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GT-POWER/SIMULINK SIMULATION
AS A TOOL
TO IMPROVE INDIVIDUAL CYLINDER AFR
CONTROL
IN A MULTICYLINDER S.I. ENGINE

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IN CONVENTIONAL MULTICYLINDER S.I. ENGINES, FUEL ECONOMY, EXHAUST EMISSIONS AND DRIVEABILITY COULD BE MARKEDLY IMPROVED IF AFR IMBALANCES BETWEEN DIFFERENT CYLINDERS (DUE TO THE VARIABILITY OF THE INJECTORS AND TO THE DIFFERENT BREATHING CHARACTERISTICS) WERE ELIMINATED BY INDIVIDUALLY MODIFYING FUEL-INJECTORS COMMANDS.

(data from Kainz et al., SAE 1999-01-0546)
INTRODUCTION (2)

however, because the λ sensor is exposed to an exhaust gas mixture that originates from multiple cylinders, only the average value of AFR is sensed, and usually no compensation is performed for each individual cylinder.

therefore several attempts have been made to obtain an estimation of the AFR for each cylinder by means of a single λ sensor, and universal exhaust gas oxygen (UEGO) sensors have frequently been used, instead of the conventional switching EGO sensors.
AIM OF THE WORK

BECAUSE DESIGNING AND TUNING THE CONTROL SYSTEM STILL REMAINS A TIME CONSUMING ACTIVITY, SEVERAL EFFORTS HAVE BEEN MADE TO EXPLORE WAYS THAT COULD LEAD TO SIGNIFICANT REDUCTIONS OF THE DEVELOPMENT PROCESS: IN PARTICULAR, THE USE OF NUMERICAL SIMULATION TO BUILD ENGINE MODELS BY WHICH CONTROL STRATEGIES CAN BE TESTED AND TUNED “ON A DESK” SEEMS TO BE VERY PROMISING.

THE AIM OF THIS WORK IS THEREFORE TO EVALUATE THE USE OF A COMBINED GT-POWER/SIMULINK SIMULATION AS A TOOL TO ANALYZE POSSIBLE STRATEGIES TO IMPROVE INDIVIDUAL CYLINDER AFR CONTROL IN A MULTICYLINDER S.I. ENGINE.
WORK OVERVIEW

• BUILDING A GT-POWER MODEL TO REPRODUCE AFR TRACES MEASURED BY A UEGO SENSOR IN THE EXHAUST MANIFOLD

• BUILDING A MATLAB SIMULINK MODEL OF AN OBSERVER TO ESTIMATE INDIVIDUAL AFR FROM THE “MANIFOLD” SIGNAL

• COUPLING THE TWO SUB-MODELS TO EVALUATE POSSIBLE STRATEGIES FOR INDIVIDUAL CYLINDER AFR CONTROL
### EXPERIMENTAL SET-UP

#### ENGINE CHARACTERISTICS

<table>
<thead>
<tr>
<th>TYPE</th>
<th>4 STROKE S.I. 4 CYLINDERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>BORE/STROKE</td>
<td>86.4/67.4 MM</td>
</tr>
<tr>
<td>DISPLACEMENT</td>
<td>1581 CM$^3$</td>
</tr>
<tr>
<td>COMPRESSION RATIO</td>
<td>10.5:1</td>
</tr>
<tr>
<td>MAXIMUM POWER</td>
<td>76 KW AT 5750 RPM</td>
</tr>
<tr>
<td>MAXIMUM TORQUE</td>
<td>144 NM AT 4000 RPM</td>
</tr>
<tr>
<td>FUEL METERING SYSTEM</td>
<td>MULTI-POINT ELECTRONIC INJECTION</td>
</tr>
<tr>
<td>DISTRIBUTION</td>
<td>DOHC, 4 VALVES/CYLINDER</td>
</tr>
</tbody>
</table>
EXPERIMENTAL SET-UP

PROTOTYPE EXHAUST MANIFOLD

A UEGO SENSOR WAS PLACED ON THE TOP OF THE EXHAUST MANIFOLD.

MOREOVER, TO MEASURE THE INDIVIDUAL AFR VALUES OF EACH CYLINDER DURING THE EXPERIMENTAL TESTS, FOUR ADDITIONAL UEGO SENSORS WERE PLACED IN THE PRIMARY RUNNERS.

OBVIOUSLY, ONLY THE SIGNAL MEASURED IN THE EXHAUST MANIFOLD WILL BE AVAILABLE FOR THE CONTROL SYSTEM.
EXPERIMENTAL PROCEDURE

THE EXPERIMENTAL INVESTIGATION WAS MAINLY FOCUSED ON PART-LOAD ENGINE OPERATING CONDITIONS, AND THE FOLLOWING TWO OPERATING POINTS WERE SELECTED:

“2x2” (i.e. n = 2000 rpm - bmep = 2 bar)

“3x4” (i.e. n = 3000 rpm - bmep = 4 bar)

AT EACH SELECTED ENGINE OPERATING POINT:

• THE CLOSED-LOOP AFR CONTROL WAS DISABLED

• THE FUEL MASS INJECTED INTO EACH CYLINDER WAS ADJUSTED IN ORDER TO OBTAIN A STOICHIOMETRIC AFR

• THE FUEL MASS INJECTED INTO CYLINDER #1 WAS INCREASED BY 10%, AND THE CORRESPONDING AFR VALUES MEASURED BY THE ALL THE FIVE UEGO SENSORS WERE MEASURED

• THE PROCEDURE WAS REPEATED FOR CYLINDERS #2, 3 AND 4, TO HIGHLIGHT THE CORRELATION BETWEEN THE AFR SIGNAL DETECTED BY THE UEGO SENSOR PLACED IN THE EXHAUST MANIFOLD AND THE INDIVIDUAL AFR VALUE OF EACH CYLINDER
EXPERIMENTAL DATA FOR MODEL VALIDATION

n = 2000 rpm - bmep = 2 bar

cyl.#1 $\lambda=0.9$, cyl. #2,3,4 $\lambda\approx1$

166 consecutive engine cycles

---

**AFR**

UEGO 1

UEGO 2

UEGO 3

UEGO 4

UEGO man.
EXPERIMENTAL DATA FOR MODEL VALIDATION

n = 2000 rpm - bmep = 2 bar

cyl.#1 $\lambda \approx 0.9$, cyl. #2,3,4 $\lambda \approx 1$

10 consecutive engine cycles

AFR

UEGO 1
UEGO 2
UEGO 3
UEGO 4
UEGO man.
EXPERIMENTAL DATA FOR MODEL VALIDATION

n = 2000 rpm - bmep = 2 bar

cyl.#1 $\lambda \approx 0.9$, cyl. #2,3,4 $\lambda \approx 1$

“ensemble average” over an engine cycle
EXPERIMENTAL DATA FOR MODEL VALIDATION

n = 2000 rpm - bmep = 2 bar

cyl. #2 $\lambda \approx 0.9$, cyl. #1,3,4 $\lambda \approx 1$

“ensemble average” over an engine cycle
ENGINE SIMULATION MODEL

COMPUTER SIMULATIONS WERE CARRIED OUT USING GT-POWER, WHICH WAS LINKED TO MATLAB-SIMULINK FOR THE ANALYSIS OF THE INJECTION CONTROL SYSTEM.

IN A GT-POWER MODEL DIFFERENT FUEL QUANTITIES CAN BE INJECTED IN EACH ENGINE CYLINDER, AND THUS THE EXPERIMENTAL TESTS CAN BE REPRODUCED CLOSELY.

MOREOVER, PID CONTROLLERS AND OTHER CONTROL TOOLS CAN BE IMPLEMENTED DIRECTLY IN THE GT-POWER MODEL.
ENGINE SIMULATION MODEL

A careful study of the scheme adopted for the manifold junction was required: the junction was divided in sub-volumes trying to reproduce, as close as possible, the different flow patterns followed by the exhaust gases inside the manifold.

Nevertheless, the gas mixing processes that occur in the manifold junction can hardly be fully captured by a one-dimensional code, and would therefore require a 3-D modeling of the manifold junction.
COMPARISON BETWEEN SIMULATED AND MEASURED AFR VALUES (WITH GT-POWER STANDARD AFR SENSOR)

n = 2000 rpm, bmep = 2 bar

cil. # 1 $\lambda \approx 0.9$, cil. # 2,3,4 $\lambda \approx 1$
UEGO SENSOR DYNAMIC BEHAVIOR

THE AFR VALUES MEASURED BY THE UEGO SENSORS DO NOT CORRESPOND TO THE “REAL” AFR VALUES, BECAUSE OF THE LIMITED BANDWIDTH OF THE SENSOR: ACTUALLY A UEGO SENSOR CAN BE REPRESENTED BY A FIRST ORDER SYSTEM, WITH A TIME CONSTANT $\tau$ WHICH IS USUALLY BETWEEN 30 AND 50 ms.


IN ORDER TO EVALUATE THE TIME CONSTANT $\tau$ AND THE DELAY OF THE UEGO SENSORS, FURTHER EXPERIMENTAL TESTS HAVE THEREFORE BEEN PERFORMED, TRYING TO PRODUCE A STEP VARIATION IN THE AFR, BY DELIBERATELY CAUSING A MISFIRE IN ONE CYLINDER.

UEGO SENSOR DYNAMIC BEHAVIOR

AFR

0 200 400 600 800 1000 t [ms]

ref. TDC

UEGO man.

init.
COMPARISON BETWEEN SIMULATED AND MEASURED AFR VALUES (WITH UEGO MODEL)

\[ n = 2000 \text{ rpm}, \ \text{bmep} = 2 \text{ bar} \]
\[ \text{cil. # 1 } \lambda \approx 0.9, \ \text{cil. # 2,3,4 } \lambda \approx 1 \]
COMPARISON BETWEEN SIMULATED AND MEASURED AFR VALUES (WITH UEGO MODEL)

\[ n = 2000 \text{ rpm, bmep} = 2 \text{ bar} \]
\[ \text{cil. # 2 } \lambda \approx 0.9, \text{ cil. # 1,3,4 } \lambda \approx 1 \]
COMPARISON BETWEEN SIMULATED AND MEASURED AFR VALUES
(WITH UEGO MODEL)

\[ n = 3000 \text{ rpm, bmep} = 4 \text{ bar} \]

cil. # 1 \( \lambda \approx 0.9 \), cil. # 2,3,4 \( \lambda \approx 1 \)
COMPARISON BETWEEN SIMULATED AND MEASURED AFR VALUES
(WITH UEGO MODEL)

n = 3000 rpm, bmep = 4 bar
cil. # 2 $\lambda \approx 0.9$, cil. # 1,3,4 $\lambda \approx 1$
ESTIMATION OF THE AFR VALUE OF EACH CYLINDER FROM THE AFR VALUE MEASURED IN THE EXHAUST MANIFOLD

SEVERAL METHODS HAVE BEEN PROPOSED IN LITERATURE TO ESTIMATE THE INDIVIDUAL CYLINDER AFR FROM THE “MANIFOLD” SIGNAL: IN THIS WORK THE APPROACH FOLLOWED BY Hasagawa et al. (SAE 940376) WAS CHOSEN.

ACCORDING TO THE OBSERVER THEORY, THE AFR VALUE FOR EACH CYLINDER CAN BE DETERMINED FROM THE ACTUAL AFR VALUE MEASURED AT THE CONFLUENCE POINT AS FOLLOWS.

ASSUMING THAT AFR VALUES ARE SAMPLED AT TIME INTERVALS EQUAL TO 180 CA°, THE AFR VALUE MEASURED IN THE MANIFOLD AT INSTANT $k$ CAN BE EXPRESSED AS A WEIGHTED AVERAGE OF THE AFR VALUES OF DIFFERENT CYLINDERS, WITH WEIGHTING FACTORS DECREASING ACCORDING TO THE FIRING SEQUENCE:

$$AFR_{man} (k) = c_4 \cdot AFR_{cyl} (k) + c_3 \cdot AFR_{cyl} (k - 1) + c_2 \cdot AFR_{cyl} (k - 2) + c_1 \cdot AFR_{cyl} (k - 3)$$
ESTIMATION OF THE AFR VALUE OF EACH CYLINDER FROM THE AFR VALUE MEASURED IN THE EXHAUST MANIFOLD

THE WEIGHTING FACTORS $c_i$ CAN BE DETERMINED FROM AN EXPERIMENTAL DATA SET, AND THE EQUATION CAN BE WRITTEN IN THE FORM OF A MATRIX EQUATION:

$$AFR_{man}(k) = \begin{bmatrix} AFR_{cyl}(k) & AFR_{cyl}(k-1) & AFR_{cyl}(k-2) & AFR_{cyl}(k-3) \end{bmatrix} \begin{bmatrix} c_4 \\ c_3 \\ c_2 \\ c_1 \end{bmatrix}$$

OR, WITH A MORE COMPACT NOTATION:

$$Y(k) = C X(k)$$

AFTER A COMPLETE FIRING SEQUENCE, AT STEADY STATE OPERATING CONDITIONS:

$$AFR_{cyl}(k+1) = AFR_{cyl}(k-3)$$

OR, WITH A MORE COMPACT NOTATION:

$$X(k+1) = A X(k)$$
ESTIMATION OF THE AFR VALUE OF EACH CYLINDER FROM THE AFR VALUE MEASURED IN THE EXHAUST MANIFOLD

\[
Y(k) = C \cdot X(k)
\]

\[
X(k + 1) = A \cdot X(k)
\]

FINALLY, FROM THE OBSERVER THEORY:

\[
\hat{X}(k + 1) = A \cdot \hat{X}(k) + K \left( Y(k) - \hat{Y}(k) \right)
\]

\[
\hat{X}(k + 1) = (A - KC) \cdot \hat{X}(k) + KY(k)
\]

ONCE THE K MATRIX HAS BEEN DETERMINED, THE INTERNAL STATE VARIABLE X (i.e. THE INDIVIDUAL CYLINDER AFR) CAN BE EVALUATED FROM THE OBSERVED OUTPUT Y (i.e. THE AFR IN THE EXHAUST MANIFOLD).
ESTIMATION OF THE AFR VALUE OF EACH CYLINDER FROM THE AFR VALUE MEASURED IN THE EXHAUST MANIFOLD

\[ n = 2000 \text{ rpm}, \text{ bmep} = 2 \text{ bar} \]

\[ \text{cil.} \ #1 \lambda \approx 0.9, \text{ cil.} \ #2,3,4 \lambda \approx 1 \]
MATLAB/SIMULINK MODEL

The observer for the estimate of the AFR of each cylinder was implemented in a MATLAB/SIMULINK model, the input of which was the AFR value in the exhaust manifold simulated by the GT-Power model.
COUPLING THE TWO SUB-MODELS

OBSERVER MODEL (MATLAB/SIMULINK)

ENGINE MODEL (GT-POWER)
EXAMPLE OF INDIVIDUAL AFR CONTROL

n = 2000 rpm, pme = 2 bar

cil. 1 $\lambda \approx 0.9$, cil. 2,3,4 $\lambda \approx 1$
CONCLUSIONS

A GT-POWER ENGINE MODEL HAS BEEN EMPLOYED, IN CONJUNCTION WITH MATLAB-SIMULINK, AS A TOOL TO IMPROVE INDIVIDUAL CYLINDER AFR CONTROL IN A MULTICYLINDER S.I. ENGINE.

THE NUMERICAL SIMULATION HAS BEEN USED TO REPRODUCE A MISFUNCTION OF THE FUELLING SYSTEM, WHICH CAUSED ONE OF THE FOUR CYLINDERS TO BE FUELLED WITH AN AIR/FUEL RATIO 10% RICHER THAN THE OTHERS, AND, AFTER COMPARING THE SIMULATED UEGO RESPONSE WITH EXPERIMENTAL MEASUREMENTS, THE NUMERICAL SIMULATION HAS BEEN SHOWN TO BE RELIABLE AND HELPFUL FOR THE STUDY OF A PROPER FUEL INJECTION CONTROL STRATEGY “ON A DESK”, THUS REDUCING THE EXPERIMENTAL TESTS REQUIRED.
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