

Development of a New Model Based Air-Fuel Ratio Control System

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ABSTRACT

The second-generation air-fuel ratio control method has been developed to reduce exhaust gas emissions in accordance with the improvements in catalysts. The control system consists of a feedforward control using a fuel behavior model, a feedback control using an universal exhaust gas oxygen (UEGO) sensor and a feedback control utilizing the heated exhaust gas oxygen (HEGO) sensor. This significantly improves air-fuel ratio tracking performance by feedforward control derived from the models that express the dynamic phenomena and the disturbance attenuation by UEGO feedback controller which compensates for the long dead-time characteristics by the state predictive control. The tracking performance and the disturbance attenuation can be achieved independently by a two-degree-of-freedom structure presented in this paper. The exhaust air-fuel ratio downstream of the catalyst precisely converges to stoichiometry, which maximizes the conversion efficiency of the catalyst. Experimental results on actual vehicles show the effectiveness of presented method.

INTRODUCTION

In order to protect the environment, exhaust emission regulations, as represented by California's ULEV/SULEV standards, are becoming increasingly strict. Many corporations and research institutions have been working to develop a variety of technologies to meet these standards, one of which is air-fuel ratio control. It is necessary to maximize the conversion efficiency of the catalyst to reduce emissions. The efficiency is

strongly dependent on the air-fuel ratio. Therefore, various methods for improving air-fuel-ratio-control precision have been proposed. For example, model-based methods based on linear control theory [1 2 3], sliding mode control to deal with nonlinear characteristics [4], compensation of dead time from the injection to the detection of air-fuel ratio by the UEGO sensor [5 6] and adaptive control [7 8] and so on are proposed. The catalytic converters have also developed for many years and the oxygen storage capacity (OSC) of the catalyst has been remarkably increased. Although the old-fashioned catalytic converters easily emit hydrocarbons (HC) and carbon monoxide (CO) or oxides of nitrogen (NO_x) for small disturbances, modern catalytic converters can endure larger disturbances. Most of the previous methods are aimed to keep the air-fuel ratio upstream of the catalyst at stoichiometry. However, because of progress in the catalyst technology, exhaust gas emissions can be reduced even more by modifying the reference air-fuel ratio appropriately, than by holding the reference at stoichiometry. Therefore, the tracking performance of air-fuel ratio control is getting more important for reducing emissions than before.

In this paper, the control system improves the tracking performance without deteriorating disturbance attenuation. The former is achieved by feedforward control which compensates the fuel behavior under transient engine operating conditions using inverse model; the latter by UEGO feedback control which compensates for the dynamics that exist between fuel injection and the UEGO sensor output, especially the long dead time which significantly impacts the robustness of air-fuel-ratio control by applying state

predictive control, which predicts the state after the dead time has elapsed. Furthermore, a two-degree-of-freedom structure is applied in order to regulate tracking performance and disturbance attenuation independently.

This control method was applied to a 2.5-liter in-line 4-cylinder engine and it was verified to result in lower exhaust emissions than conventional methods. Other tests have also confirmed that the new method effectively achieves exhaust emissions standards like SULEV.

SYSTEM CONFIGURATION

Figure1 shows the engine exhaust system and air-fuel-ratio-control system described in this paper.

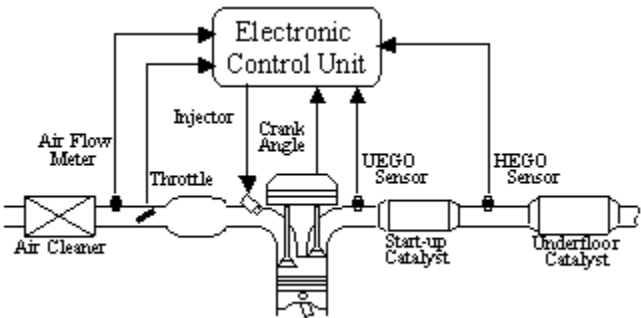


Figure 1:Air-fuel ratio Control System and Exhaust System

The exhaust system has a start-up catalyst and an under-floor catalyst. The UEGO sensor with a wide detection range is installed upstream of the start-up catalyst, and primarily compensates for fast and large air-fuel ratio variations. Meanwhile, a HEGO sensor with a narrow detection range but one that is capable of precisely detecting the stoichiometric air-fuel ratio, is installed downstream of the start-up catalyst.

METHOD OF AIR-FUEL RATIO CONTROL

The basic concept of control method is as follows.

1. The air-fuel ratio of the emissions exiting the catalyst, sensed by the HEGO sensor downstream of the

catalyst, is tuned to remain near the stoichiometric value under all operating conditions.

2. To achieve the objective in 1, the target air-fuel ratio upstream of the catalyst is computed based on the value sensed by the HEGO sensor downstream of the catalyst and, based on the value sensed by the UEGO sensor upstream of the catalyst, the air-fuel ratio quickly converges to the target value.

Achievement of the above objectives maximizes the conversion efficiency of the catalyst.

MODEL-BASED CONTROL DESIGN

As shown in Figure 2, the controller consists of three parts, namely (i) feedforward control using an inverse fuel model, (ii) feedback control using the UEGO sensor upstream of the catalyst and (iii) feedback control using a HEGO sensor downstream of the catalyst.

The HEGO feedback calculates the reference equivalence ratio of feedforward controller and UEGO feedback in order to minimize the difference between the reference value and the output of the HEGO sensor.

The feedforward controller and the UEGO feedback regulate the air-fuel ratio upstream of the catalyst to the reference air-fuel ratio. In order to achieve both high tracking performance and disturbance compensation independently, a two-degree-of-freedom structure is presented. Tracking performance can be determined by filtering the feedforward controller, and the disturbance compensation by parameters of the feedback controller.

$$f_i(k) = f_{ie}(k) \cdot \phi_{fb}(k) \tag{1}$$

where

- f_i : amount of fuel injected
- f_{ie} : amount of nominal fuel injected, which is calculated in feedforward controller
- ϕ_{fb} : equivalence ratio of feedback compensation

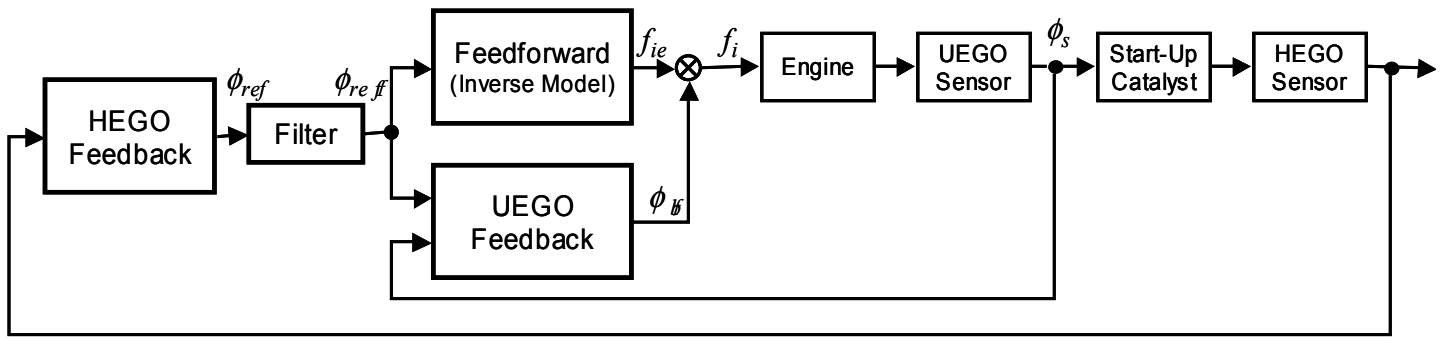


Figure 2:Block Diagram of Air fuel ratio control system

FEEDFORWARD CONTROL USING INVERSE MODEL

In order to achieve fast reference air-fuel-ratio response, the following feedforward controller, which compensates for the fuel-film behavior under transient engine operating conditions, is applied. It calculates the nominal value of the fuel injection by using the inverse model which is introduced from the fuel-behavior model shown in Equation (2), (3).

Modeling of the fuel dynamics for the feedforward controller

$$f_w(k + d_{cy}) = p \cdot f_w(k) + r \cdot f_i(k) \quad (2)$$

$$f_c(k + d_{cy}) = (1 - p) \cdot f_w(k) + (1 - r) \cdot f_i(k) \quad (3)$$

where

- f_w : amount of fuel film
- f_c : amount of fuel induced into the cylinder
- p : rate of fuel left behind in F_w
- r : rate of adherence
- k : engine stroke index (1 stroke = 180° crank)
- d_{cy} : engine cycle delay

Not all of the injected fuel enters the cylinder and some adheres to the intake-port wall surface and forms a fuel film. The remaining fuel becomes mist in the intake port and is sucked into the cylinder in the intake stroke. Some of fuel film is gradually inducted into the cylinder or it evaporate and is absorbed into the cylinder together with the air flow in the intake stroke. And there is engine cycle delay from the moment the intake valve starts to open until the moment the exhaust valve closes. Assuming that the mass of fuel inducted into the cylinder is the same as the mass in the expansion stroke, the fuel injected at the time k corresponds to the fuel in the cylinder at the time $k + d_{cy}$.

There are some errors in these simple discrete models compared to the actual engine behavior, but such errors are compensated for by the feedback control.

Feedforward control design

$$f_{cr}(k) = m_c(k + d_{cy}) \cdot \phi_{reff} \quad (4)$$

$$\phi_{reff}(k + 1) = c_{ff} \cdot \phi_{reff}(k) + (1 - c_{ff}) \cdot \phi_{ref}(k) \quad (5)$$

$$f_{ie}(k) = \frac{f_{cr}(k + d_{cy}) - (1 - p) \cdot f_{we}(k)}{1 - r} \quad (6)$$

$$f_{we}(k) = p \cdot f_{we}(k - d_{cy}) + r \cdot f_{ie}(k - d_{cy}) \quad (7)$$

where

- f_{cr} : amount of fuel corresponding to the reference equivalence ratio
- m_c : mass of air flowing in the cylinder
- ϕ_{ref} : reference equivalence ratio
- ϕ_{reff} : filtered reference equivalence ratio
- c_{ff} : parameter corresponding to filter time constant
- f_{we} : amount of nominal fuel film

$m_c(k + d_{cy})$ is the air inducted into the cylinder, predicted from the intake manifold pressure and engine speed. As the fuel injection must be done properly to provide the reference equivalence ratio ϕ_{reff} in the cylinder, the required mass of fuel to be inducted into the cylinder f_{cr} is expressed in Equation (4). For desired reference response, a first-order filter shown in Equation (5), is applied. By this filter, the tracking performance can be regulated independently of disturbance rejection.

Therefore the nominal value of fuel mass, the output of the feedforward controller, is expressed in Equation (6).