

Multi-Variable Air-Path Management for a Clean Diesel Engine Using Model Predictive Control

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ABSTRACT

Recently, emission regulations have been strict in many countries, and it is very difficult technical issue to reduce emissions of diesel cars.

In order to reduce the emissions, various combustion technologies such as Massive EGR, PCCI, Rich combustion, etc. have been researched. The combustion technologies require precise control of the states of in-cylinder gas (air mass flow, EGR rate etc.). However, a conventional controller such as PID controller could not provide sufficient control accuracy of the states of in-cylinder gas because the air-pass system controlled by an EGR valve, a throttle valve, a variable nozzle turbo, etc. is a multi-input, multi-output (MIMO) coupled system. Model predictive control (MPC) is well known as the advanced MIMO control method for industrial process. Generally, the sampling period of industrial process is rather long so there is enough time to carry out the optimization calculation for MPC. However, due to the progress of the computer in the last decade and improvement of the optimization algorithm, the MPC can be applied to 'fast' process such as mechanical systems.

The air-pass management system for the diesel engine is assumed a two-input, two-output system in this research. The inputs of the system are the throttle valve and the EGR valve, and the outputs air mass flow and EGR rate. Consequently, MPC was applied to air-pass management system and was modified by adding the disturbance observer to eliminate steady-state error and

the compensator for nonlinear characteristics of actuators.

The performance of the proposed control system was examined by using an actual testing vehicle. From the experiments, it was shown that an accurate decoupled control of two outputs, i.e. air mass flow and EGR rate, was accomplished by the proposed MPC control.

INTRODUCTION

Diesel engines display higher thermal efficiency and emit less CO₂ than gasoline engines, and have therefore attracted attention as a form of internal combustion engine that is effective in combating global warming. However, diesel engines are basically lean combustion engines, and the simple after-treatment systems involving three-way catalysts with close to 100% reduction efficiency that are employed in gasoline engines cannot be employed in them. This makes it necessary to reduce the amount of NO_x, HC, soot and other emissions that are found in the exhaust gas in the combustion process in the cylinders.

The reduction of NO_x in diesel engines is particularly important, and exhaust gas recirculation (EGR) systems are well known as an effective means of doing so. The higher the maximum temperature of combustion gas is the more NO_x increases. Consequently, EGR reduces NO_x by mixing the inert gases present in the exhaust with the intake air, reducing the oxygen concentration, and thus reducing the maximum temperature of combustion. However, as EGR is steadily increased,

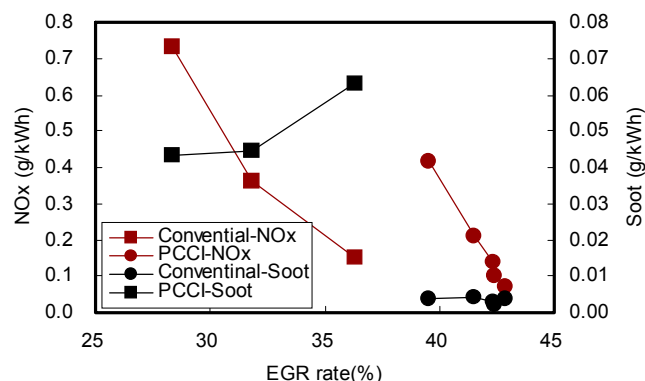


Figure 1 Emission characteristics of conventional and PCCI combustion

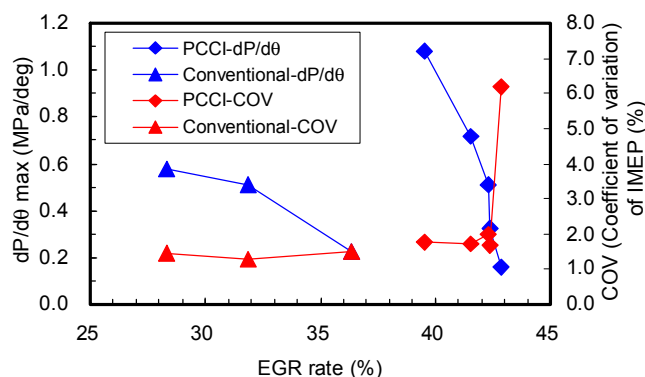


Figure 2 Noise and vibration characteristics of conventional and PCCI combustion

there is a rapid increase in the volume of soot produced above a certain excess air factor. In order to effectively reduce NOx while controlling soot production, therefore, it is necessary to accurately control the state of combustion (parameters such as the excess air factor, etc.) to within a desired range by controlling EGR and fuel injection.

PCCI combustion has been researched as a technology to reduce both NOx and soot emissions. PCCI combustion is premixed one achieved by increasing EGR amount and extending the ignition delay period. However, as indicated by the results of tests on steady-state PCCI combustion (Figures 1, 2), the state of the intake EGR produces significant variations in the characteristics of emissions. Therefore, the tracking response characteristics of fuel injection control and EGR control should be improved to achieve PCCI combustion during transient operating conditions.

There are, however, limits of further reductions in engine-out emissions. So, NOx exhaust after-treatment system, for example a NOx catalyst, is recently researching to enable further emissions reductions. The NOx catalyst system requires a regenerative combustion control known as rich control, which reduces the NOx that is adsorbed during lean combustion [1]. The rich control requires high-accuracy fuel injection control tracking air-fuel ratios on target values in order to keep

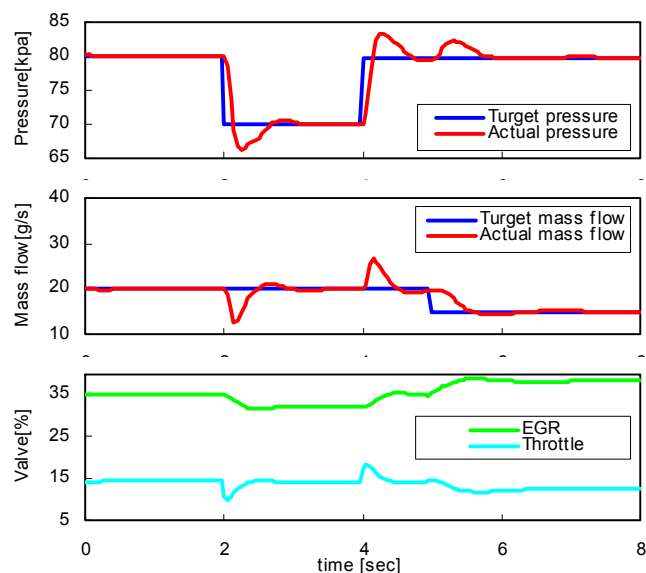


Figure 3 PI control simulation results

combustion noise performance and drivability. Furthermore, high-accuracy intake EGR control is also important to realize this combustion control.

The various requirements discussed above indicate that the necessity for more precise control of the state of intake EGR is increasing.

1. DEVELOPMENT AIMS

The EGR valves, throttle valves, etc., are the intake actuators to directly operate the controlled object in intake control. The controlled outputs of the controlled object are oxygen and inert gases in the cylinder. The amounts or ratios meanings these two parameters also used as the controlled output.

However, in general, if one of the intake actuators is changed, both controlled outputs also change. The system indicates this behavior is known as a coupled system, and in such cases to design feedback control systems using conventional methods, such as PID controllers, is known to represent a challenge. Figure 3 shows oscillations caused by interference when a basic PID controller is employed in an engine simulator demonstrating behaviors of the controlled object discussed above.

Model predictive control (MPC), which enables multiple outputs to be controlled to target values, is known as a control algorithm that can be applied to multi-input, multi-output systems. Because MPC requires optimization calculations to be performed in real-time for each sampling period, it is mainly employed in applications in which the sampling period is long, such as in petrochemical plants.

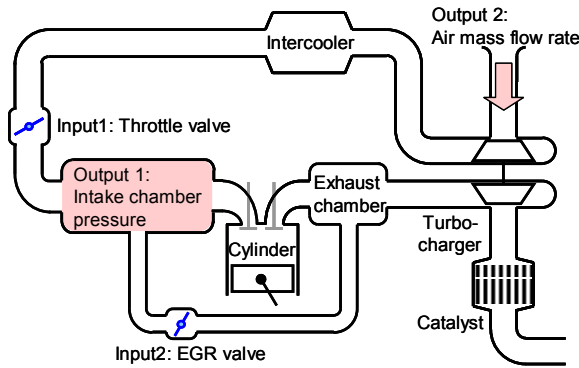


Figure 4 Air-path system of diesel engine and definition of the controlled object

However, increases in calculation speed with higher-speed processing of ECU and improvements in calculation algorithms [2] have increased the potential for the application of MPC to comparatively fast systems [3]. The project discussed here applied MPC in the construction of an air mass flow/EGR feedback control system for a diesel engine. This paper will mention the basic configuration of the system and discuss the results of tests conducted to verify its effectiveness.

2. MODELING

Figure 4 shows the configuration of the intake and exhaust system of a diesel engine. The project discussed here assumed a two-input, two-output controlled object, with input and output parameters defined as follows:

- Inputs: EGR valve and throttle valve
- Outputs: Intake chamber pressure and mass flow rate of new air intake (air mass flow)

When employing MPC or any other model-based control theory such as optimal control or adaptive control, the dynamic characteristics of the controlled object must be modeled by using the simultaneous equations of differential or difference equations. In other word, the dynamic characteristics are expressed using state-space equations.

A model based on physical equations was therefore first constructed to enable the configuration of the controlled object to be understood, and the order of the state-space equations was estimated. Next, system identification was employed to determine the physical parameters in the state-space equations in order to obtain the state-space equations employed in the control theory incorporated in a real engine.

2.1. PHYSICAL MODELING - As Figure 4 shows, the intake and exhaust system of a diesel engine is made up of valve and chamber elements. Here, an example of modeling based on physical principles will be provided,

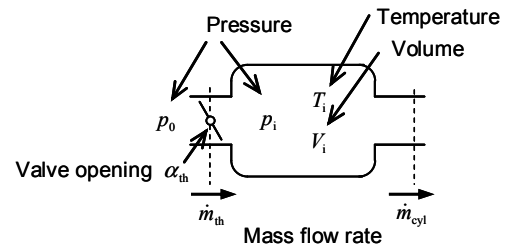


Figure 5 Element model of valve and chamber system

focusing on the valve and chamber in its wake shown in Figure 5.

The mass flow rate past the throttle valve is expressed using a convergent nozzle equation [4], [9].

$$\dot{m}_{th} = A_{th}(\alpha_{th}) \cdot \sqrt{2p_0\rho_0} \cdot \Phi$$

$$\Phi = \begin{cases} \sqrt{\frac{\kappa}{\kappa-1} \left\{ \left(\frac{p_i}{p_0} \right)^{\frac{2}{\kappa}} - \left(\frac{p_i}{p_0} \right)^{\frac{\kappa+1}{\kappa}} \right\}}, & \left(\frac{p_i}{p_0} \right) > \left(\frac{2}{\kappa+1} \right)^{\frac{\kappa}{\kappa-1}} \\ \left(\frac{2}{\kappa+1} \right)^{\frac{\kappa}{\kappa-1}} \sqrt{\frac{\kappa}{\kappa+1}}, & \left(\frac{p_i}{p_0} \right) \leq \left(\frac{2}{\kappa+1} \right)^{\frac{\kappa}{\kappa-1}} \end{cases} \quad (1)$$

where:

$\dot{m}_{th}$: Mass flow in throttle valve section, A_{th} : Effective opening area, α_{th} : Valve opening, p_0 : Upstream pressure, ρ_0 : Upstream density, κ : Specific heat ratio, p_i : Downstream pressure

From the equation of state for an ideal gas in the cylinder and the principle of conservation of mass [10]

$$p_i V_i = M_i R_i T_i \quad (2)$$

$$\frac{dM_i}{dt} = \dot{m}_{th} - \dot{m}_{cyl} \quad (3)$$

where:

$\dot{m}_{cyl}$: Mass flow in cylinder inflow part

Pressure variation in the intake chamber can be expressed by the following equation:

$$\frac{dp_i}{dt} = n \frac{RT_i}{V_i} (\dot{m}_{th} - \dot{m}_{cyl}) \quad (4)$$

where:

n : Polytropic index