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Setup of an Engine Rapid Control Prototyping System for Catalyst Research and Evaluation Testing

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ABSTRACT

To fulfill ever increasingly stringent emission regulations, a great many studies on engine control and catalytic converter performance have been made. Topics of great interest in this area, to name a few, include: the relationship between catalyst light-off time and air-fuel (A/F) ratio; the relationship between forced A/F ratio modulation and catalyst efficiency; the effects of phase-shifted A/F ratio modulation between banks of a dual bank engine, or among cylinders of a single manifold engine on catalyst efficiency; and methods of modeling and measuring the oxygen storage capacity of a catalytic converter by rich-lean transition, A/F ratio sweeping, or other on-line estimation methods.

To undertake this type of research, an engine control system with necessary functions, especially with very flexible A/F ratio control capabilities, is needed. Mass production ECU does not provide the flexibility desired and it is also hard to develop and integrate the control algorithms needed for catalyst testing into the existing ECU software. An engine rapid control prototyping system is set up in an engine dynamometer test cell environment to overcome the limitations of mass production ECU and fulfill the requirements for catalyst research and testing. Model-based development methodology is adopted for the design and implementation of necessary software. Control algorithms, including individual bank control of a dual bank engine, A/F ratio modulation of different frequencies and amplitudes, with and without phase shift between banks, A/F ratio rich-lean transition and sweeping etc, are designed using graphical language, automatically converted into executables to run on the real-time target. UDP communication for real-time command and variable exchange between the engine controller and the test cell controller is developed to facilitate testing. The system provides the flexibility and good control performance desired for catalyst research and evaluation testing. Application and results of the system on a 4.6L V8 gasoline engine is given.

INTRODUCTION

With environmental protection in the forefront of world issues, increasingly stringent emission regulations are being enforced worldwide. Facing these challenging requirements on emissions, OEMs and suppliers have been working in many areas of engine and vehicle development to achieve their goals. Among these areas, the three-way catalytic converter application is of extraordinary importance and is an area where much research and testing has been conducted. Major activities in this area can be categorized into two groups. The first group mainly focuses on the improvement of converter performance through catalyst technology, such as the development of oxygen storage material; improvement of composition and arrangement of precious metals for better conversion efficiency; optimization of the structure to create a catalyst self-regeneration function and mitigate deterioration, etc. The second group includes various activities in engine control, especially in A/F ratio control to increase the performance of the catalyst [1-13].

It is well known that A/F ratio has great effect on catalyst conversion efficiency. Research topics in this area include among others:

- The influence of A/F ratio on catalyst light-off time [1,13]
- The relationship between forced A/F ratio modulation (frequency and amplitude) and catalyst conversion efficiency [2,3,4,7,8]
- The effect of phase-shifted A/F ratio modulation between banks or among cylinders on conversion efficiency [2,3,9]
- methods of modeling and measuring the oxygen storage capacity of a catalytic converter by rich-lean transition, A/F ratio sweeping, or other on-line estimation mechanisms [4-7,10-12]

We will briefly review the above cases. It is reported that operating an engine with retarded ignition timing combined with lean A/F ratio will decrease catalyst light-off time and consequently reduce engine emission [1]. It is also reported that perturbing the A/F ratio to make use of the oxygen storage capacity of the catalyst yields better conversion efficiency than just keeping the constant stoichiometric value upstream of the converter [4]. These researches involve controlling the A/F ratio at desired constant value or desired average value with perturbation.

For dual bank engines, some research indicates that independently controlling the A/F ratio of each bank to make their lean and rich status just opposite to each other (called phase-shifted A/F ratio modulation) will benefit catalyst efficiency since both rich and lean exhaust species are present simultaneously at the converter and provide a highly reactive mixture to the catalyst [2,3]. It is also claimed that this mechanism will reduce the demand on the oxygen storage capacity of the catalyst since the exhaust from the two banks will combine and achieve a near-stoichiometric mixture prior to entering the converter. This research involves individually control the fuel injection of the banks so that their A/F ratio waveforms have the desired average value, modulation frequency, perturbation amplitude and phase shift.

When carrying out measurement of the oxygen storage capacity of the catalyst, commonly used methods involve controlling the engine to run under certain A/F ratio patterns and monitoring the engine and catalyst behavior, such as studying the response delay of a downstream A/F ratio sensor when the engine is going through rich and lean transitions, or measuring the break-through perturbing oxygen quantity when doing engine A/F ratio sweeping [4,5]. These cases require the A/F ratio to go through square wave, or low frequency triangle wave superimposed with higher frequency modulation.

We see all these studies and testing require flexible control of A/F ratio — desired constant value, desired average value, various modulation frequencies, desired perturbation amplitude, and with or without phase-shifting between banks. Mass production ECU does not provide the flexibility needed for these purposes. It is hard to develop catalyst testing algorithms and integrate them into the existing ECU software. We set up an engine rapid control prototyping system in an engine dynamometer test cell environment to overcome these limitations. By the use of model-based development methods, algorithms are specified in a high-level graphical language and directly compiled into executables to run on the real-time hardware. The engine control features stated above are easily designed and implemented to fulfill the catalyst study and testing requirements.

To facilitate testing, a mechanism for real-time exchange of commands and variables between the engine controller and the test cell controller is desired. UDP communication is developed to fulfill this need. The test cell controller sends commands to the engine controller through the UDP interface so that the engine is put into specific operating modes for testing and measurement. Various engine operating modes are designed and implemented to realize various A/F ratio patterns. Engine control parameters and variables are also transferred to the test cell controller through UDP communication for analysis purpose.

The system is applied to a 4.6L V8 gasoline engine. Results of A/F ratio control for various testing needs are presented. The application and results reflect the flexibility and good control performance of the system.

This paper is organized into the following four sections:

I. ***System Overview*** describing the overall design and configuration of the integrated system.
II. ***Engine Rapid Prototyping Controller Setup*** describing the features of the controller, its hardware and software configurations, and the function modules used for engine control.
III. ***Model-Based Software Development and Application Results*** describing the development of needed engine control features, especially the algorithms for steady state A/F ratio modulation and phase-shifting, rich-lean transition, and A/F ratio sweeping etc. The results of application on a V8 engine are also given.
IV. ***Conclusion*** summarizing the features and the performance of the system.

I. SYSTEM OVERVIEW

Figure 1 shows an overview of the integrated system. It consists of a real-time test cell controller, and a rapid prototyping engine controller. The test cell controller, together with all the necessary signal interfaces and power units etc, realizes real-time control of the engine test cell environment, including the dynamometer, engine throttle, and other accessories. It sets the engine operation point (speed and load) and maintains the accessories, such as coolant conditioning system, oil conditioning system etc, in proper condition. The controller is connected to a host PC through Ethernet for graphical user interface (GUI).

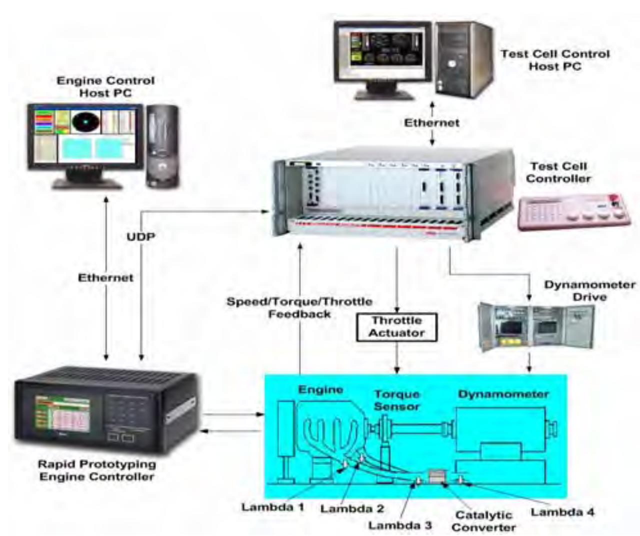


Fig. 1 Overview of the Integrated System

The engine rapid prototyping controller, together with necessary signal conditioning and power electronics modules, realizes the functions necessary for engine operation, including ignition and fuel injection. Engine A/F ratio control algorithms for various catalyst research and testing purposes are developed. These functions are designed and implemented using the model-based engineering methodology. First the control algorithms are specified using The MathWorks products (MATLAB®/Simulink®/Stateflow®) on a host PC. Necessary S-functions for the specific real-time hardware target are developed and integrated in the controls. Then the control algorithms are converted into C code by Real-Time Workshop®, and compiled, linked, and downloaded to the target platform to control engine operation. The rapid prototyping controller is connected to a host PC through Ethernet. GUI is developed such that control parameters can be adjusted and engine behavior easily monitored in real time.

Communication between the test cell controller and the engine controller can facilitate catalytic converter testing. We realize this function through the User Datagram Protocol (UDP) over Ethernet physical layer. UDP is a simple message-based protocol that provides an efficient means for communicating short packets of data between processes, avoiding the overhead of flow control and data stream checking and correcting. Considering the real time nature of the communication between the engine controller and the test cell controller, and also the limited data volume, UDP is a very suitable solution. With this mechanism, the test cell controller sends out mode commands requesting the engine controller to fulfill. The engine controller receives the command and runs the engine in the requested mode, fulfilling different types of catalyst evaluation testing, such as catalyst light-off, lean-rich A/F ratio transition, A/F ratio sweeping, A/F ratio modulation, and phase-shifting etc. The engine controller also sends such control parameters as spark advance, fuel injection width, and lambda values etc, together with other variables indicating the engine status back to the test cell controller for monitoring, logging and analysis purposes.

Necessary A/F ratio sensors and thermocouples are installed. Engine-out exhaust temperature and mass flow entering the catalytic converter should be regulated per the test requirements. Based on research or testing needs, up to 4 Lambda sensors can be installed in the system. As shown in Figure 1 for a V8 gasoline engine, a Lambda sensor is installed at each manifold corresponding to the left and right bank. A third sensor is installed upstream of the catalytic converter, after the left and right bank manifolds merge together. A fourth one is installed downstream of the catalytic converter. With such a configuration, the studies mentioned above, such as the effect of phase shift of A/F ratio modulation on catalyst conversion efficiency, and the measurement of oxygen storage capacity through the response delay of downstream A/F ratio sensor etc, can all be performed.

II. ENGINE RAPID PROTOTYPING CONTROLLER SETUP

The engine rapid prototyping controller together with necessary function modules, signal conditioning and power stage modules form the hardware platform for engine control. Figure 2 shows the hardware framework of the engine rapid prototyping controller [14]. It has a dual CPU architecture, using a PentiumM processor for high-speed simulation and control, and a Renesas SH4 processor for running the human-machine interface, including color touch-screen LCD, function keys, and Ethernet communication with the host PC. A bus controller on the active back plane handles the data transfer between the interface boards and the CPUs. This design frees up the PentiumM CPU and enables execution of highly efficient digital signal processing operations. The controller has a modular design for function modules. Simulink® S-functions to access module functionalities are developed.

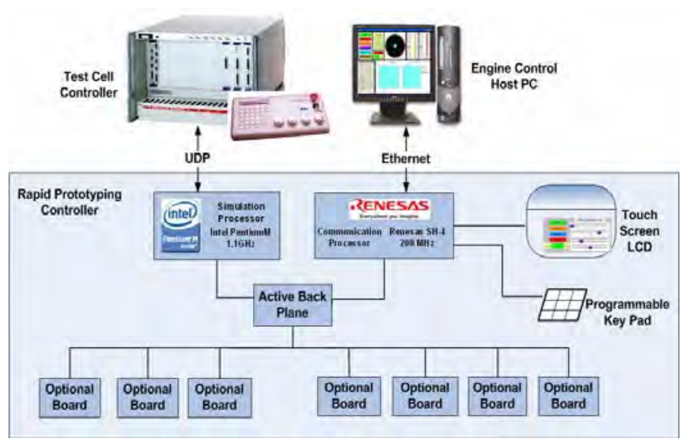


Fig. 2 Hardware Architecture of the Engine Rapid Prototyping Controller

Figure 3 shows the software architecture of the controller and the specific role of each software component. MathWorks products MATLAB®/Simulink®/Stateflow® are used to develop control logic in the form of model block diagrams. The S-functions for system hardware and function modules are developed and integrated in the block diagram. Real-Time Workshop® converts the block diagram into C code, which is then compiled, linked, and downloaded automatically to the target platform for real-time execution under the RT-Linux operating system. VirtualConsole software is the graphical user interface to the controller that enables the arrangement of various screen elements on the host PC and on the color touch-screen LCD. These screen elements are associated with the variables or parameters of the Simulink® model, enabling real-time parameter setting and signal monitoring.

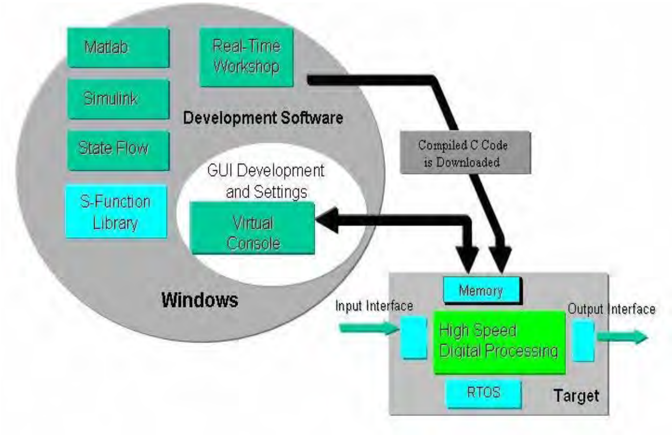


Fig. 3 Specific Roles of the Rapid Prototyping Controller Software Components

To perform engine control for the catalyst research and testing purpose, two function modules are integrated in the controller: a general purpose A/D input board, and an engine timing detection and control board. The analog input board is used for measuring such variables as throttle position, manifold absolute pressure, intake mass air flow rate, intake air temperature, and engine coolant temperature, etc. It is also used to measure the A/F ratio, which are analog signals from A/F ratio meters. The engine timing detection and control board is used for processing the crankshaft and camshaft input signals, obtaining engine speed and timing, as well as sending out control commands for ignition and fuel injection. Necessary signal conditioning modules, as well as power electronics modules with proper functions for actuator operation are also developed and integrated in the system.

III. MODEL-BASED SOFTWARE DEVELOPMENT AND APPLICATION RESULTS

Model-based software development provides seamless transition from design to implementation and testing. Based on the hardware platform described in the above sections, control algorithms are developed using model-based methodology to realize various fundamental features necessary for engine operation, such as analog input signal sampling, filtering and conversion; engine timing detection; speed calculation and filtering; look-up-tables for basic spark advance and fuel injection duration; dwell angle calculation; ignition and injection implementation; engine cold start strategy; Individual bank control for a dual bank engine; and UDP communication etc.

Based on these basic control features we implement the more complex engine operation modes required by the catalyst research and evaluation testing, through feedback and feed-forward mechanisms. Figure 4 shows part of the Simulink® algorithm model of the engine controller, which includes various algorithms for A/F ratio control. For catalytic converter evaluation testing, OEMs might have different procedures. The most commonly adopted include steady state A/F ratio modulation with or without phase-shifting, rich-lean A/F ratio transition, and A/F ratio sweeping. The idea is to control the A/F ratio upstream of the catalyst (Lambda1 and Lambda2 in Figure 1) to fulfill desired patterns and study the performance of the converter and the engine under that condition. Below we will give more details of the design and realization of these A/F ratio control algorithms. Implementation and results on a V8 engine are also given. One thing need be pointed out is that how the downstream sensors (Lambda3 and Lambda4 in Figure 1) react to the A/F ratio patterns is not the major topic of this paper and therefore will not be covered.

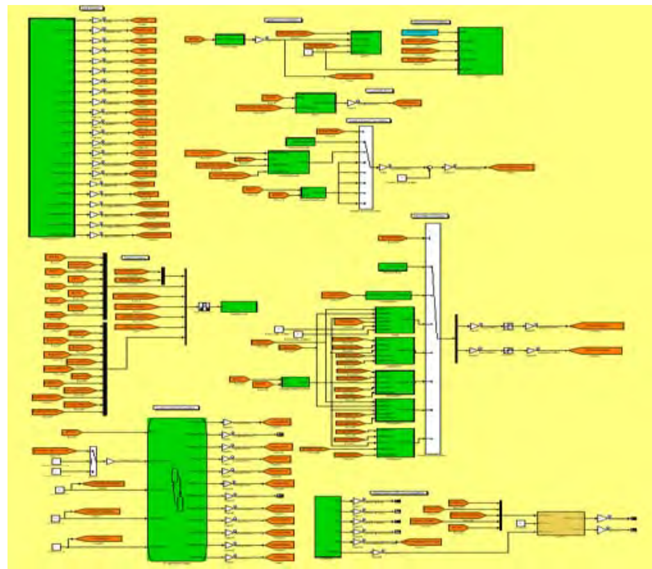


Fig. 4 Part of the Engine Control Software

Steady State A/F Ratio Modulation and Phase-Shifting

We design the algorithm shown in Figure 5 to realize steady state A/F ratio modulation and phase-shifting. The key feature of this algorithm is that the base fuel width which corresponds to the targeted average A/F ratio is obtained through a feedback loop, while the high frequency A/F ratio modulation is realized by modulating the base fuel width with proper amplitude, frequency and phase in the feed-forward path. To obtain the base fuel width, the average A/F ratio during the engine operation need be obtained. We realize this by performing a rolling average calculation of the A/F ratio, with the time window equal to the period of the desired A/F ratio modulation. By doing so, we get the average A/F ratio during the engine operation despite the A/F ratio modulation. A PI controller is used to obtain the base fuel injection duration based on the deviation between the targeted average A/F ratio and the real-time rolling average value. The base fuel injection duration is modulated with the desired frequency and amplitude, as well as a phase shift for the phase-shifted implementation, and output to control the engine operation. For the case of a dual bank engine, both Lambda sensor values upstream of the catalytic converter are used and the banks are individually controlled.

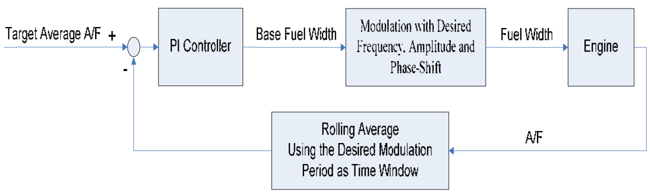
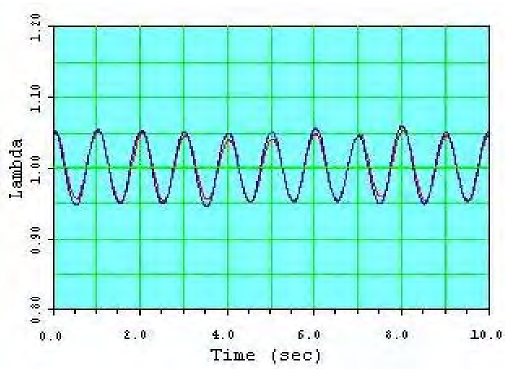
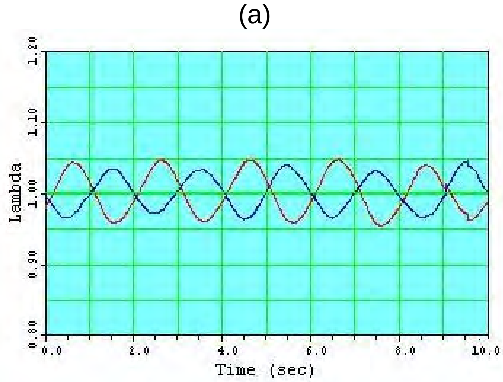


Fig. 5 Algorithm to Realize A/F Ratio Modulation and Phase-Shifting

Figure 6 shows the results of applying the above described algorithm on a 4.6 liter V8 engine. The left and right banks are controlled individually and both lambda values (Lambda1 and Lambda2 in Figure 1) are shown. Figure 6(a) is the result of achieving stoichiometry as the target average A/F ratio, with 1 Hz modulation of 5% perturbation amplitude, and the left and right banks in phase. Figure 6(b) shows the result of 180 degree phase-shifted half Hz A/F ratio modulation between the banks. We see the designed algorithm gives excellent control performance realizing the desired A/F ratio modulation and phase shifting.



(a)



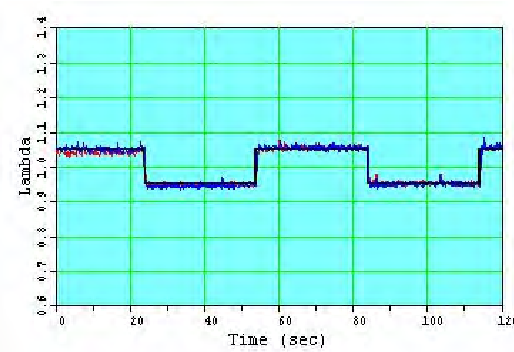
(b)

Fig. 6 Left and Right Bank Lambda Values Without and With Phase-shifting

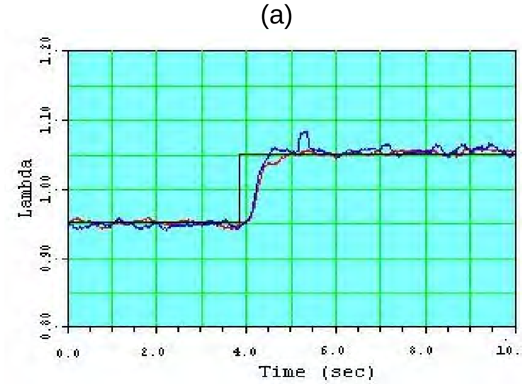
Rich-Lean Transition

Rich-lean transition mode is often used to measure the oxygen storage capacity of the catalyst [4,5,6]. Accurate determination of the oxygen storage capacity will facilitate the optimal design of A/F ratio control, allow a better adaptive control algorithm, and also help catalyst monitoring which is required by OBDII. In this mode, the A/F ratio is controlled to follow the square wave of 5% rich and 5% lean that lasts a certain amount of time. The rich bias stage will remove the stored oxygen of the catalyst. The lean stage will fill the catalyst with oxygen until it reaches an equilibrium oxygen storage condition. Because of the oxygen storage property, the lambda sensor downstream of the catalyst has a delay in indicating the lean condition compared with the lambda sensor upstream of the catalyst, until the catalyst is saturated with oxygen. The oxygen storage capacity of the catalyst is calculated by integrating the oxygen entering and exiting the catalyst.

The rich-lean A/F ratio is achieved via a feed-forward mechanism. Fuel duration look-up-tables targeting the desired rich and lean A/F ratios are obtained and integrated in the engine controller software to realize this operation mode. Figure 7 shows the result of this application on the test engine. The left and right banks are controlled individually. Figure 7(a) shows the control performance of 120 seconds. Each of the rich and lean stages lasts 30 seconds for a 60 seconds cycle. Figure 7(b) covers only 10 seconds to show the detail of a rich to lean transition.



(a)



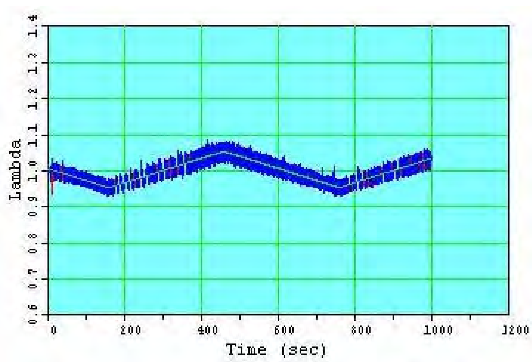
(b)

Fig. 7 Left and Right Bank Lambda Values during Rich-Lean Transition

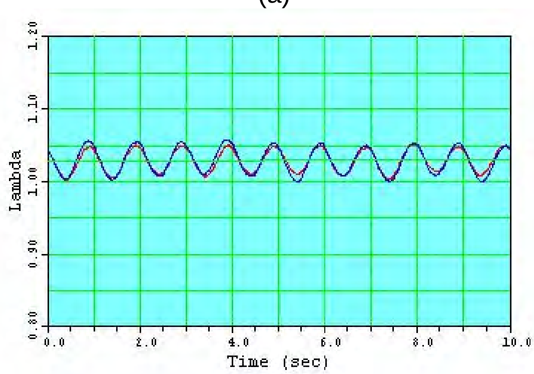
A/F Ratio Sweeping

Another operation mode that is used for oxygen storage capacity measurement is A/F ratio sweeping [4]. In this mode, the engine is controlled such that the average A/F ratio changes from rich to lean and back at a very slow rate, lasting as much as 10 minutes for the whole sweeping cycle. During this process, a much faster (1 Hz) A/F ratio modulation of certain amplitude is superimposed on the average value. Using this mechanism, the oxygen storage capacity is determined by calculating the perturbing oxygen quantity just before the break-through (the downstream A/F ratio being out of stoichiometric) occurs.

The A/F ratio sweeping mode is achieved by adopting a similar control algorithm to the steady state modulation mode shown in Figure 5. The difference is that the target average A/F ratio is not a constant in this mode, but following the very slowly changing triangle waveform. The high frequency A/F ratio modulation is still realized by modulating the base fuel width in the feed-forward path. Figure 8 shows the result of this application on the test engine. The target average A/F ratio changes between 5% rich and 5% lean, following the very slowly changing triangles. The superimposed perturbation is a 1 Hz, ±2.5% modulation. An entire sweeping cycle lasts for 10 minutes. Figure 8(a) covers about 1000 seconds and shows very clearly the control performance of following the desired average A/F ratio. Figure 8(b) covers a segment of only 10 seconds to show the detail of the 1 Hz modulation during the sweeping process. It is obvious the designed algorithm results in excellent control performance in achieving the desired A/F ratio modulation during the sweeping process.



(a)



(b)

Fig. 8 Left and Right Bank Lambda Values during A/F Ratio Sweeping and Modulation

CONCLUSION

To overcome the limitations of mass production ECU, an engine rapid control prototyping system is set up in an engine dynamometer test cell environment to fulfill the requirements for catalyst research and evaluation testing. Setting of engine operation point is performed by a real-time test cell controller. Necessary engine control functions are realized by a rapid prototyping controller, which adopts model-based engineering methodology for software development. Algorithms to realize various A/F ratio control features, including A/F ratio modulation of different frequencies and amplitudes, phase shift between banks, rich-lean transition and A/F ratio sweeping etc, are designed and implemented. UDP communication is developed for real-time command and variable exchange between the engine controller and the test cell controller. The integrated system fulfills the need of realizing various A/F ratio patterns for catalyst research and evaluation testing. Application and results of the system on a 4.6L V8 gasoline engine demonstrate the flexibility and good performance of the system.

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