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ADAPTIVE CONTROL OF THE IDLE SPEED

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ABSTRACT

Idle speed control of an spark ignition automotive engine based on adaptive techniques has been presented. In the paper the ignition advance control was activated to stabilise the idle speed. The adaptation of the spark advance angle requires defining an adaptive coefficient, which is a compromise between operation speed and estimation accuracy. The adaptive coefficient design was evaluated through engine testing, and the performance was compared with an up-to-date tuned PID controller. The success of the adaptive controller was demonstrated in engine testing. The controller tracks not only the set point speed but also shows robustness to the load torque disturbances.

NOMENCLATURE

e – engine speed error;
k_A – adaptive coefficient;
k_p – proportional coefficient;
K_1 – auxiliary value;
l – auxiliary value;
l_1 – auxiliary value;
n – engine speed [RPM];
$\hat{n}$ – estimated engine speed [RPM];
n_0 – desirable engine speed [RPM];
P_{11} – covariance;
u – control signal value;
u_0 – initial value of control signal;
β – forgetting factor;
ν – model parameter;
ϑ – model parameter.

INTRODUCTION

The main task of a motor vehicle is to produce a driving torque required in a given moment to overcome the resistance to motion of a vehicle which moves at a given speed. Supplying power to supplementary onboard devices is another task required of an engine. These supplementary devices include those which engage an engine directly: a coolant pump, an oil pump, a hydraulic power steering pump, a pneumatic system compressor, an air-conditioning compressor and an alternator (which engage the engine mechanically– by a V-belt) and those devices which engage it indirectly (by consuming electrical power generated by an alternator). When looking at the operation of a motor engine in idle speed from the perspective of it being the source of power for a vehicle's electric systems, a systematic growth in the number of onboard devices supplied by electric energy may be noted. This means that a demand for en energy of fuel combustion, transformed by the assembly of crankshaft, pistons and connectingrods, belt drive and alternator, to electric power, is increasing. It is estimated that in the next two years, an average demand for electric power will reach the level of over two kilowatts [1, 11]. Switching on (or off) individual electric receivers is done discretely, and this fact, combined with the same nature of activating systems such as power steering or air-conditioning, results in the engine being engaged (or disengaged) with a turning moment of several Nm. In idle speed, this results in undesirable changes in the rotational speed of the engine.

During an assembly of the idle speed control system, it is necessary to take into account a number of disturbances in the control process (see Figure 1).

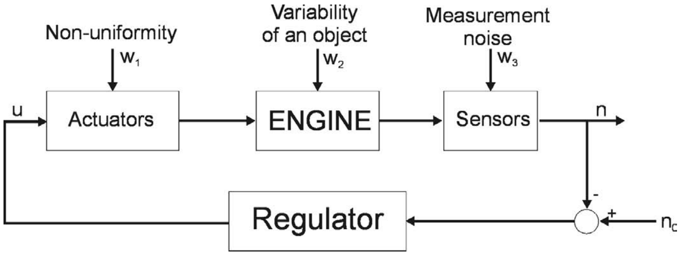

Figure 1. The system for speed control in the idle run of a combustion engine

The strategy of the idle run control is an important component of a motor engine control system, as the proportion of idle speed time in the total time of an engine's operation reaches the level of 15-20% [14]. The purpose of controlling an engine running in idle speed is to stabilise its rotational speed at a desirable level. Any oscillation in the speed of a crankshaft results in vibrations of the components of a motor-car body, resulting in a lower evaluation of the engine's quality. The objectives of reducing the emission of toxic combustion gases and the consumption of fuel in idle speed are mainly accomplished by ensuring a stoichiometric composition of the mixture by controlling petrol injection. The remaining key control variables, such as an ignition advance angle and a load mass (cylinder filling factor) are used to control the rotational speed. The most common way of changing the load mass at idle speed in modern designs of SI engines is to use a controlled air by-pass valve. Alternative methods, such as throttle control or direct control of inlet valves represent a significantly smaller proportion of the solutions offered on the market.

The methods for synthesizing the vector of control enhancement ratios for idle run speed are connected with the adopted control quality ratio. Currently used idle speed control algorithms are based on a PID controller. There are many publications discussing examples of synthesizing the parameters for such controllers [2,8,9,12]. The control systems which use the model of the condition of an object (i.e. an engine) are usually LQR (Linear Quadratic Regulator) systems, in which the quality indicator is associated with optimisation of the speed with which a value controlled returns to a desirable level [3,7,10]. The presence of disturbances in the control process (resulting from a wrong structure of the model, a non-stationary nature of an object and the measurement noise) may result in the controller being unstable. The values of control enhancements synthesized using the LQR method may be too large and result in a resonance of the rotational speed for particular ranges of interference frequencies.

Two solutions have been discussed in the literature for the problem of an impact of interference on weaker response or even a lack of stability of the controller. The first approach, namely the H_∞ method [4,7], changes the notation of the quality indicator to a form which enforces elimination of the resonance in the Bode characteristics. The second approach, namely the LQG (Linear Quadratic Gausian) control system, includes a Kalman filter which “cleanses” the rotational speed measurement from stationary interference. Both solutions continue to assume the invariability in time of the state of an object of control and the invariability in time of the controller’s structure and parameters [4,5,6].

Every control system which has been properly designed is characterised by a natural resistance to errors in the structure of an engine model and a certain natural insensitivity to changes in the characteristics of an engine. It is a positive effect of a negative feedback from the value controlled. The feedback compensates for the changes in a value controlled irrespective of their source (interference, a modelling error, a change in the characteristics of an engine). However, the ability of the feedback to compensate for an error in modelling or changes in an engine’s characteristics is limited. Its presence, when the model’s inconsistencies are significant, may negatively affect the controller’s ability to respond or even result in its instability. The only way to prevent it is to retune the controllers which is a time-consuming procedure. In the case of objects whose characteristics are quickly changing (such as a combustion engine), the new settings which have been calculated become superseded in the same moment when they are input.

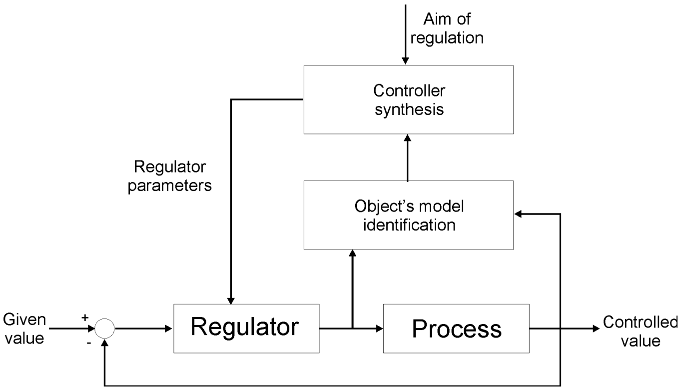

Figure 2. The system of adaptive control with indirect identification

An adaptive control represents an attempt to solve the problem of a quick retuning of the controller. It basically consists in *automatically adjusting the parameters of a controller to the changing characteristics of an object of control and its environment*, so as to ensure a higher resistance of the control system to changes [13]. For purposes of synthesizing combustion engine control systems, an adaptive control with indirect identification is used in most cases (see Figure 2).

The difficulty in estimating the parameters of an object model results from the existence of a correlation between the controlled signal and the interfering signal, an issue frequently occurring during the operation of mechanical systems. It is therefore necessary to increase the complexity of the model (approximating the model to real-life conditions), which is possible by including the previous readings of the output signal in the model. At presents, no results of any tests of adaptive controllers for the idle speed of engines with spark ignition are known. Synthesising an adaptive control system usually requires a large number of heuristic improvements in the control algorithm.

SI engine control algorithms developed by car manufacturers contain many restrictions to the movement of a by-pass valve, and thus in nearly all the cases, only ignition control is activated to stabilise the idle speed. Only in the case of larger deviations in the rotational speed, the by-pass valve is activated. The purpose of this research was to obtain understanding of how sensitive the control system is to the structure and parameters of an ignition advance angle control.

IDLE SPEED CONTROL ALGORITHM

The engine model has been represented in the following linear relationship:

$$u = k_p \cdot n \tag{1}$$

The law of control which aims to ensure that $n = n_0$ may be represented as follows:

$$u(t) = k_p(t) \cdot n_0 = k_A(t) \frac{u_0}{n_0} n_0 \tag{2}$$

and finally:

$$u(t) = k_A(t) \cdot u_0 \tag{3}$$

The purpose of the algorithm is to determine (estimate) the value of k_A ratio which ensures that a rotational speed of n_0 is being reached (see Figure 3).

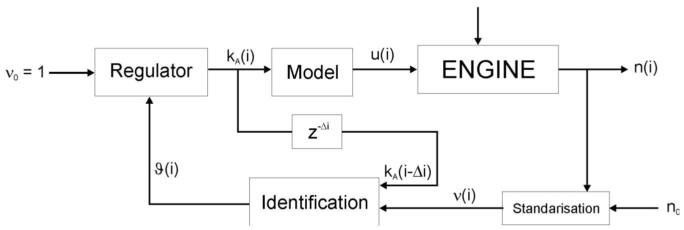

Figure 3. Adaptive control system for an spark advance angle

For such an engine model, the calculation of an adaptive control system is as follows. The control system performed its duty (control) in the prior step *i-1*:

$$u(i-1) = k_A(i-1) \cdot u_0 \tag{4}$$

The estimated resulting speed of the engine in this step should obviously equal the desirable speed:

$$\hat{n}(i) = \nu(i) \cdot n_0 = \vartheta(i-1) \cdot k_A(i-1) \cdot n_0 \tag{5}$$

Since:

$$k_A(i-1) = \frac{1}{\vartheta(i-1)}, \tag{6}$$

then

$$\hat{n}(i) = n_0 . \tag{7}$$

The value of *n(i)* is obtained from a current measurement of the speed, and a control error is calculated on its basis:

$$e = \frac{n(i) - \hat{n}(i)}{n_0} \tag{8}$$

and then, the “knowledge” of the adaptive system is being updated:

$$l_1 = P_{11}(i-1) \cdot k_A(i-1) \tag{9}$$

$$l = l_1 \cdot k_A(i-1) \tag{10}$$

$$K_1 = \frac{l_1}{\beta + l} \tag{11}$$

$$P_{11}(i) = \frac{P_{11}(i-1) - K_1 \cdot l_1}{\beta} \tag{12}$$

$$\vartheta(i) = \vartheta(i-1) - K_1 \cdot e \tag{13}$$

$$k_A(i) = \frac{1}{\vartheta(i)} \tag{14}$$

The new value for the control variable is calculated similarly as in (4):

$$u(i) = k_A(i) \cdot u_0 \tag{15}$$

For purposes of adaptive calculations, a historic value of the control variable of $k_A(i-\Delta i)$ should be used, where Δi represents a number of steps of displacement between a given control activity and its effect, i.e. the desirable rotational value. The time-lag Δi for ignition control is equal to 1, which results from the fact that the torque changes during the same cycle in which the ignition takes places, and therefore an impact of a change in the ignition advance angle will be noted in the next cycle. Adaptive control of the ignition advance angle requires that an initial value of $u_0=\Delta\alpha_{z0}$ and the value of P_{11} are determined.

TEST STAND

Tests performed to synthesize the algorithm need to ensure an ability to implement an arbitrary algorithm developed to the control system and an ability to continually and fully observe its operation. These requirements can only be met when an original controller is replaced by a customised controller. Such a system should have an ability to fully control all engine control values (all operating systems with which the engine is equipped) and to operate a larger number of measurement signals than the one resulting from the construction of an original (manufacturer’s) control system (additional sensors). Assembling a separate control system allows testing of all and any control algorithms, both in steady and unsteady states. At the same time, the controller should enable continuous monitoring and registering of all signals from sensors, control signals and internal parameters of control algorithms. This allows to subsequently visualise and analyse the results obtained. A sufficiently fast communication with a PC computer, most commonly used as a monitoring and registering system, is another requirement.

As an object of tests, an engine for a POLONEZ 1.5 GLI car, equipped by the manufacturer with a MULTEC control system (one-point injection system with an ignition system based on a DIS non-distributional ignition module) has been selected.

A universal engine controller AMX 200 CAN has been developed for purposes of testing control algorithms for a spark ignition engine. The system enables the control of an engine equipped with a one-point or multi-point injection system (up to a maximum of 4 injector groups), a DIS non-distributional ignition system and a by-pass air control system with a stepper motor. The controller can read the signals from eight onboard sensors. Installation of a CAN bus enabled the real-time control of the engine from the level of a PC computer. The main block of the controller consists of a 80C196KB processor (16 bit, working with a frequency of 12 MHz, with an 8-channel, 10 bit analogue-to-digital converter and a static RAM memory of 4 KB, with a maximum addressable memory of 16 MB). An electronic environment of the processor includes the memories RAM 62C256, EPROM 27C256 with a recorded program, a pre-programmed GAL16V8 system and a TTL system of eight terminals of the 74HCT573 line. The memory EEPROM SDA2516 is another part of the block. It is a re-programmable static memory whose cells retain previously recorded information even if the power supply is disconnected. It may be used for registering various types of configuration parameters.

The working principle of the system will therefore be based on a continuous exchange of information between the controller and the PC computer (see Figure 4). Given the fact that the control is only possible at a frequency equal to the frequency of ignition (half a turn of a crankshaft for a 4-cylinder engine), the information will be exchanged at this frequency.

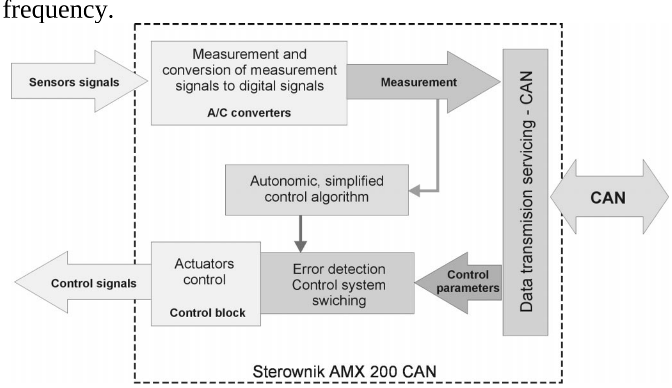

Figure 4. Flow-chart for the software of the AMX 200 CAN controller

The measurement is taken after a break from GMP has been sent by DIS. This activates the measurement of signals from all available sensors. The data obtained is then transmitted through the CAN bus to the data transmission servicing module, where it is coded and transmitted to the PC computer. On receipt of the control data from the PC computer, the transmission servicing module is decoding and transferring it to the control module. Control parameters captured are realised by the control module in the next cycle of the engine's work.

Changes in additional engagement of the engine were effected by an engaging system consisting of a group of light bulbs connected in a parallel manner with the engine's wiring system. A discrete change in the consumption of power from the wiring system results in an increased generation of power by an alternator (as a result of voltage controller operation), thus increasing the alternator's resistance. The use of bulbs allows for a stable engagement to be attached discretely, as the power consumption in bulbs does not change significantly when switching the system on and off, and at the same time, activation of a full power consumption occurs in a sufficiently short time (shorter than a single computation cycle of the control system). When analysing the results, it has been determined that the consumption of energy at the level of 150 W corresponds to an increase in the torque of the engine's resistance of approximately 2,5 Nm.

TEST RESULTS

Tests were performed for the speed of 800 rpm, in the condition of a steady state of a warm engine (the temperature of the coolant was 90^{o}C, the temperature of the lubricating oil was 92^{o}C). The initial value of the ignition advance angle was 15 deg.˙, after 40 seconds of the start of another experiment the registration of data started, after the next 40 seconds there was a discrete increase in the engagement of the crankshaft of approximately 2,5 Nm, and after yet another several seconds, additional engagement returned to the level of 0 Nm; after ca 30 seconds the registration of data was terminated. The first testing period of 40 seconds was aimed at stabilising the parameters of the adaptive algorithm. Given an impact of the non-repeatability of the tests, the experiment has been performed thrice (to enable drawing an average of the final results). Figure 5 presents examples of the progress of the spark advance control. The changes in the engagement, the control value and the rotational speed of the crankshaft can be seen in the figure. That test allows to check quality of control algorithm in stable and sudden change load conditions.

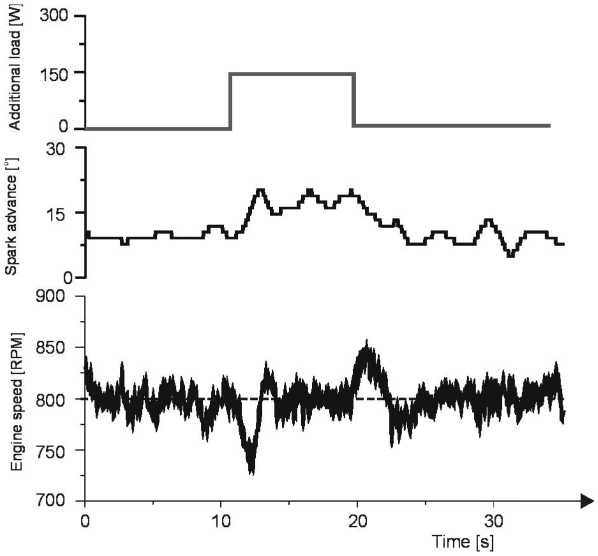

Figure 5. An example of changes in the ignition advance angle control for a PID controller

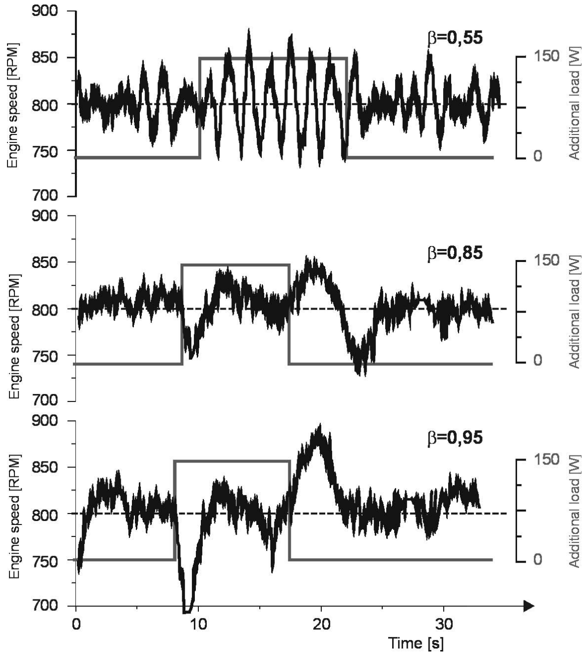

Figure 6. Changes in the rotational speed for three different β values (adaptive control of the ignition advance angle)

Graph 6 compares the changes, as a function of time, for the three values of the adaptation ratio β for ignition control. Low value of forgetting factor β allows react quickly to sudden change of load, but simultaneously causes reaction to noise – which results in unstability of engine work under stable load. High value of forgetting factor β gives noise immunity but significantly decreases time of reaction to sudden change of working conditions. Therefore, the value of forgetting factor β must be a compromise between speed and stability. Figure 7 shows the characteristics which present the impact of the β ratio on the aggregate indicator of the quality of control w:

$$w = \frac{1}{N}\sqrt{\sum_{i=0}^{N}\left(n_i - n_0\right)^2} \tag{16}$$

where:
n_i – rotational speed of the engine in an i'th performance,
n_0 –desirable rotational speed of the engine,
N – the number of measurement points taken into account in an analysis.

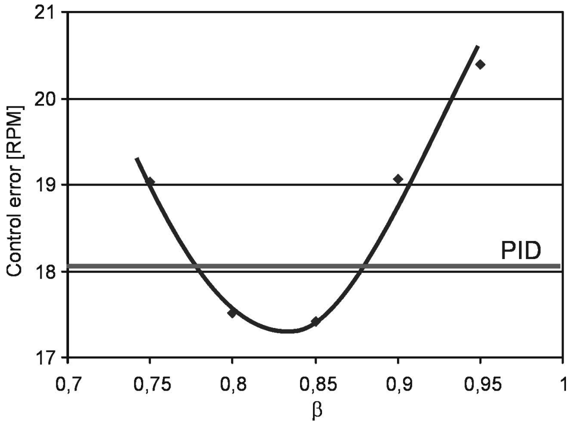

Figure 7. The impact of the adaptation ratio β on the aggregate adaptive control error. Error for an optimum PID controller is shown in the Figure

CONCLUSIONS

An argument that the control error of the idle running rotational speed control in a spark ignition engine decreases after introducing an adaptive function to the algorithm has been proved. It has been determined that there is an optimum value of an adaptation ratio β which ensures minimising the control error of the idle running rotational speed at the level lower than the level of error for an optimum PID controller.

The authors are aware of many limitations imposed arbitrarily on the scope of tests. First, only one SI engine with a one-point injection has been tested. Second, the structure of an adaptive algorithm with a linear model of an object has been extremely simplified. Nevertheless, there are clear analogies allowing to extrapolate the results presented in this dissertation to other scopes of testing. Control systems for SI engines with petrol injection always make use of the ignition advance angle control and the size of the stream of the air fed. There are phenomena common to all SI engine control systems which make it difficult to synthesise an algorithm for idle speed control: multidimensional, non-liner, cyclical, inert, non-stationary and random nature of the engine characteristics. Any differences are quantitative, and not qualitative. The structure of an adaptive controller was simplified on purpose. Since such a simple controller, armed only with an ability to learn, proved to be better than a PID controller, a more complex structure of an adaptive controller can only improve the result.

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