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DESIGN OF AN EXPERIMENTAL WORKBENCH FOR TESTING OF CONTROL APPROACHES ON A SPARK IGNITION COMBUSTION ENGINE

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Abstract: The following document describes a design and a build-up of a workbench dedicated for implementation of different control approaches on a four-stroke spark ignition engine. It consists of a host PC, target hardware with high computational power able to execute real-time applications for control of a combustion engine and an engine itself. Aim of this activity is to have a fully programmable control system, which offers to a user implementation of different control approaches and algorithms. This allows to unstick from the standard look-up table control of todays' engines and implement into the control advanced predictive or robust algorithms. Result of this effort should be better control of engines with increased power and decreased fuel consumption and emissions of CO, CH_x and NO_x in exhaust gasses.

Keywords: Engine control, dSpace system, RapidPro

1. INTRODUCTION

Development of combustion engines for vehicles of nowadays is mainly focused on the optimization of the combustion process. That concerns the biggest possible turn of the energy hidden in the fuel into the driving power of the engine while keeping the level of emissions as low, as possible. Speaking about spark ignition combustion engines, there are three groups of gases, causing a remarkable harm to the nature and living organisms: carbon hydrates (CH_x), carbon oxide (CO) and nitrogen oxides (NO_x) (L. Guzzella (2004)). Their acceptable (or allowed) amount in the exhaust gases is limited by international standards, which are having narrower tolerance with every release. That is creating an enormous pressure to the engine producers, who are forced to search for more and more sophisticated ways how to decrease the engine consumption and keep with the requirements of international standards.

One of the most significant invention in the field of consumption reduction is for sure introduction of the direct injection of the fuel into the combustion chamber (engine's cylinder bounded from the bottom side by a piston) and a numerical control of the combustion process by Engine Control Unit (ECU) introduced in 80's of the last century. Above listed measures decreased the fuel consumption at 20%.

2. STATE OF THE ART

2.1 *Engine Control*

Modern ECUs are controlling the combustion process based on the look-up table principle. Amount of the fuel injected into the cylinder depends on the input variables provided by motor sensors, in the simplest case motor revolutions and the motor load (determined from the position of the throttle valve situated in the air intake letting the fresh air in). Having defined a working point of the engine by these two independent variables is the ECU able to look-up into producer-predefined tables and choose the most suitable amount of the injected fuel and a correct position of the piston (in degrees before top dead center) for the ignition start. Value from that basic table can be consequently corrected by other tables taking into the account motor temperature, altitude of a car (and the change in the atmospheric pressure), voltage of a car battery, air humidity and others.

Introduced approach is based on a feedforward control applied for unstable working states of an engine – at its acceleration or deceleration (related to its revolutions). In the stable work region is activated a feedback control maintaining so called lambda ratio equal to one. The lambda ratio (Eq. 1) is the ratio of the real air mass in the cylinder related to the ideal mass of the air needed for a combustion of a fuel situated in the cylinder (Polóni (2008)):

$$\lambda = \frac{m_a}{L_{th} m_f} \tag{1}$$

where:

m_a is an air mass in a cylinder
m_f is a fuel mass in a cylinder
L_{th} is a stochiometric air/fuel mass ratio

Keeping the lambda ratio equal to one ensures the best possible catalytic reaction in the 3-way vehicle catalytic converter reducing the dangerous emissions to the possible lowest level. The lambda probe is situated in the engine exhaust duct and its working principle is based on sensing the residual oxygen amount in exhaust gases.

2.2 *Problems and Solutions*

Even though is the presented way of spark ignition engine control used in up-to-date cars it has its limitations and offers new directions for more advanced engine control. First of the problems is the look-up logic itself. The predefined table values, even in big amount, don't continually cover all possible working points of an engine and lets the ECU to interpolate among them, causing an error. The feedback control is also not used continually and a lambda probe situated in the exhaust duct works with an unwanted delay.

Solution of these negative phenomenas is an ECU of a new generation using dynamic algorithms computing a proper fuel (and air) amount for each working point, utilizing advanced robust and predictive control (see e.g. Nicolao et al. (2000), Wang et al. (2006), Manzie et al. (2002), Gorinevsky et al. (2003) and Polóni (2008)).

3. EXPERIMENTAL WORKBENCH

To start research in such a complicated field one needs sophisticated tools allowing to implement complex algorithms needing high computational force to ensure its real-time run. We have decided to implement to our experimental bench a dSpace system, usually used for HIL (hardware-in-loop) applications with attached RapidPro system (Fig. 1) dedicated especially for the engine control, which are going to be connected to a spark ignition engine. Main focus is on the creation of a fully programmable environment allowing us to reach into the motor control and add and/or change parts of a control system logic to be able to follow our target. As a software environment has been used Matlab/Simulink program offering enough flexibility through pre-programmed Simulink blocks and additional Simulink custom-made S-functions.

Fig. 1. Hardware assembly of the workbench

3.1 *dSpace*

dSpace Systems is a company providing hardware and software tools for automotive engineering, aerospace, and industrial control in the field of prototyping, model based control, simulation and calibration. As it has been already mentioned, their products are disposing huge computational power providing environment for the run of real time processes. Detailed description of dSpace modules operating in our configuration may enlighten functionality of the workbench from the point of view of the engine control, signal acquisition and generation.

`DS1005 PPC Board`
The DS1005 PPC Board (dSp) is one of dSPACE's processor boards that form the core of dSPACE's modular hardware. Processor boards provide the computing power for the real-time system and also function as interfaces to the I/O boards and the host PC. The DS1005 is the board of choice for applications with high sampling rates and a lot of I/O capacity. Great processor power plus fast access to I/O hardware with minimum latencies make dSPACE processor boards considerably faster than solutions based on commonly available PCs.

Main features:

- PowerPC 750GX, 1 GHz
- Fully programmable from Simulink®
- High-speed connection to all dSPACE I/O boards via PHS bus

`DS2202 HIL I/O Board`
The DS2202 HIL I/O Board has been designed for hardware-in-the-loop simulation in automotive applications, and is tailored to the simulation and measurement of automotive signals. The board contains signal conditioning for typical signal levels of automotive systems and supports 2-voltage systems up to 42 V. Typical use cases are body electronics, transmission, and component tests performed by automotive suppliers, or as an additional HIL I/O board in large powertrain and vehicle dynamics HIL applications.

Main features:

- I/O hardware with signal conditioning up to 42V
- 20 D/A channels and 16 A/D channels
- Up to 38 digital inputs Supports 2-voltage systems

`DS4121 ECU Interface Board`
The DS4121 provides the link between electronic control unit (ECU) or RapidPro system and a dSPACE modular system. Bypassing individual ECU algorithms and calculating them on a prototyping system is a typical application example. The connection is made via a dual-port memory plug-on device (DPMEM POD), on-chip debug interfaces like the DCI-GSI1 or an LVDS-Ethernet Link cable. Two independent ECUs can be connected to the DS4121 at the same time. This offers the flexibility to operate such things as powertrain control modules containing the engine and transmission controllers, or valve controls up to 12-cylinder engines.

Main features:

- Real-time interface to ECUs with 8-, 16- and 32-bit microprocessors
- Two LVDS channels for high-speed, low latency communication
- Standard ECU interface blockset fully integrated in MATLAB®/Simulink®

3.2 *RapidPro*

It is a sub-module of a dSpace system dedicated for the control of an ignition engine. It consists of two units:

- the Control Unit, able to handle complex I/O tasks
- the Power Unit, supporting high current signals for driving actuators

Particularly, the RapidPro module is used to acquire signals from motor sensors and to drive the motor actuators. Its functionality support the following installed modules:

- in the Control unit
  - Lambda probe module
  - Crankshaft/Camshaft signal DAq. module
  - Knock sensor signal conditioning module
- in the Power unit
  - Ignition and Lambda probe heating module
  - Injector control

The following figure (Fig. 2) shows detailed signal and current flows between the bench and the engine. More information about dSpace and RapidPro products can be found at www.dspace.com .

3.3 *Programming, User Interface, Development Software*

The dSpace system is fully programable from Simulink. The Simulink builds a real time application for the target platform DS1005 by Real Time Workshop and uploads it inhere at the same time. Communication with the running application is performed at the host computer through the Control Desk software. This software enables to create a graphic user interface (GUI) for the running application in so called Design mode and to interact with the application in the Animation mode. As an application interface (API) for programming in the Simulink serves the Real-Time-Interface (RTI) included in the Simulink as a library of blocks. During the ECU programming, represented in this case by a modular RapidPro system, it is necessary to include a hardware topology file into the Simulink model. Mentioned file includes information about the hardware topology (its structural and firmware information) available from the Configuration Desk after the hardware scan of a system.

3.4 *Engine*

For the experiment is used an engine from Skoda Fabia 1.4 16V. This is a 4-cylinder four stroke spark ignition combustion engine.

Features:

- Engine code: AUA
- Engine volume: 1390 ccm
- Number of cylinders: 4
- Number of valves: 16
- Bore x stroke: 76,5 x 75,6 mm
- Compression ratio: 10,5
- Power: 55 kW (75HP) at 5000 rpm
- Torque: 126 Nm at 3800 rpm
- Injection: multipoint, 1 injector per cylinder
- Ignition: electronic, wasted spark
- Camshaft system: DOHC
- Fuel: Natural 95

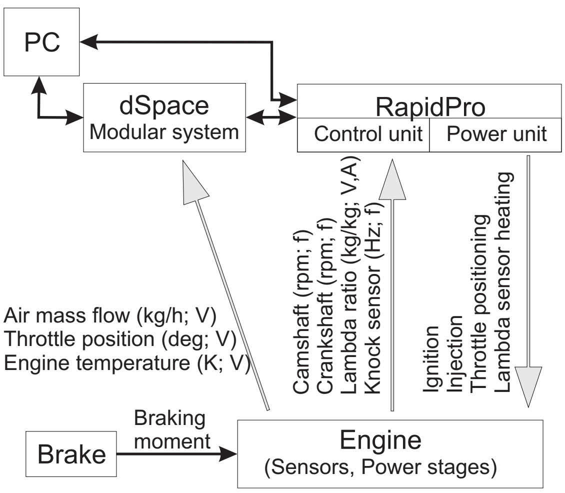

Fig. 2. Signal flow between the engine and the workbench

3.5 *Brake*

As a brake simulating the load on the motor is used dynamometer based on eddy current principle. The brake slows an object creating eddy currents through electromagnetic induction which creates resistance, and in turn either heat or electricity.

4. PROJECT STATUS

To control a combustion engine means to engage a particular activator (injector or ignition coil) in the right position. That means, a combustion engine is a task-triggered process. Tasks are in this case angle positions of the engine, or better, of the crankshaft. Motor works with a period defined through one revolution of the camshaft (360°). The crankshaft executes within this period 2 revolutions (720°) and each piston of the four stroke combustion engine executes all four strokes (intake, compression, combustion and exhaust). That is why is it crucial to know exact position of the crankshaft within the whole range of $\langle 0 \div 719.9^\circ \rangle$. This angle value gives us not only the instantaneous position of each piston, but differentiating its changing value in time determines angular velocity and acceleration/decceleration of the motor, as well. Logically it indicates, that the first stage of the project is a successful determination of the angular position of the engine.

4.1 *Determination of an angular Position of the Engine*

The RapidPro unit computes the angular position of the motor automatically from acquired signals of the crankshaft and camshaft sensors. Initial condition for unproblematic run is mutual synchronization of those signals, or so called synchronization of the angle measurement. Synchronization of the angle measurement is a process, when an angular position of 0° of the crankshaft is determined according to a specific shape and a mutual position of both - camshaft and crankshaft sensor signals. After the synchronization are all possible positions of the crankshaft known. The angle is determined with the precision of 0,1°. Sample of signals acquired from our experimental device is shown in the following figure:

From the signals can be also seen, how are the situated and distributed the marks of those shafts. Configuration of the used engine is following:

- Crankshaft: 60 marks and one gap created by 2 missing marks
- Camshaft: 3 marks (with coordinates from rising to falling edges related to revolutions

of crankshaft (in (°)): 36→102, 258→456, 576→636).

Crankshaft positioned at 0° is defined at the rising edge of the first mark of the crankshaft after the gap. The synchronization starts at the engine start and is related to this position.

It succeeds as follows:

(1) As soon as the angle computational unit (ACU) detects the gap among crankshaft marks, sets the angle counter to zero degrees. From now on starts the measurement of engine revolutions (rpm).
(2) In the step 2 are compared defined camshaft marks with a real signal. If are they identical, the ACU starts to compute the crankshaft angle, if not, to the first mark after the gap is assigned the angle of 360° and the computation starts. Having this operation completed is the synchronization done. From this moment knows the ACU exact value of the angle related to the signal shapes of the shafts. If occurs a mismatch among them, the synchronization is lost.

4.2 *Project Status and next Steps*

Angle measurement of our engine has been already experimentally tested at the workbench. Crankshaft and camshaft signals were generated by dSpace and by hardware model of an engine (Fig.4). Both are generating identical signals as the real engine.

The today's effort is to start generation of signals for ignition coils and injectors. When it works, is the next step connection of a system to the real engine.

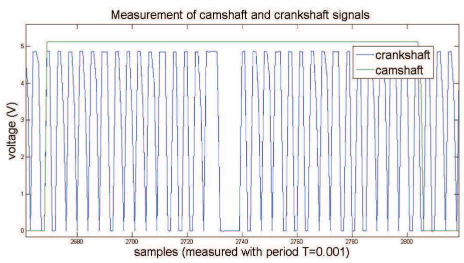

Fig. 3. Sample of camshaft and crankshaft signals

5. CONCLUSION

In this article the preliminary design of an experimental workbench for testing of advanced control algorithms for SI engines is presented. The first intended algorithms to be verified under the real-time conditions will exploit predictive and multimodel techniques developed and simulated in Polóni et al. (2007) and Polóni et al. (2008) for the air-fuel ratio control.

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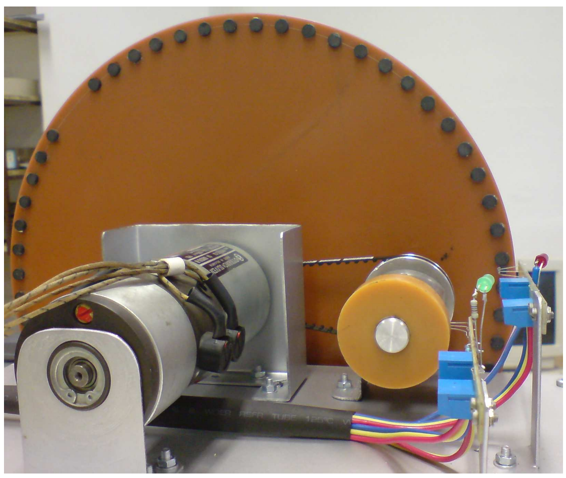

Fig. 4. Hardware simulation of crank- and camshaft signals

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