15th Triennial World Congress, Barcelona, Spain

HARDWARE IN THE LOOP TESTING OF EOBD STRATEGIES

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Abstract: European regulations regarding exhaust gas emissions have constantly become more restricted in the last decades. Components of the exhaust gas after-treatment system and ECU strategies have become correspondingly more complicated in order to fulfil the prescribed limits. This paper describes how a real time HIL engine simulator can be used to test EOBD ECU strategies, in order to reduce the amount of costly experimental tests. Strategies for the exhaust gas after-treatment system have been tested on HIL. The results of the tests show the feasibility of HIL testing of EOBD strategies. *Copyright © 2002 IFAC*

Keywords: Automotive emissions, Fault diagnosis, Tests, Hardware in the Loop, Computer aided testing.

1. INTRODUCTION

European regulations regarding exhaust gas emissions (EOBD, European On Board Diagnosis) have constantly become more restricted in the last decades. Components of the exhaust gas after-treatment system and (Electronic Control Unit) ECU strategies have become correspondingly more complicated in order to fulfil the prescribed limits.

Development and calibration of the system therefore requires a more accurate tuning within the imposed constraints of costs and time to market.

New development methods, exploiting the increased computing power of current computers, are becoming more and more important. The methods are based on the use of simulation models of the system, in order to predict since the early phase of the project any problem that could arise later on. Among the simulation methods, one that is showing very useful is Hardware In the Loop (HIL) testing, where a computer with a real time simulation model of the engine and vehicle system is connected to a real ECU, in order to test the final embedded software.

Benefits of such approach are: reduction of experimental costs, reproducible experiments, flexibility in vehicle and engine configuration, possibility of concurrent design of the engine, transmission and vehicle, thus providing an optimised development process.

This paper describes how a real time HIL engine simulator can be used to test EOBD ECU strategies, in order to reduce the amount of costly experimental tests.

The engine simulator interfaces to ECU and includes models of the main dynamics of engine, transmission and vehicle. The engine model is a semi-physical engine model with instantaneous torque calculation per cylinder, synchronous to the crankshaft angle.

A detailed model of the exhaust gas after-treatment system has been included in order to allow realistic tests and tuning of the EOBD strategies for this system (TWC and lambda sensor EOBD).

Tracking of the prescribed speed profile of the European regulatory tests for EOBD strategies as been ensured by including a proper driver model into the simulation environment, and a test automation procedure has been designed.

With the above set-up, fast and reliable simulation of the tests has been done under various conditions, representing good and bad behaviours of the exhaust gas after-treatment system. The results of the tests show the feasibility of HIL testing of EOBD strategies.

2. ON BOARD DIAGNOSIS

On board diagnosis of components and functions of the emission control system is required by environment protection legislation. Any fault or malfunction which can lead to exceed emissions limits has to be stored in the ECU and a MIL should be switched on. A very high reliability of the EOBD tests is needed and particular care should be given to setting proper thresholds for failures detection. Indeed too stringent limits would cause unnecessary maintenance costs, while too soft ones can lead to costly field recall, if violation of emission limits is detected without fault indication.

European regulations regarding OBD (EOBD) impose, among others, a monitoring of the correct behaviour of oxygen sensor and catalyst. A specific driving cycle, NEDC, is prescribed by regulations, where emissions have to be measured, and compared with respect to given limits. Any violation of the limits should be indicated by the illumination of the MIL, to be commanded by the diagnosis strategy. Several indices are computed within the ECU, which are related to the functioning of oxygen sensor and catalyst. These indices are used the decide if the MIL should be switched on.

A correlation between components parameters, for example the oxygen storage capacity of the TWC, and resulting emissions can be obtained through a test campaign. On the other hand these parameters can be correlated to the degradation indices and an optimisation of the OBD strategy and parameters can be done in HIL tests.

In the following sections we first present the HIL experimental set-up and the simulation models of the TWC and oxygen sensor which allow to include the degradation of the components, then the results of the HIL tests will be presented and discussed.

3. HARDWARE IN THE LOOP

The hardware used for the HIL testing consists mainly of a computer with the GUI software, two dSPACE boards and a remote-controlled power supply (battery simulation). The DS1005 PPC board is a PowerPC-based processor with a floating-point PowerPC 750, where integration of system dimacis in performed in real time, with a capability better than 0.2ms frame step-sizes. The DS2210 HIL I/O is a compact I/O hardware that was developed especially for HIL signal generation and measurement. This board generates and measures all typical I/O signals for engines and contains the signal conditioning for automotive signal levels. Specially via the Angular Processing Unit (APU) the board provides crankshaft and camshaft sensor simulation with true angular phase accumulator. The engine speed can be changed each 1μs, with a continuous speed range from 0 to 29000 RPM in 0.9 RPM steps with 8192 crankshaft/camshaft wave samples per 720° engine cycle and a resolution better then 0.1°. This board also provides knock signal generation, ignition-injection angle and time measurement.

For hardware-in-the-loop simulation with dSPACE Simulator we use completely parameterizable real-time models to model the real environment. The main model is en-DYNA, a physical Simulink model for internal combustion engines. In this model, by Tesis-Dynaware, the combustion torque is calculated separately for each cylinder in synchronicity with the crankshaft via semi-physical models and engine friction and pumping torque are included; moreover a drive line model is included. We validated the model behaviour in steady state, as shown in Fig. 1, and during fast transients for the FIAT engine named FIRE 1.2 8v and 16v.

In order to test the TWC and lambda sensor models we developed a new driver model to follow the NEDC. The driver consists of a PI controller with anti wind-up and a feed-forward action (wind, rolling and climbing resistance and vehicle dynamic), with the actual vehicle speed as input and the braking force and the throttle angle as actuation; the fine calibration of the driver model led to a smooth actuation resulting into a good tracking of the NEDC speed profile with no chattering of the actuation variables at steady states, which is a necessary condition for the diagnosis to be enabled.

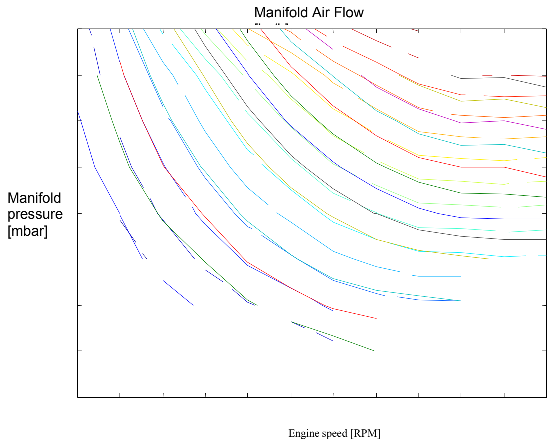

Figure 1: En-DYNA model behaviour in steady state.

4. LAMBDA SENSOR MODEL

The inputs to the model are the oxygen concentration index, the gas temperature at the sensor location, and the air mass flow rate. The model includes the static characteristic of the sensor, relating the oxygen concentration index to the sensor voltage, plus a delay time and a first order filter, both having different parameter values for the lean to rich and rich to lean switching.

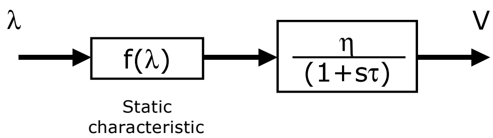

Figure 2: Lambda sensor block diagram mode

The equations (Fiengo*, et al., 2000*) describing the lambda sensor model are

$$\dot{V} = \begin{cases} -\dfrac{1}{\tau_{rich}(A)}\left(V - \eta f(\lambda_{US})\right) & \lambda_{US} < 1 \\ -\dfrac{1}{\tau_{lean}(A)}\left(V - \eta f(\lambda_{US})\right) & \lambda_{US} \geq 1 \end{cases}$$

$$\eta = \begin{cases} 1 & , T_{gas} < T_{thr} \\ \dfrac{T_{thr}}{T_{gas}} & , T_{gas} \in \left[T_{thr}, \dfrac{T_{thr}}{\eta_{\min}}\right] \\ \eta_{\min} & T_{gas} > \dfrac{T_{thr}}{\eta_{\min}} \end{cases}$$

The temperature input is included in order to take into account the thermal effects on the static characteristic of the sensor.

5. TWC MODEL

The TWC model (Vittorio Cioffi*, et al*., 2001), is composed of the following subsystems: the oxygen storage dynamics, the thermal dynamics, and the chemical reactions. The Oxygen Storage Capacity (OSC) makes oxidation and reduction reactions possible in the TWC, according to the composition of the incoming flow, and represents a fundamental component of the TWC behaviour. The OSC strongly influences the composition of the downstream flow, which is sensed by the lambda sensor and used as an index of the TWC state by the AFR control strategy. Therefore a model of the TWC must take into account this phenomenon. The thermal dynamics strongly influence the speed of reactions and should be correspondingly taken into account.

This paper presents the models of the oxygen storage and of the thermal dynamics.

The OSC model is a modified version of the model presented in (Brandt, E. P., *et al*., 1997), including the effect of temperature on the probability of reaction.

Let $0 \leq \theta \leq 1$ be the fraction of oxygen sites occupied in the catalyst. The oxygen storage capacity is modelled as a limited integrator in the following way:

$$\dot{\theta} = \begin{cases} \dfrac{1}{C}\left(1 - \dfrac{1}{\lambda_{US}}\right) \times A \times 0.23 \times \rho(\lambda_{US}, \theta, T_{cat}) & 0 \leq \theta \leq 1 \\ 0 & \text{otherwise} \end{cases}$$

with

$$\rho(\lambda_{US}, \theta, T_{cat}) = \begin{cases} \alpha_L(T_{cat}) f_L(\theta) & \lambda_{US} > 1 \\ \alpha_R(T_{cat}) f_R(\theta) & \lambda_{US} < 1 \end{cases}$$

$0 \leq f_L \leq 1$ representing the probability of an oxygen atom from the gas sticking to a site in the catalyst, and $0 \leq f_R \leq 1$ representing the probability of an oxygen atom being released from the catalyst and recombining with the gas. f_L and f_R vary with the relative oxygen storage, f_L is monotonically decreasing, with value one at $\theta=0$ and zero at $\theta=1$, f_R is assumed to be monotonically increasing with value zero at $\theta=0$ and one at $\theta=1$. The values α_L α_R represent the fact that the oxygen storage speed in the adsorption and in the release is asymmetric.

The resulting downstream oxygen concentration index can be computed as:

$$\lambda_{DS} = \lambda_{US} - (\lambda_{US} - 1) \times \rho(\lambda_{US}, \theta, T_{cat})$$

The above model has $\lambda_{DS} = \lambda_{US}$ when the TWC is fully empty or saturated, while in reality this is not completely true, due to secondary chemical effects (i.e. minimal oxygen fraction and sulphur poisoning) (Jones, J.C., *et al*., 2000). This has been taken into account by the introduction of an air mass dependent first order filter

$$\dot{\lambda}_{DSfilt} = -\frac{\lambda_{DSfilt}}{\tau(A)} + \frac{K(A)}{\tau(A)}\lambda_{DS}$$

The above model is only valid during the normal running, after the TWC light-off, while a different model has to be used during the warm-up phase

$$\dot{\lambda}_{DS_0} = -\frac{1}{\tau(T_{cat})} \times \lambda_{DS_0} + \frac{K_{warm}}{\tau(T_{cat})} \times \lambda_{US}$$

$$\lambda_{DS}(t) = \lambda_{DS_0}(t + \Delta)$$

$$where\ :$$

$$\tau(T_{cat}) = a + b \times T_{cat} + c \times T_{cat}^{\ 2}$$

$$\Delta = d + \frac{c}{T_{cat}}$$

Indeed during the warm-up the TWC is inactive, and the output of the TWC is equal to the input, with a transport delay depending on the catalyst temperature. The filter time constant increases with the catalyst temperature because this activates the chemical reactions that cause the filtering effect of TWC of the oxygen concentration oscillations.

The catalyst temperature model is a first order filter, whose input is a polynomial function of the gas temperature, with different coefficients before and after the light-off

$$\dot{T}_{cat} = \begin{cases} -\dfrac{1}{\tau_{catw}} \times T_{cat} + \dfrac{K_{catw}}{\tau_{catw}} \times \left(T_{gas} + T_{gas}^2\right) & T_{gas} < T_{lo} \\ -\dfrac{1}{\tau_{cataw}} \times T_{cat} + \dfrac{K_{cataw}}{\tau_{cataw}} \times \left(T_{gas} + T_{react}\right) & T_{gas} \geq T_{lo} \end{cases}$$

where T_{react} is an experimentally identified constant, taking into account the thermal energy produced in the HC and CO chemical reactions. The identification of the TWC model has been performed in two phases, one for the warm-up, the second for the normal running.

6. HIL EXPERIMENTAL RESULTS

The results of HIL tests are presented in the following figures. In Figure 3 the velocity profile of the NEDC is given, together with the velocity profile realised with the designed driver controller. As seen in Fig. 3 the two profiles match exactly. In simulation the diagnosis activation time is the same than on the bench. As an example of the controller action the throttle angle profile is given in Fig. 4 for the fourth urban part of the NEDC. The profile is very smooth and similar to what would be realised by a human driver. The temperatures of TWC, gas and coolant during the NEDC are given in Fig. 5. The voltage outputs of the two oxygen sensors models are presented in Fig. 6 and 7 for a good and a degraded TWC respectively. Fig. 8 shows the value of the TWC diagnosis index in ten diagnosis points. The index scale is percentage rating of TWC behaviour with 100 being a good TWC. These values are obtained using TWC parameters characteristics of a good TWC, and repeating four times the NEDC. The threshold for declaring a good TWC is well below the obtained values. The figure shows the good repeatability of the test results. Then parameters identified on a degraded TWC have been substituted into the TWC model, and the simulation has been repeated. In this case the index is zero, which confirms the success of the HIL test of TWC EOBD diagnosis.

In Fig. 9 the oxygen sensor static characteristic is shown both for an efficient sensor and a degraded one which is supposed to be poisoned by the lead. Also in this case the O_2 sensor diagnosis is active in all of the steady state conditions of the NEDC. In Fig. 10 the voltage outputs of the two oxygen sensors are shown together with the actual λ. The O_2 sensor US is shifted to lean conditions due to the new degraded static characteristic. The control system recognises the O_2 sensor US malfunctioning and maintains the A/F ratio close to its stoichometric value, but slightly lean. The catalyst becomes close to the oxygen saturation and so some oxygen is present close to the O_2 sensor DS. This leads the low voltage values of the O_2 sensor DS.

In Fig. 11 the sensor time response is slow to recognise the rich and lean condition that leads to have a pollution increase. This malfunction has to be recognised by the ECU so when the time diagnosis is in the range and the index diagnosis is lower than threshold the fault number increases.

Relative to a rise malfunction in Fig. 12 the O_2 sensor US has a delay to recognise the rich condition; this leads to have more HC and CO in the exhaust gas. In the fall malfunction (Fig. 13) the behaviour is opposed and this leads to have more NOx in the exhaust gas.

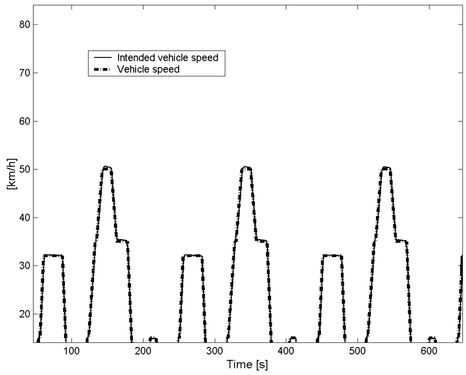

Figure 3: Velocity profile of NEDC, with TWC validation points.

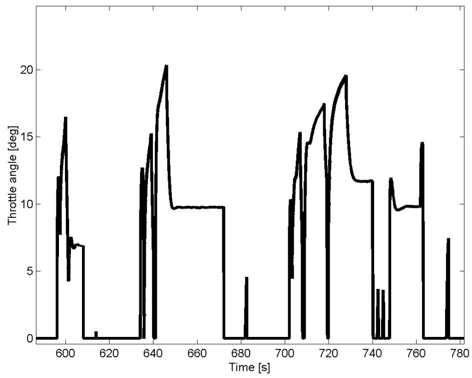

Figure 4: Throttle angle in urban part of NEDC.

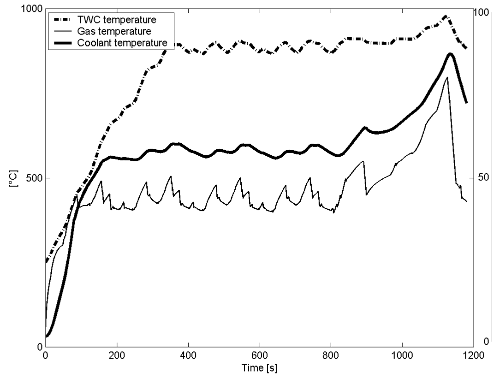

Figure 5: Temperature profiles of TWC, gas and coolant during NEDC.

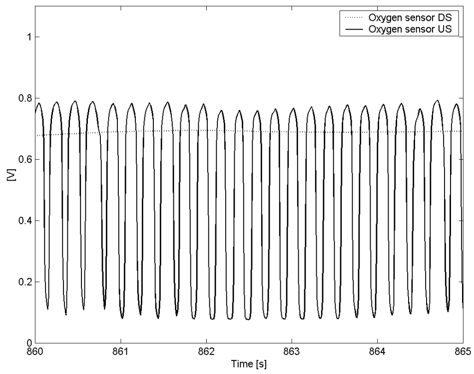

Figure 6: Oxygen sensors voltage outputs with a good TWC.

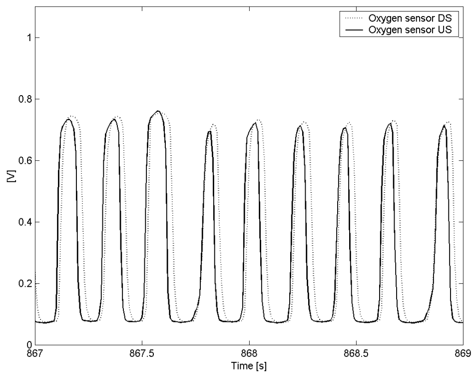

Figure 7: Oxygen sensors voltage outputs with a degraded TWC.

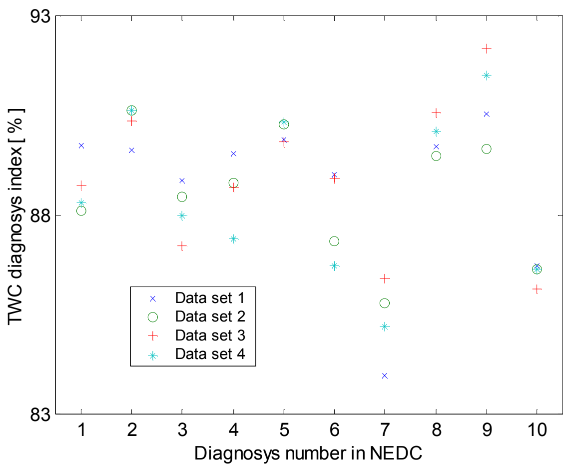

Figure 8: Validated TWC index during NEDC, with a good TWC.

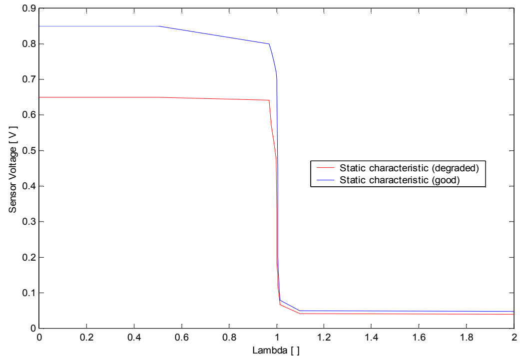

Figure 9: Oxygen sensor static characteristic: good and degraded.

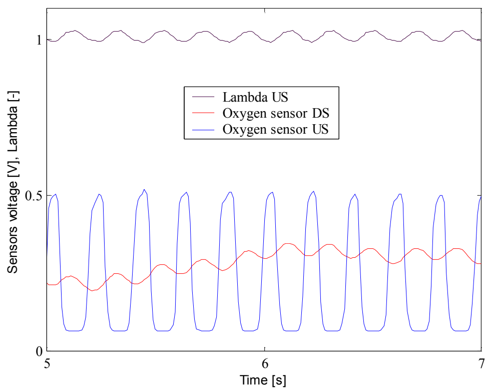

Figure 10: Oxygen sensors voltage outputs with a degraded US sensor, and actual λ.

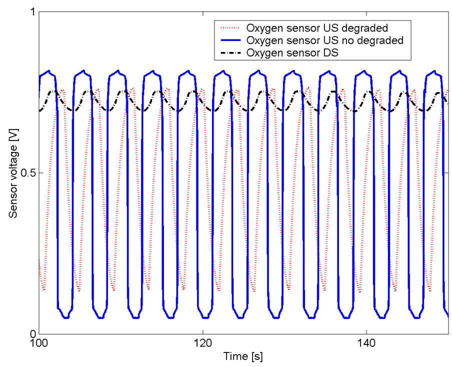

Figure 11: Oxygen sensors US frequency degraded, no degraded and DS sensor.

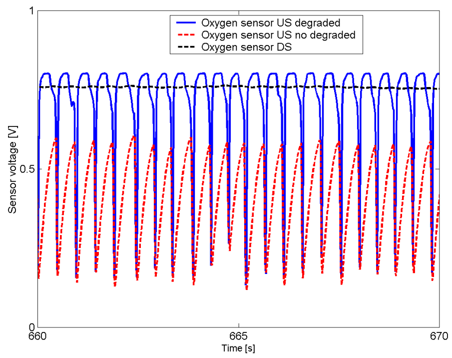

Figure 12: Oxygen sensors US rise time degraded, no degraded and DS sensor.

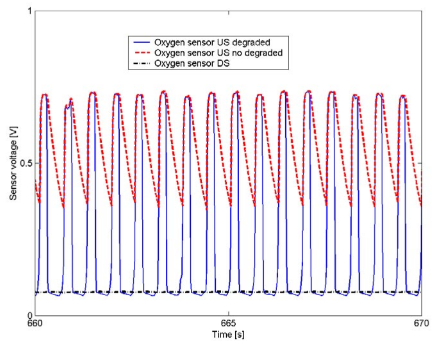

Figure 13: Oxygen sensors US fall time degraded, no degraded and DS sensor.

7. CONCLUSIONS

The use of HIL simulator for testing EOBD strategies has been demonstrated. Both TWC and O_2 sensor diagnosis have been successfully tested. The tool is now a standard one in FIAT-GM Powertrain ITALIA test procedures. Future work will address other OBD strategies.

NOMENCLATURE

T_{cat}	catalyst temperature;
K_{cataw}	gain;
T_{lo}	light-off temperature;
T_{gas}	gas temperature;
$T_{\_warmed}$	threshold gas temperature;
τ_{gas_warm}	time constant;
τ_{gas_cold}	time constant;
V	O_2 sensor voltage;
τ_{rich}	time constant O_2 sensor in rich condition;
τ_{lean}	time constant O_2 sensor in lean condition;
λ_{us}	index of oxygen concentration in the upstream exhaust flow;
λ_{ds}	index of oxygen concentration in the downstream exhaust flow;
θ	oxygen storage normalised;
A	engine air mass flow;
τ	generic time constant;
K	generic gain;
η	thermal efficiency of O_2 sensor switch;
n_E	engine speed;
UD	Up Stream
DS	Down Stream
EOBD	European On Board Diagnosis
NEDC	New European Driving Cycle
TWC	Three Way Converter
HIL	Hardware In the Loop
MIL	Malfunction Identification Lamp

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