IOP Conf. Series: Journal of Physics: Conf. Series **783** (2017) 012043 doi:10.1088/1742-6596/783/1/012043

Multimodel Control of Diesel Engines

Silviu Cirstoiu*, Dumitru Popescu*, Catalin Dimon*, Severus Olteanu*
*Faculty of Automatic Control and Computer Science, UPB, Bucharest, Romania,
E-mails: silviu.cirstoiu@yahoo.com, popescu_upb@yahoo.com, catalin.dimon@acse.pub.ro, severus.olteanu@gmail.com

Abstract. In this article it is proposed and designed a modern control configuration of the type multicontroler-multimodel (MM) that pilots the nonlinear combustion process of the Diesel engine, needed to adjust the pressure in the intake manifold and the airflow circulating through the compressor. The MM simulator developed by the authors allows the implementation of control systems represented by pairs (Mi, Ci) with the Mi candidate closest to the current operating point of the process and the paired controller Ri, for controlling the key parameters of the combustion process. The proposed configuration is built with robust controllers and thus it is able to ensure superior performance, tolerance to nonlinearities and parametric and structural perturbations in the system.

1. Introduction

Multimodel control strategy for nonlinear systems configuration is a relatively new approach. In recent studies from the literature, increasing interest is shown towards the control of nonlinear processes with multimode operations, as diesel engines, processes that can be approximated only roughly with a single global model. The first papers that have proposed solutions and methods suitable for this type of processes, are those of Balakrishnan and Narenda the 90s [1], relying mainly on the construction of adaptive-robust systems using classical algorithms. Later detailed studies and positive results were presented by Athans [20] who employed the concept of multi model control and demonstrated the effectiveness of this approach, with the disadvantage of additional computation and implementation effort. The principle of building a MM configuration is the same, and is based on known identification procedures of Mi models and design of control algorithms Ci, the differences are mainly due to the selection mode and command algorithms interchange.

Landau and Karimi [19] use the so-called Cloe (Closed Loop Output Error) procedure, adjusting the parameters in a MM control structure [6]. Later studies have appeared on the use of neural networks and fuzzy logic systems, involved in the development of MM structures. Research by the authors have been focused on proposing and testing MM control configurations for nonlinear processes implemented on punctual applications, dedicated control parameters of the combustion process in the Diesel engines.

Following the preliminary results obtained in the paper, the proposed solution for implementing the concept appeals to a control structure (MM) in a robust version, to be tolerant to nonlinearities and disturbed regime of the diesel engine combustion.

The used management configuration contains control loops (feedback) with pairs of models having robust controllers designed for the pre-specified operating points of the nonlinear characteristic of the process, dependent mainly on the variations in the engine load and actuators behaviour.

We fix three possible operating points and for the designed (Mi, Ci), i = 1,2,3, systems, presumably linearized model Mi is disrupted in parameters and/or structure. The choice of three points was made as a consequence of the observed system behaviour. A robustness analysis of systems in closed loop is performed and the nominal command is adjusted for all the preset operating points. An adaptive strategy for MM structure occurs when the engine is about to commute between two operating points. The multi model control structure designed is shown in the following figure:

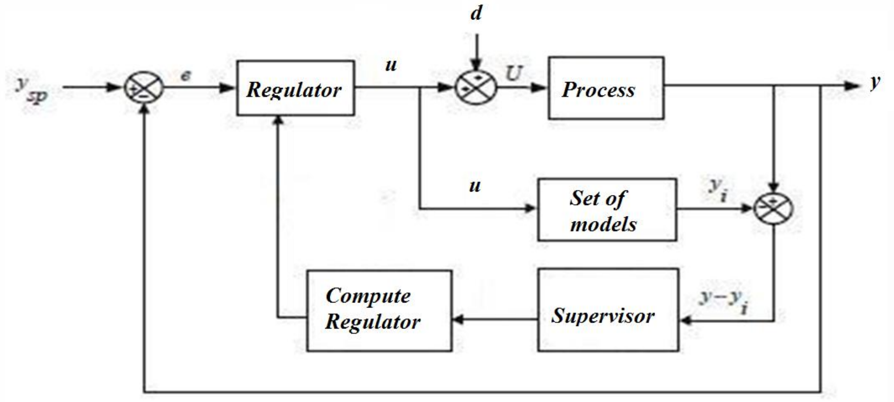

Figure 1. Multi model control structure

where,
y_{sp} – reference measure
e – the error between actual and desired output
u – command
d – disturbance
U – disturbed command
y – the controlled output of the process
y_i – i^{th} model output
$y - y_i$ – difference between process output and i model output.

The supervising module must choose the right model and control algorithm for the engine functioning point. Thus we define the model error calculated at each sampling moment, which represents the difference between output y_i and output y for the same u value of the applied command.

$$\varepsilon_i(k) = y(k) - y_i(k) \tag{1}$$

The used criteria for selection of the closest model of the current process operating point is a square criteria built with the help of the model error, as in:

$$J_i(k) = \alpha\varepsilon_i^2(k) + \beta \sum_{j-1}^{k} e^{-\lambda(k-j)}\, e_i^2(j) \tag{2}$$

where $\alpha > 0$ and $\beta > 0$ are the criteria ponderation factors, and $\gamma > 0$ is the forgiveness factor which ensures its action window limitation over the model error $\varepsilon_i(k)$.
The α, β and γ parameters choice depends on the systems' characteristics, being:

- $\alpha = 1$ and $\beta = 0$, for fast response systems:
- better performances in observing the process' changes,
- distrubances' sensibility,
- $\alpha = 0$ and $\beta = 0$, for slow response systems,
- weak performances in observing the process' changes,
- disturbances' insensibility.

We properly configured the MM structure, such that it can act on faster systems, as one can see in the case of controlling the working parameters of the diesel engine.
For each identified Mi model, a Ci regulator (controller) was computed, that meets the objectives and performance requirements; As such, we provided the set of pairs (Mi, Ci), corresponding to the possible nominal operating points Pi. For Ci control algorithms, we applied robust correction.

2. Building the MM configuration

In order to design an effective multi-model control configuration, one should consider the following issues: the inevitability of non-linear processes based on the various points of operation; the choice of the most suitable model for the dynamics of the process and the choice of algorithms respectively; the proper control for the multi-model system's commutation in order to achieve stability [8]. We represent a standard architecture for multi model configuration in Figure 2:

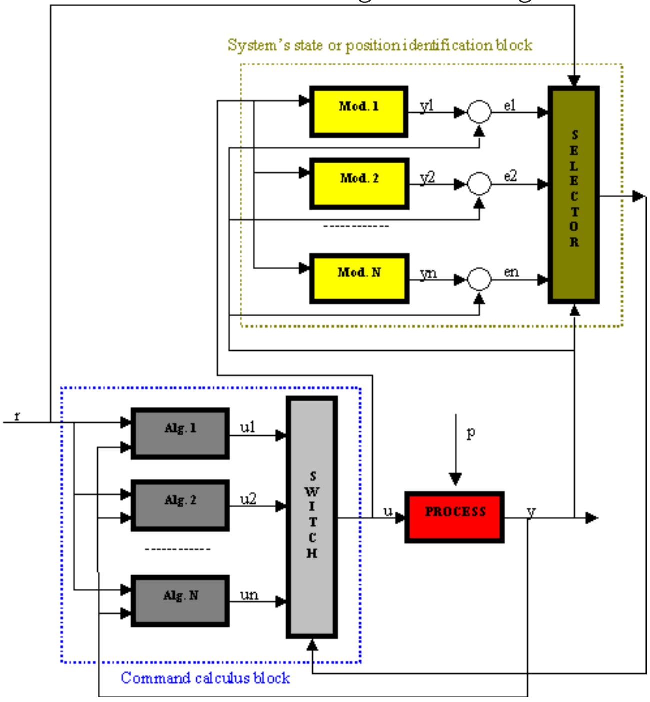

Figure 2. The classic MultiModel (MM) structure

MM framing components in Figure 2 are:
♣ PROCESS - system to be controlled;
♣ BCC - block for calculating the order;
♣ SUPERVISOR System's state - component which gives information about the best matching of operating at a time and pair model - algorithm;
♣ M1, M2, ..., Mn - models for different operating points r;
♣ C1, C2, ..., Cn - control algorithms
♣ SWITCH - switch control law;
♣ BSM - block selection most suitable model for the current state of the system based on predetermined criteria;
♣ y - process output;
♣ y_1, y_2, ..., y_N - models output;
♣ u and u_1, u_2,..., u_N - controls generated by BCC calculation block;
♣ r - reference system;
♣ p - physical disturbance process.

The overall structure can be sized according to its particularities and the system's nonlinearities. The switching is done according to procedures chosen by the reconfiguration mechanism.

After specifying the operating points and the design of the pairs (Mi, Ci), function switching control algorithms play an essential role. The issue is this: in what way and to what extent can we move from one control algorithm obtained, to another so that it preserves the stability offered by the initial performance. The novelty in this paper is given by the method used to calculate the pair (Mi, Ci) and by the approach proposed for obtaining a suitable solution for the switching operation using polynomial control algorithms of RST type.
Therefore, by selecting the most suitable model for a particular process' operating mode and by using pair adjustment mapping algorithms, one can immediately imply the requirement of switching between different selected active algorithms at a given time.
The Diesel Engine disposes of a variable geometry turbine (VGT - Variable Geometry Turbocharger), which allows efficient adaptation to the needs of the operating point of the engine equipped with exhaust gas recirculation valve, EGR (Exhaust Gas Recirculation) directing the gas flow outlet (residual) in the inlet in order to maintain a constant temperature in the combustion process. Although a technologically innovative solution, unfortunately the variable turbine geometry introduces nonlinear behaviour. Therefore, the adopted MM control design structure is justified for the control of the nonlinear regime. Thus we design the MM control solution for the key parameter: Wci airflow.

3. MM System configuration

Regarding the design of the configuration of the MM system for controlling the Wci airflow, we use the I/O model, given by the discrete transfer function:

$$Hd_{VGT-W_{ci}}(z) = \frac{0.03711*z^3-0.0785*z^2+0.09375*z+0.02185}{z^3-2.271*z^2+1.617*z-0.3458} \qquad (4)$$

The choice of the operating points was made by taking into account the actuator nonlinearity (VGT turbine xv valve opening position) that can operate through the opening in the range 0-40%, 40-60% and 60-100%. We considered a piecewise linearization around the operating points P1, P2, P3 each corresponding to the selected intervals and for each interval we associated the segment tangent to the corresponding linear model.
Under the reasoning of the previous section, we determine for each operating point, the corresponding pairs(Mi,Ci).
Using the CMMPR identification method and a sampling period Te = 0.1 sec, on the software platform Adaptech / WinPim, we obtained discrete linearized models, so that the input xv can now be adjusted to the WCI output:

M1, given by:

$$Hd_{EGR-p_i}(z) = \frac{280.8*z^3-102.9*z^2-273.6*z-99.22}{z^3-2.271*z^2+1.617*z-0.3458}$$

M2, given by:

$$Hd_{EGR-p_i}(z) = \frac{210*z^3-56.8*z^2-198.45*z-77.28}{z^3-2.271*z^2+1.617*z-0.3458}$$

M3, given by:

$$Hd_{EGR-p_i}(z) = \frac{178.5*z^3-12.7*z^2-102.33*z-24.44}{z^3-2.271*z^2+1.617*z-0.3458}$$

Next it calls for the design platform Adaptech / WinReg with pole assignment methods to calculate the RSTcontrollers.
For the first operating point, corresponding to 0-40% range, we have the following results: the controller computed with override $\xi = 0.95$ and natural pulsation $w_0 = 10.5$ rad / sec for tracking targets, respectively, $\xi= 0.95$, $w_0= 12.5$ rad/sec for setting targets, has the following components:

$$R(z^{-1}) = -1.38 - 2.98z^{-1} - 0.11z^{-2}$$

$$S(z^{-1}) = 1 - 0.96z^{-1} - 0.04z^{-2}$$
$$T(z^{-1}) = -8.45 + 4.77z^{-1} - 0.79z^{-2}$$

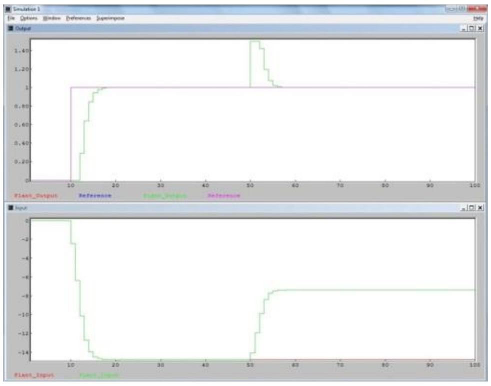

Figure 3. Nominal system response for the first operating point P1

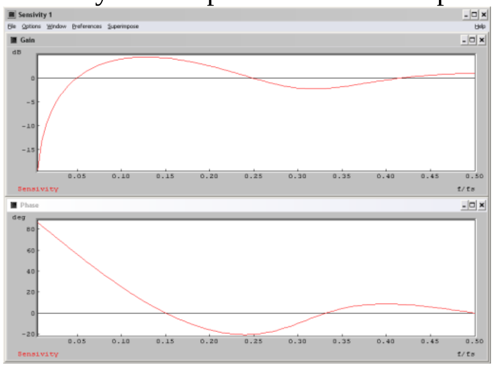

Figure 4. The sensitivity function andnthe phase characteristic of the robust system

New edge module is 0.72, which means that by introducing a pair of zeros in the polynomial S, robustness of the system was improved.

Thus, for the second operating point corresponding to the range 40-60%, we have the following results: the controller calculated similarly with $\xi = 0.95$ and $w_0 = 10.5$ rad/sec for tracking goals and $\xi = 0.95$, $w_0 = 12.5$ rad/sec for setting goals, has the following components:

$$R(z^{-1}) = -1.37 - 2.97z^{-1} - 1.09z^{-2}$$

$$S(z^{-1}) = 1 - 0.96z^{-1} - 0.037z^{-1}$$

$$T(z^{-1}) = -8.42 + 4.75z^{-1} - 0.78z^{-2}$$

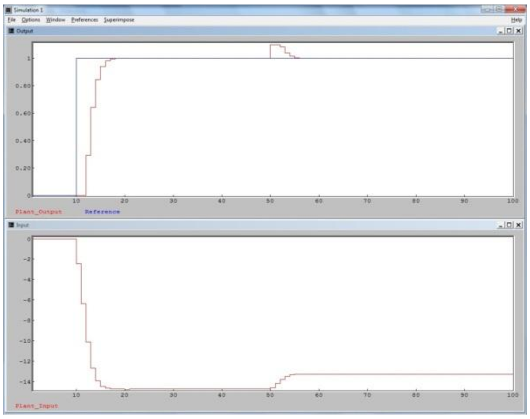

Figure 5. System response for the second functioning point P2

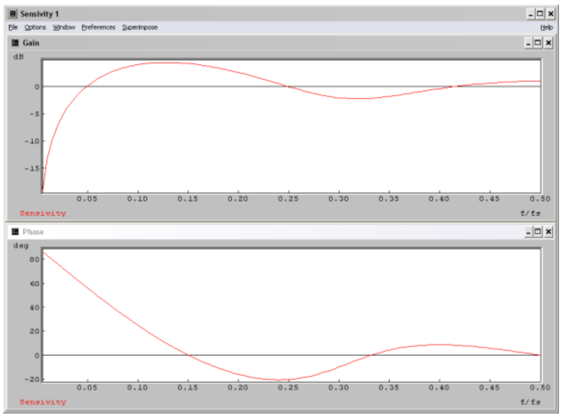

Figure 6. The sensitivity function andnthe phase characteristic of the robust system

New edge module is 0.73, which means that by introducing a pair of zeros in the polynomial S, robustness of the system was improved.

For the third operating point corresponding range 60-100%, we have the following results:
The controller computed with ξ= 0.95 and w_0 = 10.5 rad / sec for tracking goals and w_0 = 12.5 rad / sec with ξ= 0.95 for target setting, has the following components:

$$R(z^{-1}) = -2.17 - 2.02z^{-1} - 0.33z^{-2}$$

$$S(z^{-1}) = 1 - 0.82z^{-1} - 0.17z^{-2}$$

$$T(z^{-1}) = -8.56 + 4.83z^{-1} - 0.80z^{-2}$$

New edge module is 0.71, which means that by introducing a pair of zeros in the polynomial S, robustness of the system was improved.

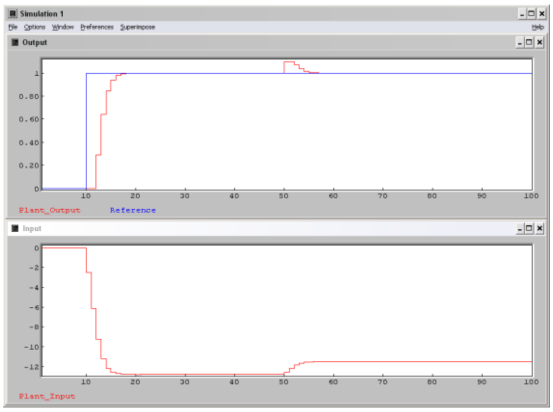

Figure 7. System response for the third functioning point P3

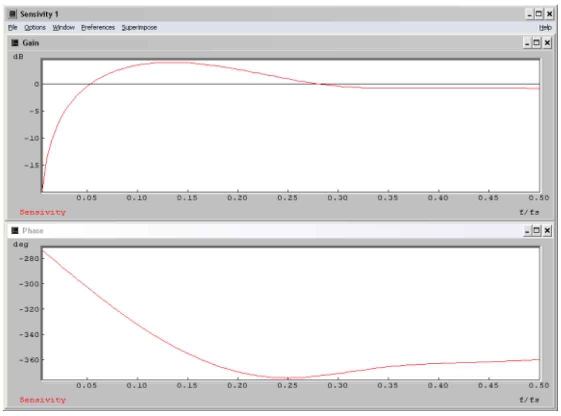

Figure 8. The sensitivity function andnthe phase characteristic of the robust system

4. The MM application and simulation results

After we have selected the operating points of the nonlinear characteristic associated to the motor functioning regime, the dynamic models (Mi-type I / O) were determined as well as the control algorithms (Ci type RST). We performed the simulation in closed loop systems to verify performance and ultimately the MM control structure was configured.

The model' selector was designed to specify the correct position in the real system and to specify the operating conditions for the switching point. It is based on the error model and the performance criteria.

$$\varepsilon_i(k) = y(k) - y_i(k) \tag{4}$$

$$J_i(k) = \alpha {\varepsilon_i}^2(k) + \beta \sum_{j=1}^{k} e^{-\lambda(k-j)} {e_i}^2 (j) \tag{5}$$

Regarding the switch control algorithm, switching is performed based on information received from the pattern selection, which builds a switching signal and calls for the new controller to be activated.
The three controllers are brought to active state, *ie*. each controller receives the information as y(k) and reference r(k), and calculate their order without letting u(k) to be applied.

For switching, the reference set will change given the output active control algorithm, and the resulting expression is:

$$y^*(k) = \frac{1}{t_0}\left[\sum_{i=0}^{n_S} s_i u(k-i) + \sum_{i=0}^{n_R} r_i y(k-i) - \sum_{i=1}^{n_T} t_i y^*(k-i)\right] \tag{5}$$

with respect to the equation:

$$y^*(k) = \frac{B_m(q^{-1})}{A_m(q^{-1})}\, r(k) \tag{6}$$

The switching system will function according to the below schematic:

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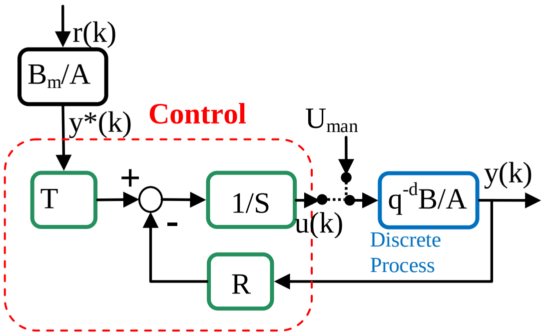

Figure 9. The set point value computation of the active algorithm using U_{man} command

The set point value will be identical to the active control algorithm's command value when switching. By using the solution shown in [9], we can eliminate the possibility of instability due to the probable gaps in the algorithm memory command.

It is therefore important to use the system memory command to always access the history in terms of switching between algorithms.

To evaluate the simulation results, we use the software application CVI - National Instruments, which allows viewing MM configuration dynamics including control algorithms behaviour in switching mode.
Simulation module is user friendly and real-time simulations are performed after all input data has been placed on the platform as shown in Fig. 10, Fig. 11, Fig. 12.

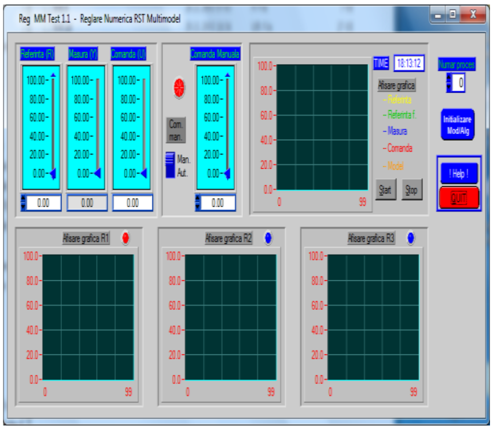

Figure 10. Software app for real time MM command

The application allows quick access to a range of information and commands, such as graphics displaying the time evolution of the process and control algorithms R1, R2, R3, highlighting the active algorithm, automatic or manual control of the system, the choice of the studied process, the possibility of initializing pairs of obtained controlled models, the possibility of selection of references, etc.
The graphical display allows simultaneously viewing the reference measure, the control and response model, each with a corresponding colour code.

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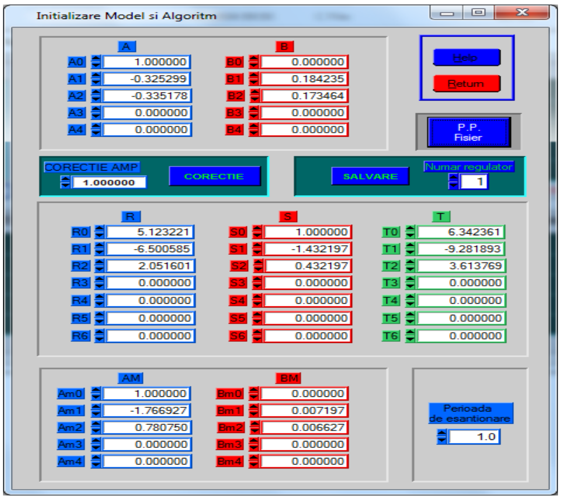

Figure 11. The initialization module for model-controller pairs

In the module initialization model, the control algorithm allows the introduction into the application of polynomial coefficients A and B for models definitions, and polynomials R, S and T for controllers.

After defining corrections, amplification and sampling period, it generates the actual simulation.
For example, we have considered the case of the multi model system for controlling the air flow Wci, in which case we considered three distinct operating points P1, P2 and P3, in accordance to the reasoning from the beginning of the chapter; following the same rationale, we have identified three models: M1 (0-40%), M2 (40-60%) and M3 (60-100%). For these models we have developed robust control algorithms, namely C1, C2, and C3.

Applying the superposition principle for model-algorithms' pairs to determine their control areas we get: M1 (0-55%), M2 (45-90%) and M3 (80-100%).

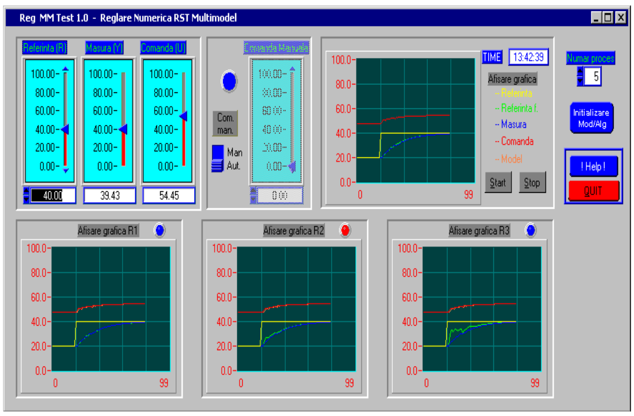

Figure 12. The MM system's response

Two switching tests were performed: the first in the range 40% -60%, and the second in the range 80% -100%, the results can be seen below.

Figure 13. Switching tests

5. Conclusions and perspectives

In this paper, an approach is proposed for modeling and controling a turbocharged Diesel engine with EGR valve. A configuration was designed and validated, in order to steer the multi model MM-multi controller nonlinear combustion process of a diesel engine, available for adjusting the intake manifold pressure and airflow circulating through the compressor.

The I/O Models are obtained by CMMP-recursive identification methods, by processing data files and considering the input EGR exit-pressure in the intake manifold, and the VGT output compressor airflow.
These models are validated by tests of statistical analysis error of prediction, allowing an interpretation closer to the real process and provides the possibility of implementing control algorithms that can be improved through adaptive strategies and robust.

Simulations carried out both on state models, and the models I / O system have shown that the stable combustion is represented by models which can be used to control the operation of the Diesel engine.

An optimal linear quadratic controller was properly designed and the MIMO system status and performance have been verified in simulation.

Two systems were designed for I / O strategy, in order to control the pressure and flow of air through the compressor in a nominal operating point. Based on an analysis of robustness in the frequency-the control algorithms were correct; the performance and capital gain were also verified in simulation.

We proposed and designed a configuration that pilots the multi-model – multi-controller MM nonlinear combustion process of the Diesel engine, available for adjusting the intake manifold pressure and air flow circulating through the compressor.

The MM software structure enables: implementing systems represented by pairs (Mi, Ci), selecting the closest one to the current operation point of the process and its corresponding controller pair, suitable for controlling air flow pressure p_i and WCI order without affecting the stability of the switching systems.

The MM control structure design was developed on the study of supervision and proposed configuration options (CLMS) switch that selects a single controller (the appropriate) of a plurality of candidate controllers, type RST robust. To select the control algorithm was used a quadratic minimization criteria built on the error between process output and exit model in question (model error).

The MM controller performance are highlighted through the use of dedicated simulators, application-specific functions built to verify the work and which can be obtained on an experimental model of a running vehicle.

After implementing the obtained results in the paper for vehicles equipped with Diesel engines, there is interest in collaborating with the Research Center Renault Romania for further research and implementing control algorithms for the real time version after a further validation on a new set of experiments simulator and pilot platforms that require access to a vehicle in circulation.

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