Virtual Sensors for Diesel Engine and After-treatment Management

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Magneti Marelli S.p.A. - Powertrain

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Company Overview
Magneti Marelli Powertrain (Diesel) System
Standard Emission trend and technologies
O2 intake Virtual Sensor for Diesel engine management
NOx Virtual Sensor for after-treatment management
NOx Virtual Sensor adaptivity concepts
Conclusions
Company Overview

Magneti Marelli is an international company committed to the design and production of hi-tech systems and components for the automotive sector.
Magneti Marelli Worldwide Presence

| Sales 2015 | 7.3 bn € |
| R&D Centers | 12 |
| R&D (of sales) | 4.6% |
| Production units | 89 |
| Application Centers | 30 |
| Investments (of sales) | 5.7% |
| Employees | 40,418 |
Magneti Marelli Powertrain Worldwide Presence

**Sales 2015** 919 mio €
**R&D Centers** 4
**R&D*** 5.7%
**Employees worldwide** 5,293

**Production units** 15
**Application Centers** 9
**Investments*** 13.7%

* % of “make” sales
Customer Brand Portfolio

[Diagram showing various brand logos around the world]
Magneti Marelli Powertrain – Diesel Systems

CONTROL SYSTEMS
- ECU
- Controls & SW
- Engine Management Calibration
- Combustion Models & Spray targeting

SENSORS
- Smart Sensors

Hybrid Impulsion
- Motor-Generator
- Power Inverter

Transmission
- AMT
- DCT

Components for SCR/SCRoF System

ACTUATORS
- Throttle Body
- VGT Actuator
- Intake man. w var. Swirl Actuator
Emission Standard trend

- Euro1, Euro2, Euro3, Euro4, Euro5, Euro6b, Euro6d
- Stage I, Stage II, Stage III, Stage IV, Stage V

Other main legislation:
- Japan
- India
- Brazil
- China

Other main requirements:
- On Board Diagnostic Requirement (OBD II, EOBD)
- Fuel consumption, CO2 Reduction

Pollutant limit:
- CO, NOx, NH3, PM, SO2, Pb

PC, LDT, LCV, NRMM, HD

- Tier 0, Tier 1, Tier 2, Tier 3, Tier 4
- LEV I, LEV II, LEV III

years
Technologies for reaching the target

Two main ways for NOx reduction on Diesel Engine

- NOx Engine Out reduction → Combustion improvement (e.g. EGR HP, EGR LP)
- After-treatment technologies (e.g. LNT, SCR, SCRonF) could be combine for reach the target

O2 Virtual Sensor

NOx Virtual Sensor
Intake O2 and NOx Virtual Sensors

- Engine parameters: rpm, SOI, AFM, m fuel
- NOx Virtual Sensor
- Intake O2
- Intake O2 estimation
- Adaptive control
- Combustion Management – EGR Control Management

Partnership with University of Salerno
Intake O2 Virtual Sensor

Purpose of intake O2 measure:

- Estimation of effective EGR ratio (e.g. EGR Valve Control Management)
- Enhancement of conventional and advanced combustion control (PCCI, HCCI, LTC)
- Improvement of NOx prediction during engine transients, suitable for both dynamic adjustments of EMS strategies and management of after-treatment devices.
MEAN VALUE MODEL

- Filling and Emptying for intake/Exhaust manifolds
- Mass and energy conservation in any control volume
- Homogeneous pressure, temperature and chemical composition in the intake manifold
- Instantaneous and perfect mixing of incoming flows
- No heat transfer through manifold walls

- Low computational demand and identification issues
- Suitable for on-board implementation
- Model accuracy fully satisfactory
Mean Value model Main equation

Oxygen mass fraction in the intake manifold

\[
\dot{O}_{2,\text{man}} = \frac{R_{\text{air}} T_{\text{man}}}{P_{\text{man}} V_{\text{man}}} \left[ (O_{2,\text{exh}} - O_{2,\text{man}}) \dot{m}_{\text{egr}} + (O_{2,\text{amb}} - O_{2,\text{man}}) \dot{m}_{\text{air}} \right]
\]

Intake manifold temperature

\[
T_{\text{man}} = \frac{R_{\text{air}} T_{\text{amb}}}{P_{\text{man}} V_{\text{man}}} \left[ (k_{\text{air}} T_{\text{egr}} - T_{\text{man}}) \dot{m}_{\text{egr}} + (k_{\text{air}} T_{\text{ic,out}} - T_{\text{man}}) \dot{m}_{\text{egr}} - (k_{\text{air}} - 1) T_{\text{man}} \dot{m}_{\text{cyl,in}} \right]
\]

Prediction of Exhaust O\textsubscript{2} concentration in place of UEGO measurement

\[
\dot{O}_{2,\text{exh}} = \frac{R_{\text{exh}} T_{\text{exh}}}{P_{\text{exh}} V_{\text{exh}}} \left[ (O_{2,\text{cyl,out}} - O_{2,\text{exh}}) \dot{m}_{\text{cyl,out}} \right]
\]

\[
O_{2,\text{cyl,out}} = \frac{\dot{m}_{\text{cyl,in}} O_{2,\text{man}} - \alpha_{\text{st}} \dot{m}_f O_{2,\text{man}}}{\dot{m}_{\text{cyl,in}} + \dot{m}_f}
\]
O2 Experimental results

Common-Rail Diesel 1.3 – EGR/HP - VGT

*O2 intake measured with O2 sensor
Common-Rail Diesel 2.3 – EGR/HP - VGT

<table>
<thead>
<tr>
<th>Engine Key characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power and Max. Torque</td>
</tr>
<tr>
<td>150Hp and 320Nm</td>
</tr>
<tr>
<td>Cylinders</td>
</tr>
<tr>
<td>4 in line</td>
</tr>
<tr>
<td>Displacement</td>
</tr>
<tr>
<td>2286 cm³</td>
</tr>
<tr>
<td>Valves per cylinder</td>
</tr>
<tr>
<td>4 (DOHC)</td>
</tr>
<tr>
<td>Combustion System</td>
</tr>
<tr>
<td>Diesel Direct Injection</td>
</tr>
<tr>
<td>Compression Ratio</td>
</tr>
<tr>
<td>19:1</td>
</tr>
<tr>
<td>Synchronisation system</td>
</tr>
<tr>
<td>• Crankshaft position sensor</td>
</tr>
<tr>
<td>• Camshaft position sensor</td>
</tr>
<tr>
<td>Fuel Injection System</td>
</tr>
<tr>
<td>Common Rail Solenoid Injectors (160 MPa)</td>
</tr>
<tr>
<td>Intake Air System</td>
</tr>
<tr>
<td>• Electrical Throttle Body actuator</td>
</tr>
<tr>
<td>• Intake manifold pressure and temperature sensor</td>
</tr>
<tr>
<td>Turbo charging System</td>
</tr>
<tr>
<td>VGT turbocharger, vacuum controlled with vacuum electro-modulator with VGT position sensor</td>
</tr>
<tr>
<td>EGR System</td>
</tr>
<tr>
<td>• DC-Motor EGR valve + position feedback</td>
</tr>
<tr>
<td>• Air Flow Meter, before Turbo-Compressor</td>
</tr>
<tr>
<td>Exhaust Gas System</td>
</tr>
<tr>
<td>• 1 linear oxygen sensor (UHEGO) in the exhaust pipe, downstream of turbine just before catalyst</td>
</tr>
<tr>
<td>After-treatment System</td>
</tr>
<tr>
<td>• Oxidant Catalyst + Diesel Particulate Filter (coated soot filter, without additive), close-coupled</td>
</tr>
<tr>
<td>• DPF Differential pressure sensor</td>
</tr>
<tr>
<td>• DPF inlet temperature sensor</td>
</tr>
</tbody>
</table>

O2 Experimental results

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### NOx Virtual Sensor

**Purpose:**
- After-Treatment Device Management (LNT, SCR, SCRoF, etc.)
- Diagnosis After-treatment system:
  - NOx Sensor diagnosis: plausibility check & functional diagnosis
Neural Network:
- Black Box Model
- Basic elements (neurons) are combined together with connections and are placed in different layers depending on the architecture
- Right inputs are fundamental for good result
- The training and validation phases are important to make more or less strong connections
- A lot of NN parameters impact the final result: number of neurons, number of layers, NN architecture, training algorithm, epoch of training, initial conditions, etc.

Recurrent Neural Network:
- The current output also depends on the previous outputs

\[
  y (t, \theta) = F \begin{bmatrix}
  y(t-1, \theta), \ldots, y(t-i, \theta), \\
  x_1(t), \ldots, x_1(t-j+1), \\
  x_2(t), \ldots, x_2(t-j+1), \\
  x_3(t), \ldots, x_3(t-j+1)
\end{bmatrix}
\]
Recurrent Neural Network training

Recurrent Neural Network

• Delay compensation from measured data

• RNN identification/ training:
  ▪ Parametric analysis and selection of the most suitable neural network structure;
  ▪ Deterministic analysis to set RNN weights initial conditions;
  ▪ RNN Pruning by means of the Optimal Brain Surgeon (OBS) algorithm.

RNN main parameters:

• N. of Layers: 3
• N. of neurons in hidden layer: 18
• N. of epoch: 80
• Lag input space: 2
• Lag output space: 2
NOx Experimental Result

Common-Rail Diesel 1.3 – EGR/HP - VGT

<table>
<thead>
<tr>
<th></th>
<th>MSE</th>
<th>R2</th>
<th>ERR.INT</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEDC</td>
<td>16,14</td>
<td>0,9746</td>
<td>0,0909</td>
</tr>
<tr>
<td>TEST</td>
<td>90,21</td>
<td>0,9756</td>
<td>0,1707</td>
</tr>
</tbody>
</table>

*NOx Engine Out measured with NOx production sensor
Recursive Least Square based Adaptation

Off/On-line parameters update (adaptivity)
- Implementation of RLS methods.
- Development of methods for neural network.

- Adaptness based on gain/offset parameter already implemented. → Low CPU load
- RNN re-training procedure → more powerful but high CPU load
Recursive Least Square based Adaptation

NOx measured, plus imposed drift of -30%.
Conclusion

• Emissions standard trend requests strict pollutant limit
• Engine Management System and after-treatment will be more complex and more expensive and Virtual Sensors represent a good opportunity
• O2 intake estimation with model based approach gives good result and could be implemented on ECU for real-time estimation
• NOx engine out estimation with Recurrent Neural Network also present good results with benefits on calibration effort
• Parameters update (adaptivity) is implemented with good result recovering the system dispersion
Thank You
Backup