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DEVELOPMENT OF CONTROL SYSTEMS OF DIESEL ENGINE USING MODEL-BASED DESIGN

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ABSTRACT

Reduction of harmful emissions from road transport is highly important for modern automotive industry. Development of new power plants to reduce CO_2 *emissions during operation of vehicles formed the basic strategy for development of motor power plants proposed by NAMI. This article considers application of simulated design upon development of new diesel engine with computer simulation unit which allows to simplify development of new engine with the best ecological characteristics; the structure of computer simulation unit, the principles of its operation and the applied software are also considered. These simulation principles are supposed to be applied for internal combustion engines in motor vehicles, and in vehicle power plants in combination with traction electric drive. Matlab-Simulink-Stateflow software package was used for mathematical simulation.*

Key words: Diesel engine, electronic control system, model-based design, vehicle with computer simulation unit, hybrid vehicle, efficiency

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1. INTRODUCTION

Despite the fact that numerous combined power plants are available at present, the issues of diesel engines are still urgent [1]. Diesel engines with high environmental safety can be used in vehicles with combined power plant both as main engine and as range extender [2]. The requirements to vehicle diesel engines are stringent and stipulate common usage of antitoxic systems improving power performances and fuel efficiency, as well as application of multistage exhaust after treatment system, its components are embedded in vehicle exhaust system and provide conformity with EURO-6 regulations for harmful emissions, mainly of nitrogen oxides and carbon fine particles [3, 4]. The most important component of exhaust after treatment system is the electronic control unit (ECU) with microprocessor embedded into unified electronic diesel control system (EDCS).

Application of diesel engine in vehicle power plants in combination with electric drive does not lower these requirements [5]. In addition to the application as range extender, diesel engines can be used as independent generator for environmentally clean regions together with renewable power sources, for instance, cells of photoelectric converters [6, 7].

Power performances of diesel engine, its fuel efficiency and environmental safety are mainly determined by fuel delivery system in combination with composition and features of supplemental systems: charging system, exhaust recirculation system, filtration of solids in exhaust gases, selective catalytic reduction (SCR), and other systems [8]. Thus, the electronic control system (ECS) of vehicle engine is a set of components and units combined into a single system of EDCS operation by means of ECU or several units distributing among them certain control functions.

Testing and adjustment of prototype ECU on actual engine involves high time consumptions and expenses for highly accurate instruments in real time and data processing equipment. Therefore, the existing approaches assume application of simulation modelling.

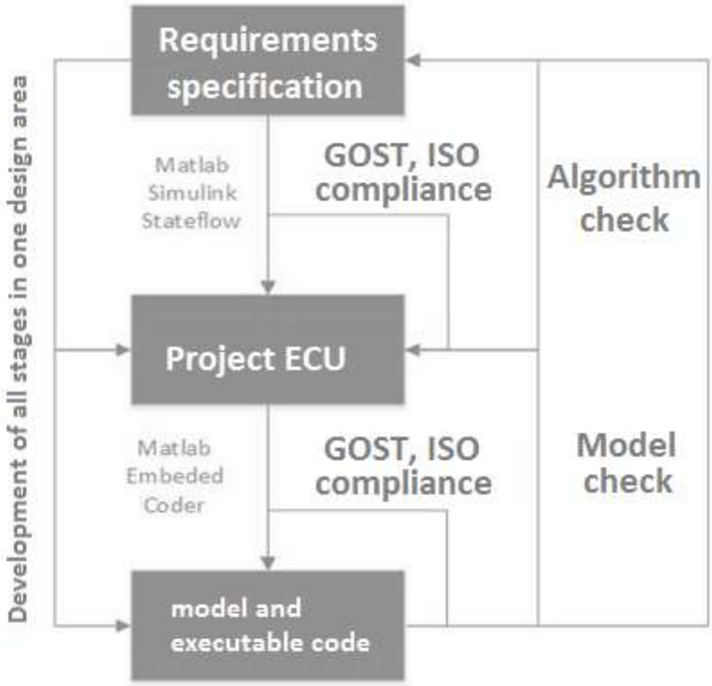

Figure 1. Model-based development

Conventional development of a new diesel engine, which is not based on simulations, would result in the following issues:

1. At the "Specifications" stage, it is difficult to determine compliance of EDCS final structure with the requirements stated in feasibility study.

2. At the "Project" stage, embedding and testing as well as manual development of software slow down the development and add undeniable influence of human factor.

3. At the "Model" and "Executable code" stages, during implementation, testing and integration of prototypes quite often issues are detected at final steps which could increase time consumption and expenses.

Model-based development (Figure 1) is a more flexible approach to perform the predefined tasks at various stages. This approach is implemented in Matlab-Simulink-Stateflow pack.

The considered in the flowchart process is characterized by the following advantages at various stages of EDCS development [9].

1. At the "Specifications" stage, complete compliance of the EDCS structure with the specifications is provided.

2. At the "Project" stage, it is possible to optimize overall EDCS by operation in unified environment and to reuse the existing models.

3. At the "Model" and "Executable code" stages, time consumptions and expenses are decreased due to semi-field tests. Code is generated automatically together with verification of model operation in real time and risk minimization of damages of expensive equipment and prototypes.

For diesel engines of medium and heavy-duty vehicles the main attention is paid to control system of selective catalytic reduction (SCR), as well as regeneration of diesel particulate filter. In this case separate ECUs are combined into a unified data system (CAN) by means of which the aforementioned control functions of diesel engine are coordinated. Efficient operation of EDCS depends on correctness of the developed control algorithm of diesel engine and its systems.

Figure 2 illustrates a variant of ECU for Russian advanced diesel engine meeting the requirements of EURO-6 regulations for harmful emissions. Such EDCS provides optimum operation efficiency of overall systems effecting diesel operation, in particular, fuel delivery at all modes of diesel operation with generation from five to seven phase and time independent pulses, efficient operation of heating plugs upon cold start and engine heating-up, protection of fuel system in emergency modes.

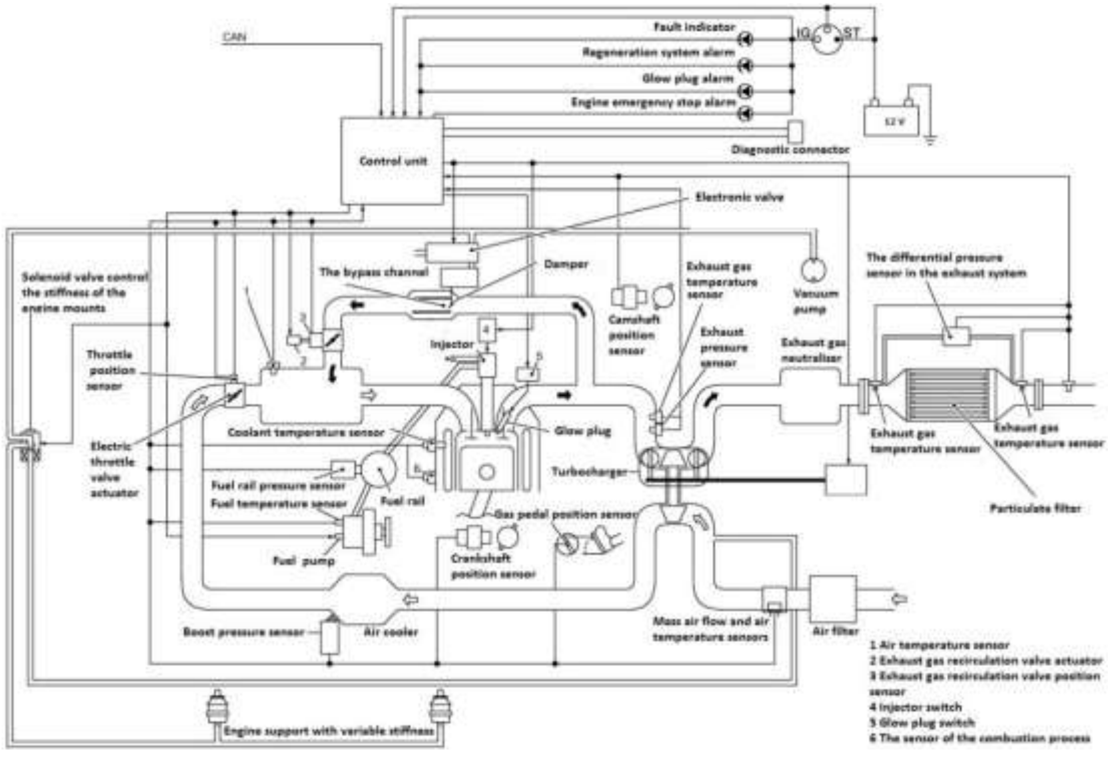

Figure 2. Control system of Russian advanced diesel engine

Therefore, upon development of ECU for Russian advanced diesel engines, it is required to describe and to formalize control functions of antitoxic systems required for fulfillment of modern technical and economical requirements including conformity with existing and scheduled regulations for harmful emissions [10].

2. METHODS

Empirical approach is used which is comprised of data acquisition, analysis, determination of hypothesis, and development of theory. In addition, the stages of simulation of fabrication of experimental samples should be included.

3. RESULTS AND DISCUSSION

3.1. Stage 1. Development of common structure and algorithms of simulation complex for testing in selected simulation environment

Development of ECU requires for significant time for designing, fabrication of prototypes, and test on real object, it is suitable only for commercial projects. Testing and tuning of ECU prototype on actual engine is also accompanied by time consumption and financing for equipment and high precision instruments for real time measurements, as well as data processing tools. Hence, modern technologies assume application of methods of rapid prototyping including the complex of simulation modelling.

Simulation modelling is the description of considered system and interaction of its certain elements in time, it should consider for the most significant interactions existing in the system. Simulation modelling is not limited by development of model and appropriate software, it requires for preparation and performance of experiment. In this regard the results of simulation modelling can be considered as valid experimental data requiring for processing and analysis. Simulation modelling should comprise the following items:

- Simulation model of diesel engine (PLANT);
- Simulation model of electronic control unit (ECU);
- Simulation model of environment (ENVIRONMENT);
- Simulation model of driver (DRIVER);

The developed algorithms should provide conformance with planned toxicity norms as well as to meet the requirements of ISO 26262 standard. The use of Model-in-the-loop (MIL) makes it possible to check and to state conformance of control system with required functional requirements at early project stages, thus obtaining confidence in operability of controller software and reducing time for calibration due to preliminary tuning using the model.

The submodel developed in NAMI on the basis of Matlab-Simulink-Stateflow software package makes it possible to modify the injection advance angle and duration of nozzle opening depending on the following parameters:

- Position of accelerator pedal;
- Engine crankshaft speed;
- Fuel pressure in the system;
- Coolant temperature.

It should be mentioned that all aforementioned models should be synchronized among themselves as well as with regard to time. Thus, it is required to develop dispatcher of modes.

Dispatcher of modes of the PLANT model can operate according to the principle of finite machine, it makes possible to synchronize the engine operation according to preset operation sequence as on actual physical object, for instance, according to ignition sequence 1-3-4-2[11,12].

Module of the dispatcher can be developed in Matlab-Simulink-Stateflow package and be comprised of a set of submodels and functions.

Each model is a virtual presentation of physical object presented as modelled analog of operation of physical object:

- Low pressure fuel pump;
- High pressure fuel pump;
- High pressure fuel battery;
- Electromagnetic nozzles;
- Fuel metering unit.

Dispatcher of modes should also coordinate models which simulate real objects of engine. The operation is activated by certain crankshaft angle. Function priority is determined by the dispatcher.

3.2. Stage 2. Main principle of testing for adjustment of the developed models

However, application of only simulation modelling cannot provide required accuracy and reliability of test results as in the case of physical experiments. This drawback can be eliminated by Hardware-in-the-loop (HIL) approach. It improves efficiency of development of new EDCS and ECU as well as algorithms of their operation, since it facilitates rapid prediction and verification of all possible physical phenomena occurring upon simulation of real diesel operation conditions and makes it possible to reproduce them as many times as necessary.

The HIL approach applies the model of controlled model and controller as existing physical analogs for implementation of EDCS. Instead of using expensive experimental equipment, the PLANT model provides all signals in real time, then they are converted into analog signals using digital-to-analog converters. Control signal is processed by analog-to-digital converter and ECU model, then it is sent again to the PLANT model [13]. The main concept of the HIL simulation is illustrated in Figure 3.

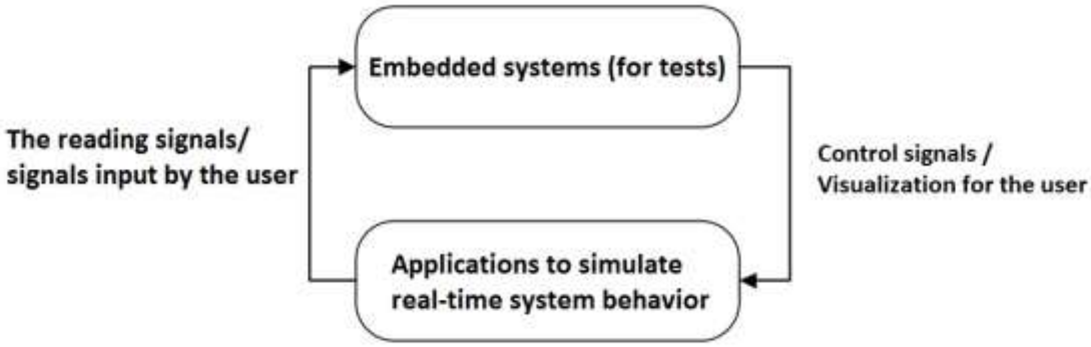

Figure 3. Main concept of HIL simulation

Using the HIL approach, it is possible to analyze operation of the controller and then to implement it in reality using microcontroller. In addition, the HIL approach makes it possible to simulate various controllable objects without additional costs.

The HIL ideology implies that a certain part of actual system is replaced with model in real time. There are many possibilities to replace actual control system by model for various situations (Figure 4).

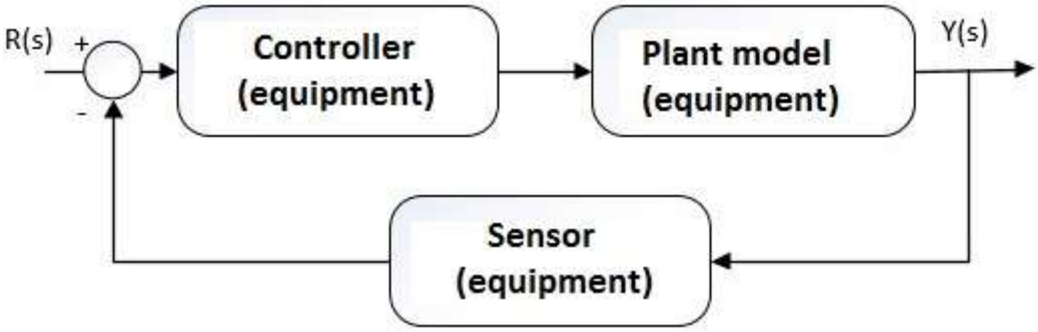

Figure 4. Classic test control

The issue of cost and experimental flexibility could be solved by supplemental hardware for process simulation. HIL based on actual replacement of models is a useful approach to solve the problems occurring in numerous experiments. The experiments with control system based on HIL are less expensive and more flexible. PLANT model in HIL approach can be readily modified since it does not require for firmware.

3.3. Stage 3. Comparison of the acquired simulation test results with experimental results.

Repeatability of test results is determined by matching degree of these results upon repetitions. While testing, the obtained results should not vary more than by 10-15%. After processing of experimental data, their analysis and comparison with numerical simulation, the model should be appropriately adjusted.

This approach makes it possible to reduce significantly the time of development and tests of software high level since it does not require for involvement of actual object. The developed model permits to reveal drawbacks upon development of diesel control algorithm at early development stage and to secure from errors which can cause faults of diesel engine and its components.

4. CONCLUSIONS

Simulated system is one of the most useful tools for embedded systems since it covers all possible simulation situations which can occur and is reproducible.

However, only simulation would not provide sufficient result of actual physical application of control theory upon solution of engineering tasks. The aforementioned drawbacks can be eliminated using the HIL approach.

Preliminary calibration of control software on the basis of simulated control processes and of diesel engine and its antitoxic devices is an efficient tool to be applied at early stages of EDCS development, which would improve the quality of developed product.

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