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OMBUSTION PROPERTY ANALYSIS AND CONTROL SYSTEM FOR THE DYNAMICS OF A SINGLE CYLINDER DIESEL ENGINE

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Abstract

Corresponding to global environment problems in recent year, the technology for reducing fuel consumption and exhaust gas emission of engine was needed. Simulation of transient engine response is needed to predict engine performance that frequently experience rapid changes of speed. The aim of this research is to develop a non-linear dynamic control model for direct injection single cylinder diesel engine which can simulate engine performance under transient conditions. In this paper, the combustion model with multistage injection and conducted experiments in the transient conditions to clarify the combustion characteristics was proposed. In order to perform the analysis of acceleration operation characteristics, it was built a Model Predictive Control (MPC) to reproduce the characteristic values of the exhaust gas and fuel consumption from the control parameters in particular. Finally, MPC is an effective method to perform the analysis of characteristic in diesel engine under transient conditions.

Key words: model predictive control (MPC), transient, diesel engine, disturbance, modeling.

I. INTRODUCTION

The big problem in the diesel engine is the exhaust gas emission such as Soot, NOx, CO and HC. These emissions are harmful not only for human being but also for environment. Many approaches have been proposed to reduce these emissions [1]. In recent years, diesel engine has been equipped with some control devices such as multiple injection equipment with common rail system and turbocharger [2]. The diesel engine with direct injection (DI) has established an effective method for improving the engine performance.

Simulation of transient diesel engine response is needed to forecast diesel engine performance including exhaust gas emissions and fuel consumptions that frequently experience rapid changes of speed. Most of the research done in this field has concentrated on steady-state control models for the purpose of modifying engine control parameters in order to minimize exhaust gas emissions and fuel consumptions. However, recent regulations have enforced stringent emissions and fuel consumptions standards that cannot longer be addressed by a steady-state analysis of the diesel engine. To contribute towards solving this problem, the current research is focused with the aim of developing a non-linear dynamic control model for direct injection of single cylinder diesel engine which can simulate the engine performance under transient operating conditions. There are two major categories in diesel dynamics model i.e. steady-state non-linear dynamics, and non-linear transient models. The steady-state nonlinear dynamics model can be found in [3, 4, 5, 6], which simulate engines to estimate engine torque and cylinder pressure.

In this paper, the research focused on the construction of engine control model with multistage injection in single cylinder diesel engine. Exhaust gas prediction is more difficult

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for diesel engine in ignition timing and diffuse combustion than in a gasoline engine. Then, for carrying out the construction of the engine control model with multistage injection, it conducted experiments in the transient operating conditions to clarify the combustion characteristics.

In order to perform the analysis of the acceleration operation characteristics, it was built a Model Predictive Control (MPC) to reproduce the characteristic values of the exhaust gas and fuel consumption from the control parameters in particular. In order to more clearly, it proposed the comparison of disturbance insertion control with model predictive control and without model predictive control. Finally, it will be evaluated the fuel consumption and exhaust characteristic improvement of the model control.

II. Basic Concepts of Model Predictive Control

Predictive Model Control (MPC) is also called receding Horizon Control is an effective tool to handle limited multivariable control problem and has been widely used in industry [7, 8]. In the 1960s, the ideas of the model predictive control can be tracked back [9].

Since the 1980s interest in this area began to increase after the publication of papers on IDCOM [10] and Dynamic Matrix Control (DMC) [11, 12], and Generalized Predictive Control (GPC) in the 1980s [13, 14]. Although the ideas underlying the DMC and GPC are similar, DMC was contained in multivariable constrained control, while GPC is especially suitable for single variable and adaptive control.

Basic structure of Model Predictive Control is illustrated in Figure 1. The name MPC come from the idea of employing an explicit plant model to be controlled which is used to predict the future output behavior. This prediction capability allows solving optimal control problems on line, where tracking error, namely the difference between the predicted output and reference trajectory, is minimized over a future horizon input, possibly subject to constraints on the manipulated inputs and outputs. The underlying principle in every type model predictive control, among others:

1. Using a process model to predict the future output within a predetermined time range (horizon).
2. Calculate the control signals to minimize the objective function (criterion function) defined previously with the aim to keep the future output that is as close as possible to the reference trajectory.
3. Control signals *u(k|k)* sent to the process, while the next predictable control signals discarded, because at the next sampling, the output *y(k+1)*is already known values. So the first step is repeated with the new value of new process output and all procedures necessary calculations repaired. The new control signal *u(k+1|k+1)*value is different from *u(k+1|k)*, obtained by using the concept of receding horizon. The concept of receding horizon can be seen in Figure2.

III. Experiment of Transient Diesel Engine

A. The Transient of a Diesel Engine

Since the diesel engine used in the transient state, in which the rotational speed and the load changes large, it is important to understand the characteristics of the transient operation very well. Then, it will be tried to analyze each characteristic of the diesel engine in the transient operation.

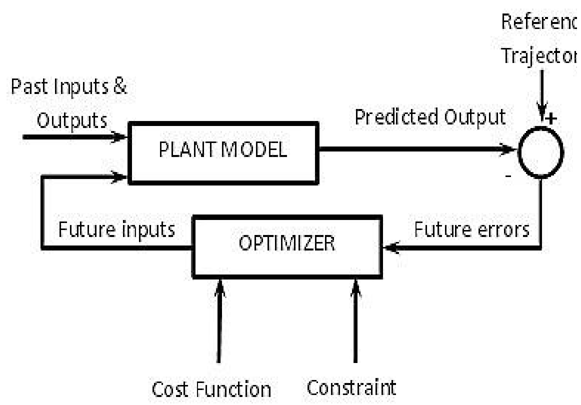


Figure 1. Basic structure of model predictive control

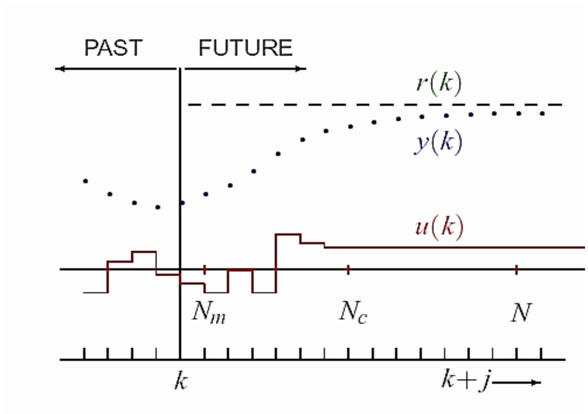


Figure 2. Receding horizon strategy

B. Transient Experiment of Diesel Engine

In this research, it will be done the experiment in transient operation based on the rotation of engine (RPM). The rotation of engine will be accelerated from 1,000 rpm to 2,000 rpm and slowdown until 1,000 rpm.

The experiments with multiple injections are performed on a diesel engine experimental device (in Figure 3) included exhaust measuring device and controller of single cylinder diesel engine (in Figure 4) whose specifications are listed in Table 1. In this research, it used the single cylinder diesel engine experimental device to get the experiment data.

The experimental device of this research is YANMAR TF70 V-E diesel engine with 4 cycle horizontal type water-cooling and equipped with a turbocharger (in Figure 3). The explanation of optimization objectives is listed as Table 2, and engine control parameters are set as Table 3. Based on experiment data, optimization objectives are formulated using stepwise method with multicollinearity. Equation (1) shows a second-order model:

Figure 3. Single cylinder diesel engine experimental device

Figure 4. Exhaust measuring device and controller of single cylinder diesel engine

$$y_a = \beta_0 + \sum_{i=1}^{p} \beta_i x_i + \sum_{i<j}^{p} \beta_{ij} x_i x_j + \sum_{i=1}^{p} \beta_{ii} x_i^2 + e_i \quad (1)$$

where y_a is the characteristic value of the optimization objective, a = 1, 2, 3, 4, β_0 is coefficient constant, β_i is coefficient on the x_i predictor, β_{ij} is coefficient on the x_i predictor and x_j predictor, β_{ii} is coefficient on the x_i predictor second-order, p is the total number of predictors and e_i is error term.

IV. Diesel Engine Modeling

A. Transient Control with Model Predictive Control

Corresponding to global environment problems in recent years and energy depletion problem, the technology of improving the fuel

Table 1.
Specification of the diesel engine

Parameter	Unit
Engine type	4-cycle, 1cylinder, DI
Bore x Stroke	78 mm x 80 mm
Top clearance	0.98 mm
Con-rod length	115 mm
Compression ratio	21.4
Cylinder capacity	0.382L
Maximum output	5.5/2600 kW/min^{-1}
Full-length	640 mm
Full-height	474 mm
Full-width	330.5 mm

Table 2.
Optimization objectives

Optimization Objective	Meaning	Unit
y_1	Power	kW
y_2	BSFC	g/kWh
y_3	NOx	ppm
y_4	soot	m^{-1}

Table 3.
Diesel engine control parameters

Control Parameter	Meaning	Unit
x_1	pilot 1 injection timing	deg. ATDC
x_2	pilot 1 injection quantity	mm^3/st
x_3	pilot 2 injection timing	deg. ATDC
x_4	pilot 2 injection quantity	mm^3/st
x_5	main injection timing	deg. ATDC
x_6	main injection quantity	mm^3/st
x_7	injection pressure	MPa
x_8	engine speed	Rpm

consumption and exhaust gas emission of an automobile engine is needed. If it compared with a gasoline engine, the diesel engine for cars has a high-thermal-efficiency and low CO_2. In other side, the amount of NOx and soot is increased.

Although many electronic control devices, such as a common rail system, EGR, and a turbocharger, are mounted on the present diesel engine, the fuel consumption and the exhaust gas emission require the technology which sets the control parameter of these devices and get the optimal value of control parameter.

Moreover, in order to realize the efficiency of engine control system, the engine control system development and engine appropriate technology of the model base is developed attract attention in recent years. One of the engine control system development is based on the prediction result of such a model. Then, the attention in last years has been paid to engine and complete power train control using the knowledge of the models [15], [16].

Model Predictive Control (MPC) is a group of algorithm of control computer that uses explicit process models to predict future responses of an application in which each control interval of a MPC algorithm tries to optimize future behavior by calculating a sequence of future adjustment of the manipulated variable. [17].

MPC meet the automotive requirements since this method can be expressed in the form of a constrained multi input multi output optimal control problem and provides an approximate solution of the problems [18].

In this research, it used the following equation to build a model predictive control.

$$f_i^{t+1} = a_i f_i^t + b_{i,1}\Delta u_1 + b_{i,2}\Delta u_2 + b_{i,3}\Delta u_3 + \dots + b_{i,7}\Delta u_7$$
$$i = 1,\dots,4$$

with f_i *is* controlled variable, u_j *is* control input (injection timing, injection quantity), and $b_{i,j} = (\partial f_i)/(\partial u_j)$ is Influence coefficient (Calculated from engine model).

It adjusted the input u as control input (pilot 1 injection timing, pilot 1 injection quantity, pilot 2 injection timing, pilot 2 injection quantity, main injection timing and main injection quantity), which is a predictive control for match the set value from the observed value output (power, BSFC, NOx, soot).

B. Derivative of the Prediction Model

Based on the previous study [19], the four optimization objectives evaluated using stepwise methods considering multicollinearity and it got the combustion model are as follows:

y_1: Power (kWh)

$$y_1 = -1.2209 + 1.5953e^{-10^{-1}}x_6 + 2.1274e^{-10^{-3}}x_6x_8 + 6.7681e^{10^{-6}}x_7x_8 - 707904e^{10^{-7}}{x_8}^2 \quad (2)$$

y_2: BSFC (g/kWh)

$$y_2 = 3.7745e^{10} - 5.7032e^{10}x_5 + 4.9796e^{10^{-2}}x_5x_8 + 1.1326e^{10}x_6x_7 - 5.8178e^{10^{-1}}x_6x_8 - 7.1307e^{10^{-2}}{x_7}^2 + 3.2240e^{10^{-4}}{x_8}^2 \quad (3)$$

y_3: NOx (ppm)

$$y_3 = 2.4205e^{10^3} + 1.7414e^{10^2}x_6 - 1.8747x_8 + 3.6476e^{10^{-2}}{x_3}^2 - 3.9282e^{10}x_6x_7 + 1.586x_6x_8 + 1.6560e^{10^{-1}}{x_7}^2 + 2.9429e^{10^{-3}}x_7x_8 \quad (4)$$

y_4: Soot (m^{-1})

$$y_4 = -4.3300 + 5.0931e^{10}x_2 + 2.0626e^{10^{-3}}x_1 + 1.1329x_1x_2 + 3.8892e^{10^{-4}}x_1x_3 + 2.5323e^{10^{-3}}x_2x_3 - 2.9668e^{10^{-4}}{x_3}^2 \quad (5)$$

In order to bring an evaluation value close to a desired value, the influence coefficient is calculated. To get value of the influence coefficient, the combustion model has to be derived. The derivative from these combustion models are as follow:

y_1: Power (kWh)

$$\dot{y}_{x_6} = 1.5953e^{-1} + 2.1274e^{-3}x_8$$
$$\dot{y}_{x_7} = 6.7681e^{-6}x_8$$
$$\dot{y}_{x_8} = 6.768e^{-6}x_7 - 707904e^{-7}2x_8$$

y_2: BSFC (g/kWh)

$$\dot{y}_{x_5} = -5.7032e^{1} + 4.9796e^{-2}x_8$$
$$\dot{y}_{x_6} = 1.1326e^{1}x_7 - 5.8178e^{-1}x_8$$
$$\dot{y}_{x_7} = 1.1326e^{1}x_6 - 7.1307e^{-2}2x_7$$
$$\dot{y}_{x_8} = 4.9796e^{-2}x_5 - 5.8178e^{-1}x_6 + 3.2240e^{-4}2x_8$$

y_3: NOx (ppm)

$$\dot{y}_{x_3} = 3.6476e^{-2}2x_3$$
$$\dot{y}_{x_6} = 1.7414e^{2} - 3.9282e^{1}x_7 + 1.586x_8$$
$$\dot{y}_{x_7} = -3.9282e^{1}x_6 + 1.6560e^{-1}2x_7 + 2.9429e^{-3}x_8$$
$$\dot{y}_{x_8} = -1.8747 + 1.586x_6 + 2.9429e^{3}x_7$$

y_4: Soot (m^{-1})

$$\dot{y}_{x_1} = 2.0626e^{-3} + 1.1329x_2 + 3.8892e^{-4}x_3$$
$$\dot{y}_{x_2} = 5.0931e^{1} + 1.1329x_1 + 2.5323e^{-3}x_3$$
$$\dot{y}_{x_3} = 3.8892e^{-4}x_2 + 2.5323e^{-3}x_2 + 2.9668e^{-4}2x_3$$

The coefficient in these four differentiation type is used for control calculation of the diesel engine transient control simulation by MATLAB/SIMULINK.

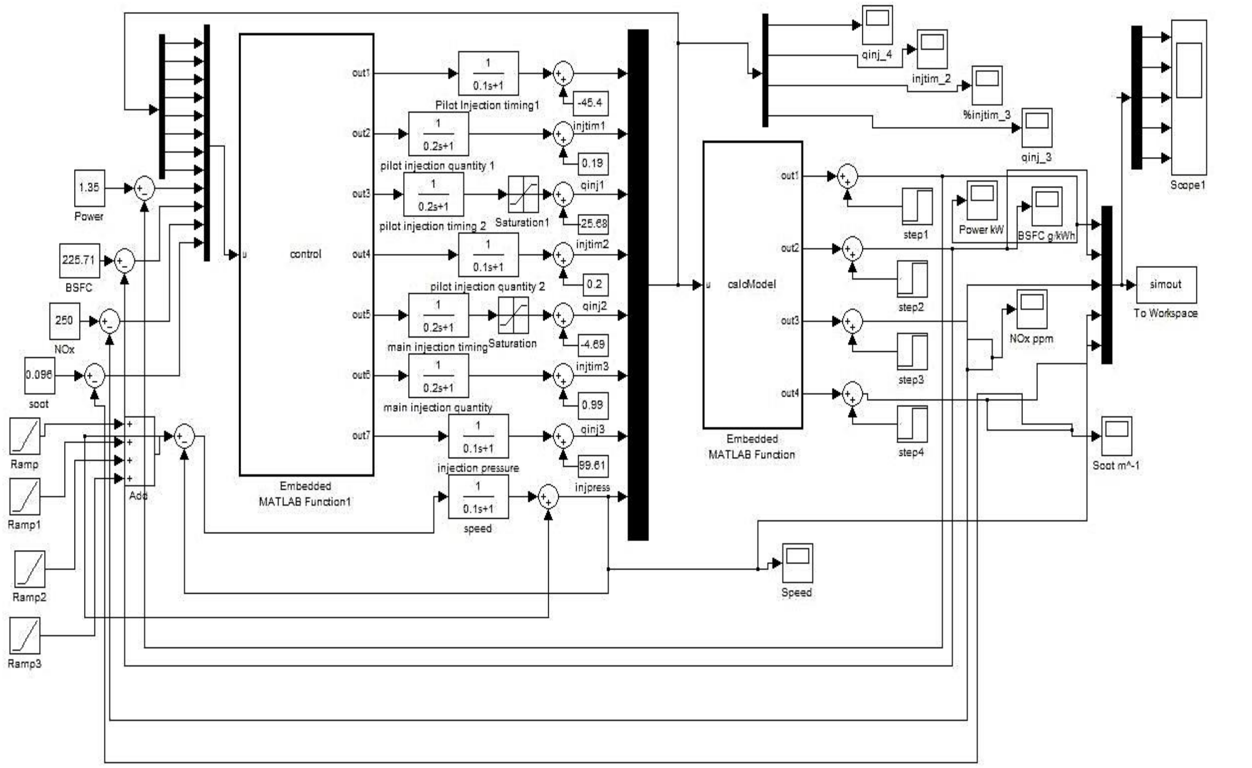


Figure 5. The transient control simulation model by SIMULINK

V. MODEL IMPLEMENTATION

A. Transient Control Simulation Model

In this section, it used the formula of predictive control model described in section III, the deviation from the optimal value, which is calculated with basis error of prediction model and disturbance to make a transient control simulation model in MATLAB / SIMULINK. Figure 5 shows transient control simulation model of the single-cylinder diesel Engine by SIMULINK. The main advantage of the SIMULINK module is its ability to represent the whole engine model with a set of interconnected blocks. Input design parameters are passed on to the blocks from the input file, but all of the operating parameters derived from the block (functions) for the other components of the system.

The control simulation of the model prediction control by the regression model of combustion was constituted. A right block is an engine revolution combustion model, and a left block is a control model. In this research, it use the model prediction control to understand the engine characteristic by change the rotation of engine from 1,000 rpm to 2,000 rpm and 2,000 rpm to 1,000 rpm.

In a control model, the relation between eight control inputs and four controlled variables is used as an influence coefficient. The result is based on the engine rotations from 1,000 rpm, 1,500 rpm, and 2,000 rpm shown below. Four variables were chosen from this result as a control input i.e. pilot 1 injection quantity, pilot 2 injection timing, main injection timing, and main injection quantity.

Influence coefficient

Ne=1000

PR =

$$1.0e{+}003 * \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0.0023 & 0 & 0 \\ 0 & 0 & 0 & 0 & -0.0072 & 0.5508 & -0.0046 & -0.0001 \\ 0 & 0 & -0.0026 & 0 & 0 & -2.1680 & -3.3029 & -0.0002 \\ 0 & -0.0170 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Ne=1500

PR =

$$1.0e{+}003 * \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0.0034 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.0177 & 0.2599 & -0.0046 & 0.0002 \\ 0 & 0 & -0.0026 & 0 & 0 & -1.3750 & -3.3014 & -0.0002 \\ 0 & -0.0170 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Ne=2000

PR =

$$1.0e{+}003 * \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0.0044 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.0426 & -0.0310 & -0.0046 & 0.0005 \\ 0 & 0 & -0.0026 & 0 & 0 & -0.5820 & -3.2999 & -0.0002 \\ 0 & -0.0170 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

The impact on output from Injection quantity of pilot 1, the injection timing of pilot 2, the main injection timing and the main injection quantity should be inserted into matrix 4 × 4 then inverse of matrix multiplied control amount of deviation that it was looking for. This is an example of a matrix of 4 × 4:

$$\begin{pmatrix} 0 & 0 & 0 & 0.0023 \\ 0 & 0 & -0.0072 & 0.5508 \\ 0 & -0.0026 & 0 & -2.1680 \\ -0.0170 & 0 & 0 & 0 \end{pmatrix}$$

B. Result of Model Predictive Control

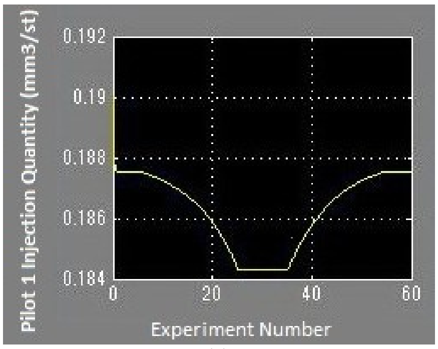
First of all, 4 optimal values (power, BSFC, NOx, soot) of engine rotation 1,000 rpm are set as target value, then changes in the characteristics of the rotation of engine from 1,000 rpm to 2,000 rpm and 2,000 rpm to 1,000 rpm is shown in the figure 6-10. In order to show the sufficient performance of a predictive model, it compared the model which has controlled and hasn't controlled.

In Figure 6, it can be seen control input when carrying out model predictive control has many variations value such as pilot 1 injection quantity (0.1900 to 0.1844 mm^3/st), pilot 2 injection timing (-25.7 to -24.8 deg. ATDC), main injection timing (-4.74 to -4.69 deg. ATDC), and main injection quantity (0.98 to 1.08 mm^3/st). If it compared with model which hasn't controlled, the all control input has stabile. It can be seen the control input of model without controlled in Figure 8.

The result of controlled variable from the experiment with transient control based on the engine rotations from 1,000 rpm to 2,000 rpm and 2,000 rpm to 1,000 rpm shown below. The controlled variable with model predictive control has variation value better than controlled variable without model predictive control especially in value of soot. I can be seen the detail value of controlled variable with model predictive control in Figure 7 i.e. engine power (1.05 to 1.8 kw), BSFC (225 to 370 g/kWh), NOx (279 to 308 ppm) and soot (0.092 to 0.094 m^{-1}) and controlled variable without model predictive control in Figure 9 i.e. engine power (0.94 to 1.41 kW), BSFC (225 to 390 g/kWh), NOx (364 to 375 ppm) and soot (0.1 m^{-1}).

In this result it can be seen that value of soot without model predictive control stable 0.1 m^{-1}. Judging from the transient control input changes suggested by (pilot 1 injection quantity, pilot 2 injection timing, main injection timing, main injection quantity) as well as the controlled variable (power, BSFC, NOx, soot), control performance can be known.

In order to more clearly, it proposed the comparison of disturbance insertion control with model predictive control and without model predictive control in Figure 10. In Figure 10(a), the value of soot and NOx is stable. This means that with a given disturbance insertion control does not change significantly. It seems different on models with MPC. From this explanation, experiment in transient operation based on the rotation of engine from 1,000 rpm to 2,000 rpm and slowdown until 1,000 rpm has been improved by model prediction control, and validity was shown.



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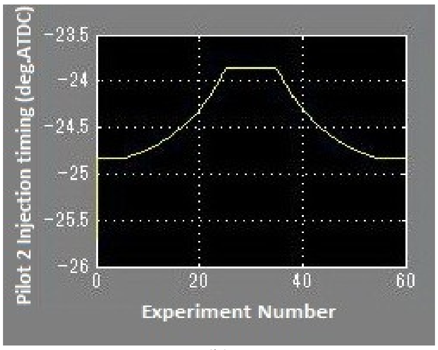

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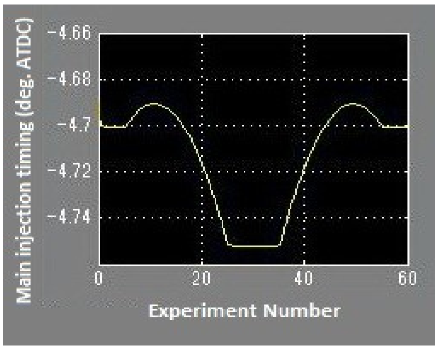

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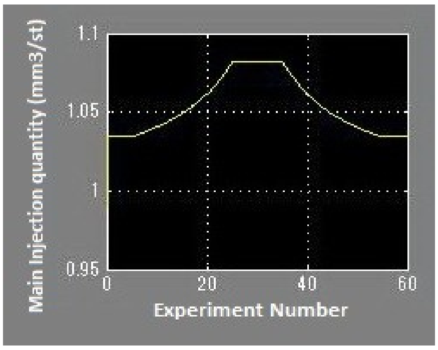
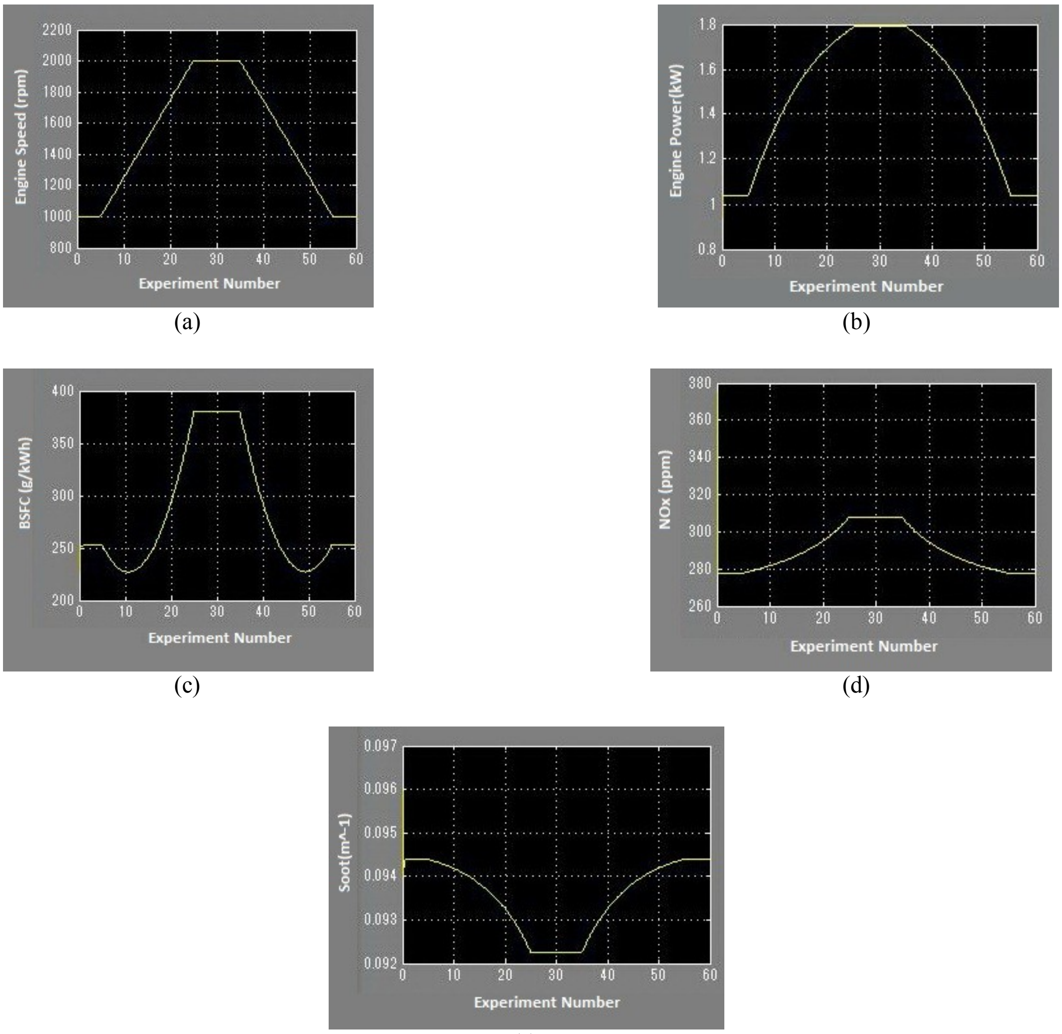


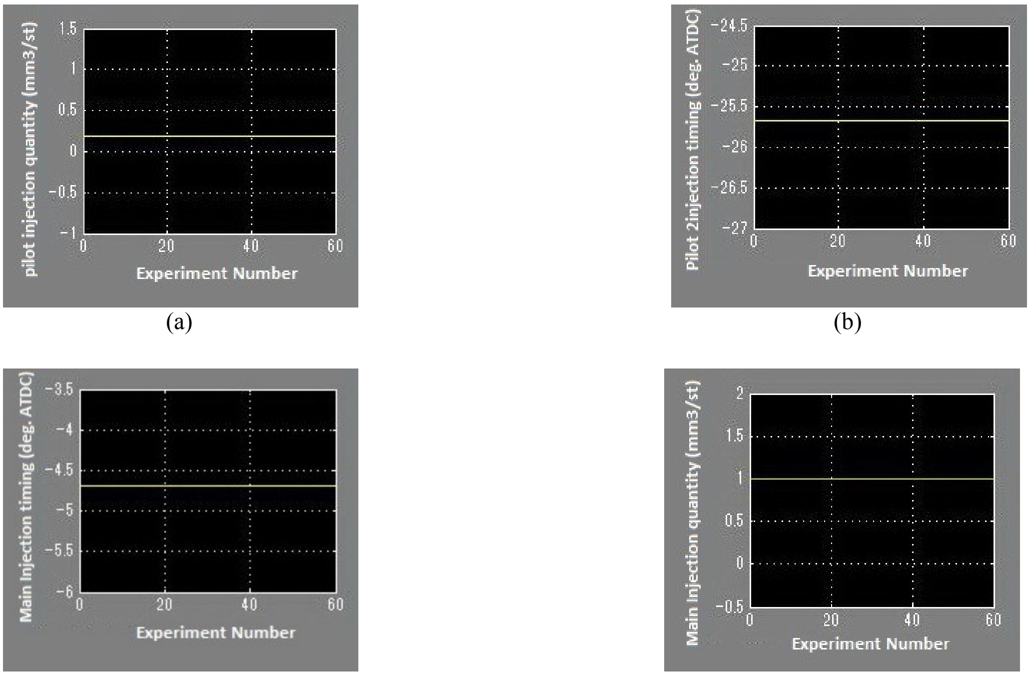
(d)

Figure 6. Control input with model predictive control; (a) pilot 1 injection quantity; (b) pilot 2 injection timing; (c) main injection timing; (d) main injection quantity



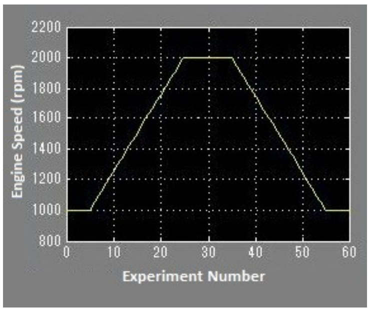
(a) (b) (c) (d) (e)

Figure 7. Controlled variable with model predictive control; (a) engine speed; (b) engine power; (c) BSFC; (d) NOx; (e) soot



(a) (b) (c) (d)

Figure 8. Control input without model predictive control; (a) pilot 1 injection quantity; (b) pilot 2 injection timing; (c) main injection timing; (d) main injection quantity



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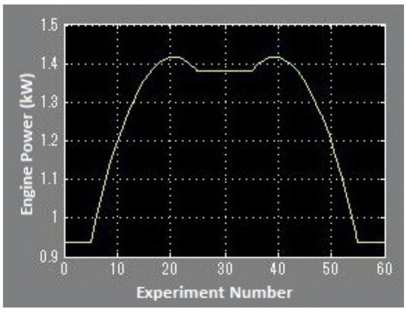

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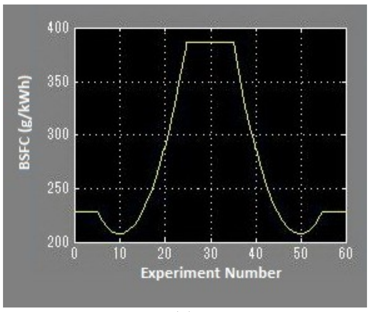

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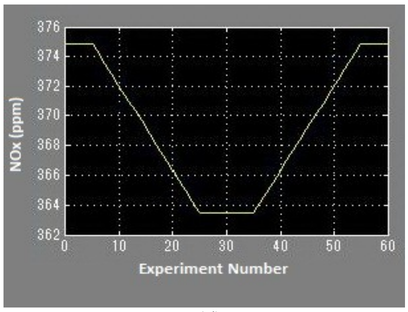

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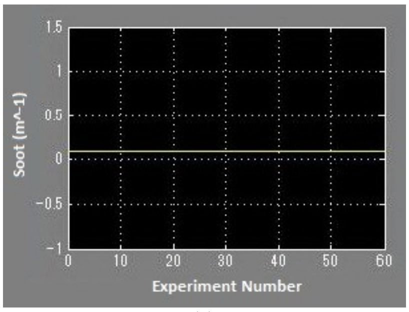
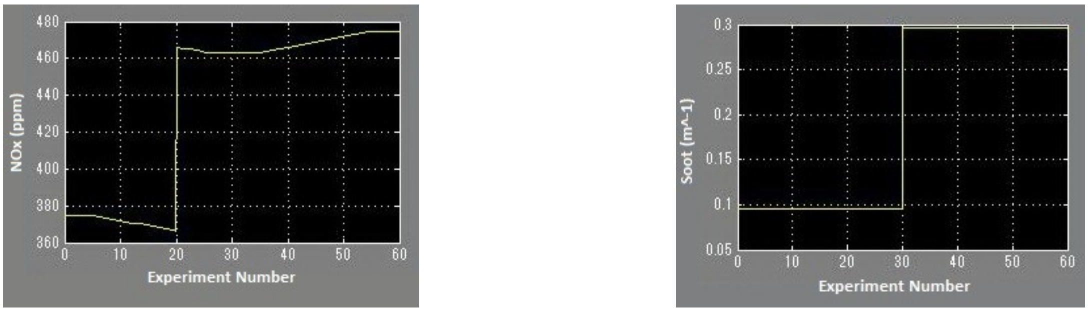
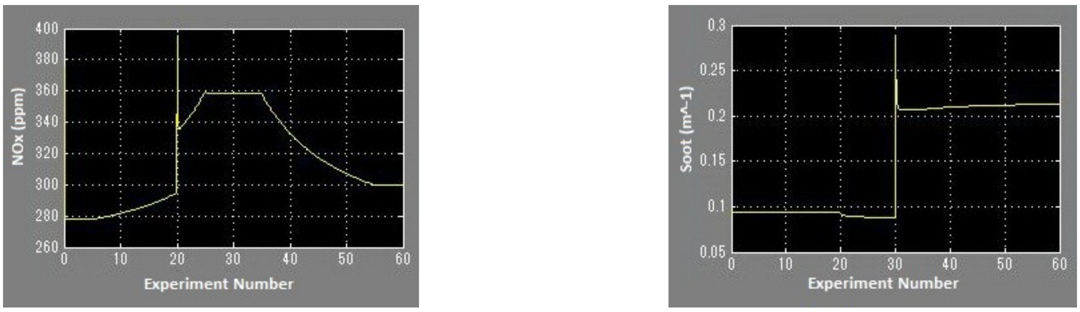


(e)

Figure 9. Controlled variable without model predictive control; (a) engine speed; (b) engine power; (c) BSFC; (d) NOx; (e) soot



(a)



b.

Figure 10. Comparison of disturbance insertion control with MPC and without MPC; (a) disturbance insertion control in NOx and soot without model predictive control; (b) disturbance insertion control in NOx and soot with model predictive control

VI. CONCLUSION

Steady-state analysis of the engine is insufficient to meet that the latest regulations imposed one missions and fuel economy. The research described in this paper has dealt with the dynamic model for a single cylinder diesel engine which can simulate the engine performance under transient operating conditions. This model is developed with investigating experiment in transient operation based on the rotation of engine from 1,000 rpm to 2,000 rpm and slowdown until 1,000 rpm.

The major conclusions of this work are:

- The transient engine simulation has been improved by model prediction control.
- The results illustrate the important of single cylinder diesel engine simulation as non-linear dynamic control system.

In the future, by improving the control model, it would be like to improve the model closer to the target value for the output more transient.

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