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Advances in Automotive Control

Preprints

VOLUME I

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Description
This Proceedings contains the papers presented at the Third IFAC Workshop on *"ADVANCES IN AUTOMOTIVE CONTROL"* held in Karlsruhe, Germany, on 28-30 March 2001.
As the subject indicates, the aim of this workshop was to discuss not only the latest advances related to motor vehicles, but also, and more generally, to exchange ideas between academic partners, car manufacturers and subcontractors. The plenary lectures are of great importance and the thematic sessions in the different sections are the essence of such workshops. However, the discussions between experts in the different fields, the meetings between people from industry, universities and public or private laboratories, as well as the resulting exchange of ideas, are as important.
Research is often criticized for providing merely theoretical results and for the insufficient number of its applications. The motor vehicle industry offers a wide field of applications in which we can validate all techniques, tools and methods. This allows us to be involved in all the areas of fundamental research, in all the different possible approaches from fundamental research to technology transfer, and to observe the actual effects of our results.
The increase in road traffic was a major problem of the last century. It is clear that one of the challenges of the XXIst century will be to improve driving safety and comfort. The sessions in the Proceedings volume are divided as follows: Driveline control, Driveline modelling, Vehicle dynamics (I and II), Electronic architecture, Intelligent components, Engine control (I and II), Engine modelling, Modelling of combustion and turbo-charging, Diagnostics and Subsystems.
The quality of the papers and the diversity of their origins clearly show the interest taken in this key sector of our research and industry.

Audience
For engineers working in all application areas of control engineering, especially automotive control.

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FUZZY MODELLING, CONTROL AND STABILITY ANALYSIS OF AN AUTOMOTIVE ENGINE *

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Abstract

This paper presents an advanced control structure and its simulation environment for a non-linear hybrid system: a GDI engine. The engine management system proposed is based on a hierarchical structure that uses fuzzy models of the engine to define piecewise linear controllers. A stability analysis of the GDI engine based on bifurcation diagrams is also presented.

Keywords: Fuzzy model, Fuzzy control, Hybrid and non-linear systems, Hierarchical controller, Nonlinear stability analysis.

Introduction

Pollutant emissions and fuel consumption reductions are still one of the main objective of Automotive research. New engine families as Gasoline Direct Injection engines (GDI) are currently studied and could provide solutions to this problem. They combine both the specific power of gasoline engines and the efficiency of diesel engines. These new developments are made possible thanks to the evolution of technology: new actuators like high pressure fuel injection, electronic throttles, and the exponential development of real time computers.

With the GDI engine technology, it is possible to change the injection timing to match the engine load, alternating two distinctive combustion modes – stratified mode and homogeneous mode.

Due to high potentialities in terms of low pollutant emissions and the low fuel consumption of the stratified mode, the engine management objective is to maintain the stratified conditions as long as possible. Unfortunately, this combustion mode is only possible for a restricted operating domain. Thus achieving good combustion and low consumption processes, preserving both car driveability and comfort while satisfying the driver requirements such as fast accelerations is a real control challenge.

The aim of this paper is to propose an efficient engine management structure coping with all these objectives. In section 1, a description of the GDI model is presented. Section 2 is devoted to the presentation of a control structure for the engine. The control results obtained in simulation are depicted in section 3. Finally, section 4 focuses on the stability analysis of the controller.

1. Model description

The model describes the behaviour of a vehicle equipped with a direct injection gasoline engine (GDI). It includes two main parts, the driver model and the vehicle model, which includes the engine, the chassis and the Engine management unit (Fig. 1).

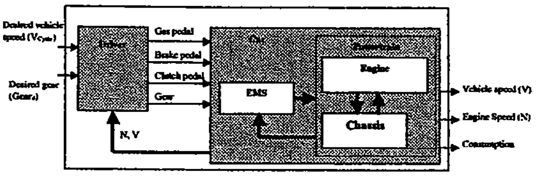


Fig. 1 GDI engine model overview

Most of the non-linearities used in this model are generally defined with non-linear mapping (look-up tables) denoted f_{NL} in the following text.

1.1 Engine model

From a macroscopic point of view, the engine process can be approximated with a continuous non-linear model that gives an approximation of the mean torque resulting from the combustion (Cylinder subsystem).

The dynamic part of the model is essentially related to the gas circulation inside the engine (Admission subsystem).

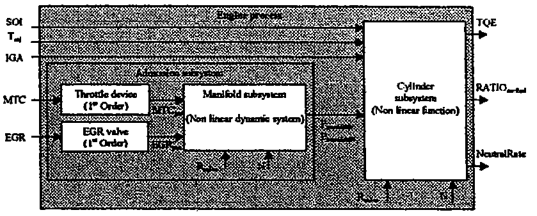


Fig. 2 Engine model overview

The engine model is able to run in two exclusive modes, homogeneous mode or stratified mode, with respect to the end of fuel injection (EOI<180° or EOI>180° respectively). For each combustion mode, the engine model can be described as follows:

Engine model inputs:

- The environmental parameters as the atmospheric pressure ($P_{atmospheric}$) and the air inlet temperature (TIA)

From the Engine Management System

- The fresh air throttle control action: Φ_{MTC}
- The EGR valve control action: Φ_{EGR}
- The injection start: SOI
- The ignition advance angle: IGA
- The fuel injection time: T_{inj}

From the chassis model

- The engine speed: N

State equations:

$$\frac{d\phi_{MTC\,POS}}{dt} = -\frac{1}{0.04}\cdot\phi_{MTC\,POS} + \frac{1}{0.04}\cdot\phi_{MTC}$$

$$\frac{d\phi_{EGR\,POS}}{dt} = -\frac{1}{0.04}\cdot\phi_{EGR\,POS} + \frac{1}{0.04}\cdot\phi_{EGR}$$

$$\frac{dP_{manifold}}{dt} = \frac{(Q_{TPS} + Q_{EGR} - Q_{cylinder})}{C_{manifold}\cdot f_{NL}(T_{IA})}$$

$$\frac{dP_{manifoldN}}{dt} = \frac{(Q_{EGR}\cdot R_{valve} - Q_{cylinderN})}{C_{manifold}\cdot f_{NL}(T_{IA})}$$

where

$\phi_{MTC\,POS}, \phi_{EGR\,POS}$ are the positions of the throttle and the EGR valve respectively,

$P_{manifold}, P_{manifoldN}$ are the global and neutral pressure inside the manifold respectively,

$$Q_{TPS} = f_{NL}(\phi_{MTC\,POS}, P_{manifold}, P_{atmospheric}),$$

$$Q_{EGR} = f_{NL}(\phi_{EGR\,POS}, P_{manifold}, P_{exhaust})$$

$$Q_{cylinder} = f_{NL}(P_{manifold}, N), Q_{cylinderN} = f_{NL}(P_{manifoldN}, N)$$

$C_{manifold}$ is the manifold capacity,

R_{valve} is the neutral rate at the EGR valve.

Engine model outputs:

The Effective torque:

$$TQE = f_{NL}(P_{manifold}, N, SOI, T_{inj}, IGA),$$

The neutral rate of the gas introduced into the cylinder:

$$NeutralRate = Q_{cylinderN} / Q_{cylinder},$$

The Air/fuel ratio:

$RATIO_{air/fuel} = Q_{cylinderAir} / (K_{stoec}\cdot Q_{fuel})$, K_{stoec} being the stoechiometric ratio (≈15),

The mean fuel consumption.

1.2 Chassis model

The chassis model describes the behaviour of a vehicle for the different situations that might occur during the simulation. The aim of this model is to represent the evolutions of the engine speed (N) and the vehicle speed (V) according to the torque produced by the engine and the driver's control actions on the three pedals (gas, brake and clutch pedals) as well as on the gear. A diagram of the different subsystems that composes the chassis model is given Fig. 3.

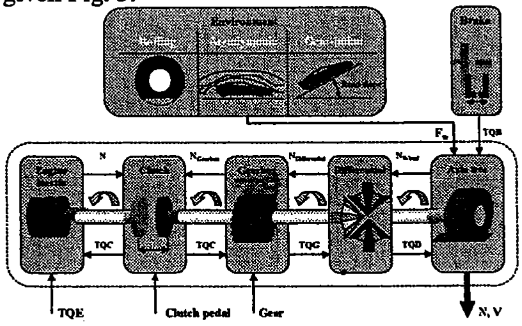


Fig. 3 Chassis Model

The **engine inertia model** defines the engine speed as a function of the effective torque produced by the engine (TQE) and the torque issued from the clutch system (TQC).

The **clutch model** defines the mechanism for engaging or disengaging the transmission of power between the engine and the gearbox. The output of this sub-system represents a torque which depends on the clutch pedal position and on the difference between the engine speed (N) and the gearbox speed ($N_{Gearbox}$).

The **gearbox model** defines the torque passed to the differential (TQG) and the gearbox speed transmitted to the clutch ($N_{Gearbox}$) according to the torque coming from the clutch (TQC), the differential speed ($N_{Differential}$) and the gear engaged (Gear).

The **differential model** defines the torque (TQD) and the differential speed transmitted to the axle tree and the gearbox respectively.

The **axle tree model** makes the balance of all forces and torques that act on the vehicle. The resulting force accelerates the vehicle mass ($m_{vehicle}$) and gives the vehicle speed (V) as well as the angular speed (N_{Wheel}).

The **brake model** defines the braking torque (TQB) as a function of the brake pedal position and the angular speed of the wheels (N_{Wheel}).

The **environment model** defines the force (Fw) resulting from the aerodynamic resistances, the rolling resistances (resistance of the tyres against their deformation during a rolling process), the climbing resistances.

1.3 Driver model

The main objective of the driver model is to control the vehicle speed so that it follows a driving scenario defined by a vehicle speed reference and a gear reference (Fig. 4). This driving scenario is issued from a normalised one (accepted by all nations of the European community) which is used to evaluate the pollutant emissions of new vehicle models that are planned to be mass-produced.

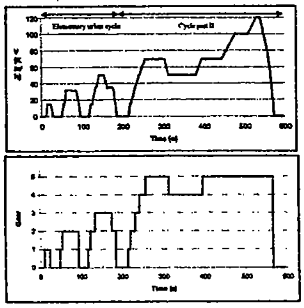


Fig. 4 Driving scenario: Car speed reference and gear reference

The driver model has been designed and identified, taking into account real driver behaviours and thus defining a "typical" characteristic. Nevertheless, by modifying some parameters, it is possible to address different driving styles: sporty, very smooth, ...

2. Control structure for the GDI engine

The objectives of the engine management system are to control the engine in order to follow the "power demands" expressed by the driver through the gas pedal, and also to ensure a constant engine speed during idle speed phases. These objectives should be achieved with respect to the engine constraints. The chosen solution (Fig. 5) to cope with these objectives consists in:

- a torque controller unit,
- a torque demand management unit.

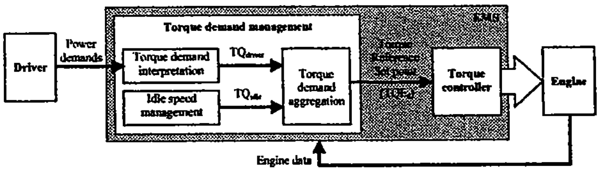


Fig. 5 General organisation of the Engine Management System

2.1 Torque demand management

The aim of this unit is to define a torque reference set point (TQE$_d$) according to the driver's actions and the idle speed regulation system. Two separate subsystems compute independently and simultaneously the torque demand expressed by the driver:

$$TQ_{driver} = \left(TQE_{max}(N) - TQE_{min}(N)\right) \cdot \frac{GasPedal}{100} + TQE_{min}(N)$$

and the torque demand required for the idle speed management:

$$TQ_{idle} = \frac{J_{car}}{\alpha} \cdot \Delta_N + \underbrace{k_{idle} \cdot \int_0^t d \cdot dt}_{\Delta_{TQ}}$$

where

J_{car} is the vehicle inertia seen from the engine (depending on the gear engaged),

k_{idle} is an integral coefficient, d is the deviation with respect to the reference trajectory.

Then, by selecting the highest values among TQE$_{driver}$ and TQE$_{idle}$, both torque demands are aggregated to define the resultant torque reference set point (TQE$_d$).

2.2 Torque controller

The engine process relies on two very different combustion modes. The choice of either one or the other depends on several observations and constraints related to the current engine operating conditions. In addition, with respect to the combustion mode, the requested behaviour for some variables should be different. Considering these observations the torque controller is based on a 3-level hierarchical structure (Fig. 6).

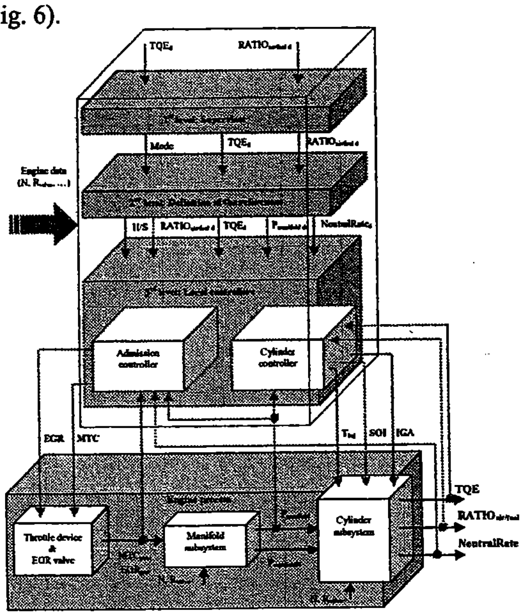


Fig. 6 Hierarchical control structure

2.2.1 Supervisory level

The aim of the supervisor is to manage the combustion mode according to the desired one. Considering the various operating engine conditions between the stratified mode and the homogeneous mode (homogeneous: more or less closed throttle, stratified: wide open throttle) and the different engine dynamics, four different operating modes are defined for the controller: The engine runs in homogeneous mode (H), the engine runs in homogeneous mode but switching to the stratified mode is prepared (H→S), the engine runs in stratified mode (S), the engine runs in stratified mode but switching to the homogeneous mode is prepared (S→H).

2.2.2 Definition of the references

The goal of the 2^{nd} level is to define the different references (air-fuel ratio, TQE, neutral rate, manifold pressure references) applied to the local controllers (3^{rd} level) according to the controller operating mode (1^{st} level) and to select the effective combustion mode of the engine (H/S).

2.2.3 Local controllers

The 3^{rd} level is composed of local controllers who compute the different control actions to apply to the engine in order to follow the references issued from the 2^{nd} level.

A first controller (Admission controller) is in charge of controlling the gas flows introduced into the cylinders with the MTC and EGR control actions whereas a second controller (Cylinder controller) regulates the torque and the air fuel ratio with the SOI, T_{inj} and IGA control actions. Nevertheless, as the behaviour of the engine differs depending on the combustion mode, specific local controllers have been defined for each combustion mode.

A general approach for the design of the local controllers has been set up. From data issued from the engine model described in section 1, Takagi-Sugeno fuzzy models describing the behaviour of the different sub-systems have been identified according to the modelling methods proposed in [1] and [4]. These models are composed of a set of rules whose premises define a fuzzy partition of the input space and whose corresponding conclusions are local linear models.

Rulei:

$\mathbf{If}\,(X_1,X_2,\ldots,X_n)\,\mathbf{is}\,A_i\,\mathbf{then}\,Y=a_{1i}\cdot X_1+a_{2i}\cdot X_2+\cdots+a_n\cdot X_n+a_{n+1}$ For each local linear model related to a given fuzzy partition, using conventional control tools, it is possible to design a local controller. Therefore, from each fuzzy model, a fuzzy Takagi-Sugeno controller can be associated [5]. This controller is composed of a set of rules whose premises define the same fuzzy partition as the fuzzy Takagi-Sugeno model and whose corresponding conclusions are local linear controllers.

Rulei:

$\mathbf{If}\,(X_1,X_2,\ldots,X_n)\,\mathbf{is}\,A_i\,\mathbf{then}\,\text{Control}=f(X_1,X_2,\ldots,X_n)$ Admission controller

The admission controller is based on an input/output de-coupling and a linearisation of the admission system by using a fuzzy state feedback loop (Fig. 7).

$$\mathbf{If}\,(\Phi_{MTC\,POS},\Phi_{EGR\,POS},P_{manifold},P_{manifoldN},R_{valve},N)\,\mathbf{is}\,A_i\,\mathbf{then}\begin{bmatrix}\Phi_{MTC}\\ \Phi_{EGR}\end{bmatrix}=\alpha^i\cdot\begin{bmatrix}P_{manifold}\\ P_{manifoldN}\end{bmatrix}+\beta^i\cdot\begin{bmatrix}V_1\\ V_2\end{bmatrix}+\varphi^i$$

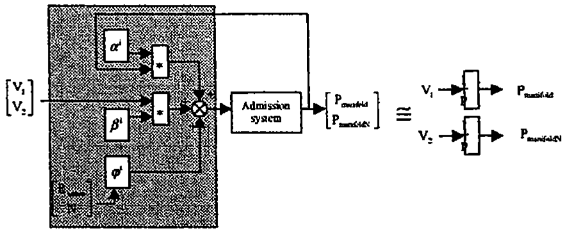


Fig. 7 Input-Output decoupling of the admission system

Two simple PI controllers then control the de-coupled subsystems.

<u>Cylinder controller in homogeneous mode</u>

The torque and air/fuel ratio controllers are based on a combination of feed-forward and feedback structures (Fig. 8). The modelling errors and the perturbations are rejected thanks to a fuzzy feedback controller containing an integral action.

$$\mathbf{If}\,(M_{fuel\ feedforward},P_{manifold},N)\,\mathbf{is}\,B_i\,\mathbf{then}\,K_{Ratio\,AF}=\frac{1}{\tau_{Ratio\,AF}}$$

$$\mathbf{If}\,(IGA_{feedforward},RATIO_{air/fuel},P_{manifold},N)\,\mathbf{is}\,C_i\,\mathbf{then}\,K_{TQE\,H}=\frac{1}{\tau_{TQE\,H}}$$

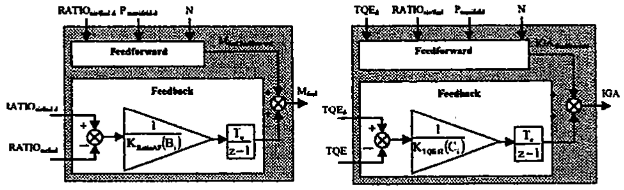


Fig. 8 air /fuel ratio and torque controllers in homogeneous mode

The fuel injection is done during the admission stroke to ensure a good mixing of the air/fuel mixture.

<u>Cylinder controller in stratified mode</u>

In a similar way, the fuel mass to be injected into the cylinders to obtain the desired torque can be calculated and implemented thanks to a feed-forward and feedback structure. Look-up tables give the other control variables (SOI, IGA).

3. Simulation results

From the driver's point of view, the engine power demands expressed through the gas pedal are satisfied and therefore the driver can easily follow the driving scenario. Moreover, during the combustion mode commutations, the torque variations are acceptable and the driver should not feel them (Fig. 9).

Fig. 10 presents some results concerning the entrance and the exit phases of idle engine speed regulation. The torque produced by the engine follows the highest torque demand among those issued from the idle regulation management unit (TQ_{idle}) and the driver's power demand interpretation unit (TQ_{driver}).

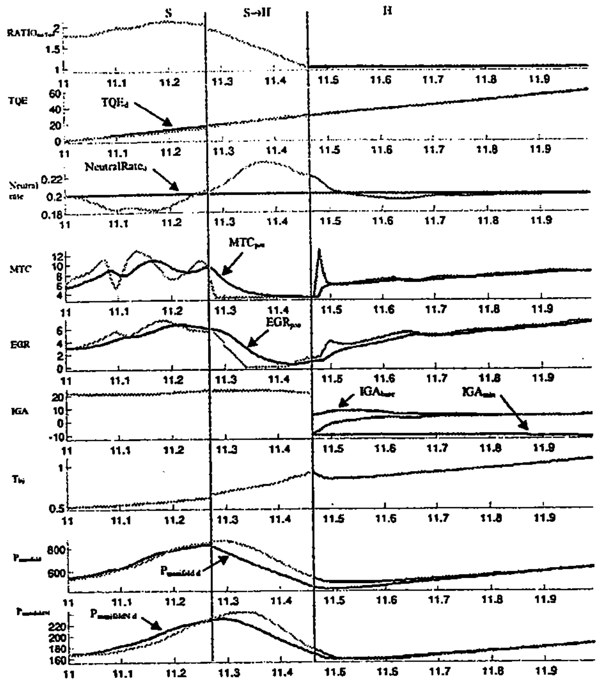


Fig. 9 Combustion mode switching from the stratified mode to homogeneous mode

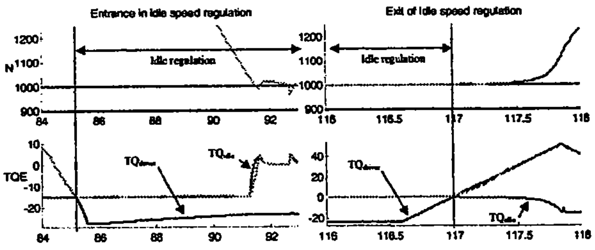


Fig. 10 Entrance and exit phases of idle speed regulation phases

4. Stability analysis

Stability analysis of non-linear systems is often dependent on the problem and, therefore, general results are difficult to carry out. Indeed, contrary to linear systems, non-linear systems often deal with multiple equilibrium points and can exhibit complex behaviours such as limit cycles, bifurcations, chaotic attractors, ...

Most results on the stability analysis of fuzzy control systems are related to local stability around an equilibrium point. Only some authors have studied the global stability involving all the space in which the variables associated to the process to be controlled can vary.

In control systems, the problem at stake is to stabilize the system at the operating point. Linearising at this point usually gives good results regarding the local stability of the system. However, the existence of other attractors, although far from the operating point, implies that the local stability is no longer global. That means that for large enough disturbances the system becomes out of control. That is why it is so important to analyse the existence of other equilibria, and not restrict the stability analysis around the operating point.

In the case of the GDI engine with its controller, a simplified model that captures the main aspects of the global behaviour was used to perform the stability analysis.

4.1 Simplified model for stability analysis

Some simplifications have been made to the GDI engine model to facilitate the stability analysis of the system. First, a reduced model of the engine, which does not consider the human driver interactions, was used. Then, as the GDI engine is able to run in two different combustion modes, the stability analysis was made separately for each combustion mode. At last, the dynamics of the GDI engine has two clearly different time scales. One is related to the dynamic of the vehicle chassis through the engine speed (N). The other one, which is much faster, corresponds to the dynamics of the gas circulation inside the engine.

With this kind of systems, the method known as the *two-time-scales decomposition* [3] can be applied. It consists of a decomposition of the dynamics of the model into two qualitatively different time-scales: one *fast* and the other one *slow*. This allows the study of a dynamical system to be simplified by means of two smaller dimension subsystems, which evolve into two different time-scales.

Thus, the GDI engine process can be decomposed as in Fig. 11.

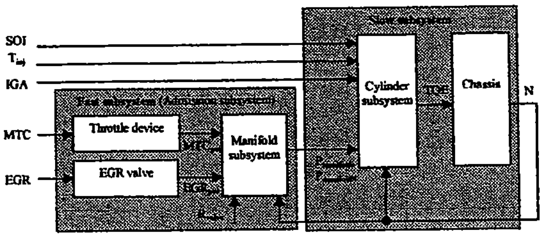


Fig. 11 GDI engine decomposition into fast and slow subsystems

In the following part, only the stability of the fast subsystem, i.e. the admission subsystem with its associated controller is presented.

4.2 Bifurcation analysis

Non-linear systems may show complex behaviours, as multiple equilibria or limit cycles. A key issue in the analysis of these systems is the study of qualitative changes in the behaviour of the system when some parameters vary. This kind of analysis is of a great interest to detect undesirable behaviours and to fix them. Such study can be performed with a continuation program, which allows to qualitatively analyse the behaviour of a system when one or more parameters vary reporting the evolution of the equilibrium points as well as periodic solutions. Information about the bifurcations, which the system suffers, is also given. Generally, the program user should provide a starting solution (an equilibrium or a periodic solution) for a value of the parameters and the algorithm "continues" the solution for the rest of the values of the parameters.

With the GDI engine controller, the AUTO continuation program [2] was used to perform the bifurcation analysis.

4.3 Stability analysis with variable control parameters

In this section, the stability analysis of the engine model is presented when two internal parameters of the admission controller, Kip_{PmN} and Kp_{PmN} (control parameters from the PI which regulates the neutral manifold pressure), are used as variable parameters.

Fig. 12 presents the bifurcation diagram obtained when the parameter Kip_{PmN} is varied.

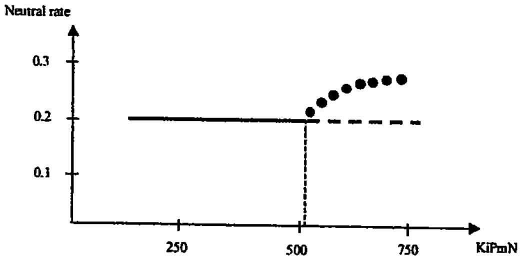
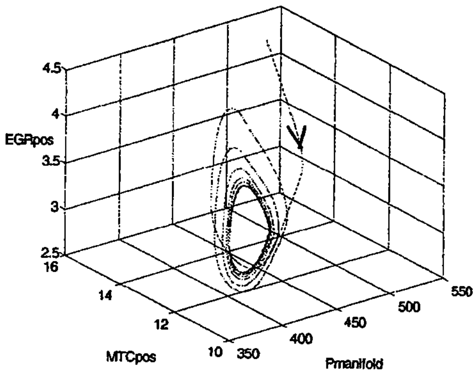


Fig. 12 Bifurcation diagram with a single variable parameter
(for N=3000 rpm and Pmd=900 mbar, with KpPmN=15)

It can be observed that the system has a stable equilibrium point (continuous line) for $Kip_{PmN} < 500$. For Kip_{PmN} close to 500, a bifurcation point occurs. That means, there is a qualitative change in the behaviour of the system at this point. Indeed, for $Kip_{PmN} > 500$, the equilibrium point turns unstable (dashed line), and a stable limit cycle (black dots) appears around the unstable equilibrium point. This is known as a Hopf bifurcation, and it is clearly a situation to be avoided when designing or tuning a controller for the GDI engine.

Simulations of the system can confirm the results of the bifurcation analysis. Fig. presents simulation results with $Kip_{PmN} > 500$, showing clearly the presence of a limit cycle.

Fig. 13 Limit cycle obtained by simulation of the engine with its controller when $Kip_{PmN} > 500$



By doing the stability analysis with two variable parameters, a stability map in the parameter space can be obtained. In Fig. 14, a stability map is represented when two controller parameters, Kip_{PmN} and Kp_{PmN}, vary. The simulations for two pairs of values, one stable and the other unstable, are also shown in Fig. 14.

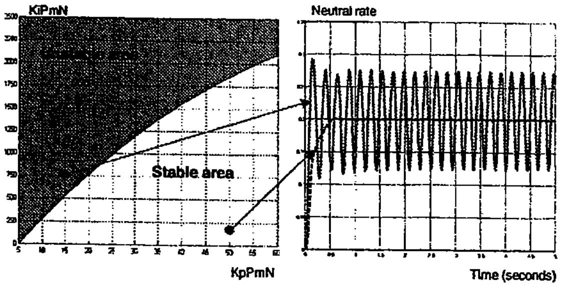


Fig. 14 Stability results obtained with two variable control parameters

5. Conclusion

The engine management system proposed shows promising perspectives in simulation. Thanks to the hierarchical controller structure, the idle regulation is tackled as a high level requirement and therefore no specific low level controller is needed. Moreover, the two combustion modes are correctly handled to optimise the engine efficiency. The use of fuzzy Takagi-Sugeno models for the design of the engine management system facilitates the control design and increases its legibility for both the motorist experts and the automatic engineers. The study of the qualitative effects of changing parameters in the controller through bifurcation analysis can be a valuable tool for designing and tuning the engine controller.

6. References

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