of the SIMC based controller |
| $\theta_{11}$, $\theta_{22}$ | scheduling variables for the EGR and VGT systems |
| $\lambda_{exh}$ | stoichiometric air-to-fuel ratio of the exhaust gas |

### *2.2 Nonlinearity of the EGR and VGT systems*

Fig. 2 indicates the nonlinear characteristics between burned gas rate in intake manifold ($x_{im}$) and an EGR valve position (top three figures) as well as between the pressure of intake manifold and VGT vane position (bottom three figures). The tendency of the burned gas rate increases monotonically in regards to an EGR valve opening for all test cases. However, the tendency of the intake manifold pressure in regards to a VGT vane closing was inconsistent depending on engine operating conditions. With a certain level of an EGR valve opening, the intake manifold pressure does not continue to monotonically increase, but starts to decrease with a VGT valve closing known as a sign inversion phenomenon (Wahlström et al., 2010). The sign inversion means that the exhaust gases flown into the EGR passage increase and that the EGR mass flow grows as the VGT vane closes.

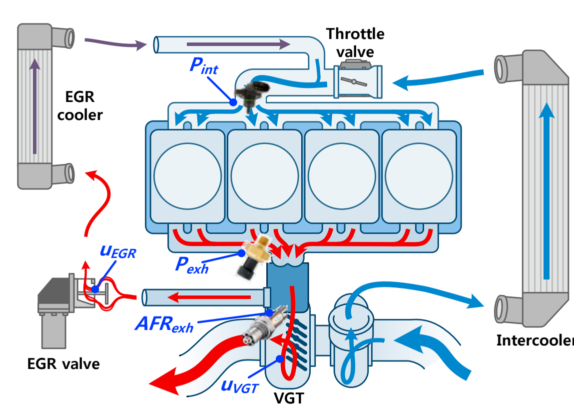


Fig. 1 Air system schematic and definition of physical states