Design of Reconfigurable Predictive Control Applied to the Air Path of a Diesel Engine

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Abstract: In this paper, a method for reconfigurable predictive control of the air path of a Diesel engine system is presented. Failures are identified indirectly by estimating the parameters of the linear engine model using the recursive least squares algorithm (RLS). The actuators of the air system considered here are a variable geometry turbine (VGT) and an exhaust gas recirculation valve (EGR). The aim of the reconfiguration controller is to track simultaneously the desired trajectories of intake pressure (P1) and exhaust pressure (P2) when faults occur. Some simulation results are presented and compared to Generalized Predictive Control (GPC) applied on the coupled Multi-Input, Multi-Output (MIMO) system. The proposed controller exhibits good control performance: it ensures global stability and tracking of output references without zero offset. Moreover, separating the optimization of the GPC parameters for each subsystem permits the controller to have good performance during transient mode especially in terms of overshoots.

Keywords: GPC, non-minimum phase system, Re-configuration, Diesel engine.

1. INTRODUCTION

For several years the industrial community has expressed a growing interest in reliability, safety, and durability of dynamic systems. This is why significant research in Fault Detection and Isolation (FDI) was widely treated in Chen and Patton (1999). Unfortunately, little attention was paid to the subsequent problem, i.e., Fault-Tolerant Control (FTC) until the mid 1980s, Looze et al. (1985). More recently, FTC problem has begun to draw more attention, Patton (1997), Huzmezan and Maciejowski (1997) and Benbouzid et al. (2007).

There has always been interest in GPC which has significantly influenced process control, Qin and Badgwell (2003). This type of control continues to be the subject of many theoretical works aiming to extend its potential fields of applications. Optimization under constraints and control of non-minimum phase MIMO systems are among the main issues studied in the literature, Watanabe et al. (1991), Ricker (1991) and Mayne et al. (2000). The introduction of flatness in GPC based on output approach theory has made this problem solvable, Fliess and Marquez (2000),Plianos et al. (2007).

This paper describes a method to design GPC dedicated to unstable non-minimum phase systems, Layerle et al. (2007). Requiring access to all state variables of a given system, the proposed design approach necessitates the use of an observer.

Since the observer parameters must be re-estimated when an actuator or/and system fault occurs, the indirect failure accommodation method is applied, Noura et al. (1994). Such an approach permits the control law parameters to be updated. The functionality and safety of the system are thus maintained.

This paper is organized as follows : in section 2 a brief description of the system to be controlled is given. In section 3 the GPC state-space approach and its instability problem are briefly described. In section 4 the development of the predictive controller is given. Some simulation results are given in section 5 and section 6 concludes the paper.

2. SYSTEM DESCRIPTION

The nomenclature of the Diesel engine variables are given in the following table. The Diesel engine configuration is schematically given in (Fig. 1). The seven-order mean-

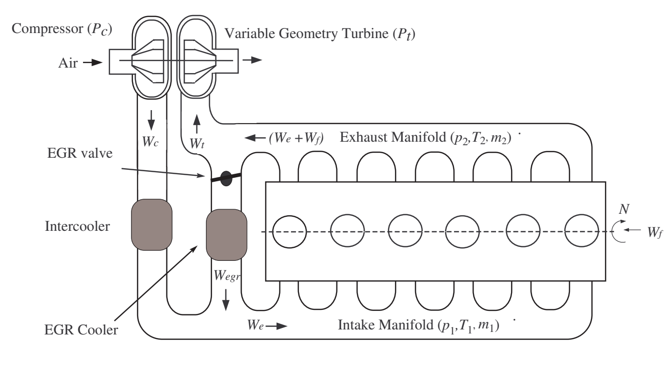

Fig. 1. Air system of Diesel engine

value model of the Diesel engine equipped with a VGT and an EGR valve in Jankovic et al. (2000) is considered. In order to reduce the system order, some hypotheses are considered as proposed in Jankovic et al. (2000):

Nomenclature	
Variable	Description
EGR	Exhaust Gas Recirculation
AFR	Air Fuel Ratio
N	Engine speed
F_1	Intake manifold burned gas fraction
F_2	Exhaust manifold burned gas fraction
m_1	Mass of gas in the intake manifold
m_2	Mass of gas in the exhaust manifold
p_1	Gas pressure in the intake manifold
p_2	Gas pressure in the exhaust manifold
P_c	Compressor power
P_t	Turbine power
W_e	Total mass flow rate into the engine
W_c	Compressor mass flow rate
W_t	Turbine mass flow rate
W_f	Fuel mass flow rate
W_{egr}	EGR mass flow rate
V_1	Intake manifold volume
V_2	Exhaust manifold volume
T_1	Intake manifold temperature
T_2	Exhaust manifold temperature
T_c	Compressor temperature
T_e	Temperature of the exhaust from the engine
T_{egr}	EGR temperature
ω_{tc}	Turbocharger speed
J_{tc}	Turbocharger moment of inertia
η_c	Compressor isentropic efficiency
η_t	Turbine isentropic efficiency
η_m	Turbocharger mechanical efficiency
γ	Specific heat ratio
R	Specific gas constant

- The fraction of burned gas in the intake and exhaust manifold F_1 and F_2 are removed from the model because they are difficult to measure.
- The mass of gas in intake and exhaust manifold m_1 and m_2 are removed from the model, because they are difficult to control.
- The turbocharger dynamics is modeled as a first-order lag power transfer with time constant τ.

For the developed below method, we are interested in a Diesel engine model with three state variables described as follows:

$$\begin{aligned} \dot{p}_1 &= k_1(W_c + W_{egr} - k_e p_1) + \frac{\dot{T}_1}{T_1} p_1 \\ \dot{p}_2 &= k_2(k_e p_1 - W_{egr} - W_t + W_f) + \frac{\dot{T}_2}{T_2} p_2 \\ \dot{P}_c &= \frac{1}{\tau}(\eta_m P_t - P_c) \end{aligned} \tag{1}$$

where k_i is the coefficient of the first law $k_i = \frac{RT_i}{V_i}$ and $k_e = k_e(N, T_1)$. T_1 and T_2 are supposed constant during the following statements. P_c and P_t are the compressor and turbine power respectively as defined by the following equations:

$$W_c = k_c \frac{P_c}{p_1^{\mu} - 1} \tag{2}$$

$$P_t = \eta_t c_p T_2 (1 - \frac{1}{p_2^{\mu}}) W_t \tag{3}$$

Note that $\mu = 0.286$ and k_c is a constant parameter, and $k_t = \eta_t c_p T_2$. In (3), η_t is the turbine isentropic efficiency and c_p the specific heat at constant pressure.

The considered system inputs are:

$$u = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} W_{egr} \\ W_t \end{bmatrix} \tag{4}$$

The considered system outputs are:

$$y = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} p_1 \\ p_2 \end{bmatrix} \tag{5}$$

As suggested in Larsen and Kokotovic (1998), the state variable representation defined by the coordinates reported to the operating point (p_{1e}, p_{2e}, p_{ce}) is carried out. The centered state variables are defined as:

$$\begin{cases} x_1 = p_1 - p_{1e} \\ x_2 = p_2 - p_{2e} \\ x_3 = p_c - p_{ce} \end{cases} \tag{6}$$

while the new control variables are given by:

$$\begin{cases} \tilde{u}_1 = u_1 - u_{1e} \\ \tilde{u}_2 = u_2 - u_{2e} \end{cases} \tag{7}$$

For a desired operating set point defined by a given air fuel ratio AFR_e and an EGR flow fraction EGR_e, the choice of the engine speed N and the fuel command W_f leads to:

$$\begin{cases} u_{1e} = \dfrac{EGR_e}{1 - EGR_e} W_{ce} \\ \\ u_{2e} = W_{ce} + W_f \end{cases} \tag{8}$$

In (8), W_{ce} is expressed:

$$W_{ce} = \frac{W_f}{2}\left[\delta + \sqrt{\delta^2 - 4(1 - EGR_e)AFR_e}\right] \tag{9}$$

where $\delta = AFR_e(1 - EGR_e) + 15.6 EGR_e - 1$.
and:

$$\begin{cases} p_{1e} = \dfrac{1}{k_e}(W_{ce} + W_f) \\ \\ p_{2e} = \left[1 - \dfrac{W_{ce}}{W_{ce} + W_f}\dfrac{1}{k_t k_c \eta_m}(p_{1e}^{\mu} - 1)\right]^{-\frac{1}{\mu}} \\ \\ p_{ce} = \dfrac{W_{ce}}{k_c}(p_{1e}^{\mu} - 1) \end{cases} \tag{10}$$

In the centered coordinates, the nonlinear model is given by:

$$\begin{cases} \dot{x}_1 = -k_1 k_e x_1 - \varphi_1(x_1) + \psi_1(x_1) x_3 + k_1 \tilde{u}_1 \\ \dot{x}_2 = k_2 k_e x_1 - k_2 \tilde{u}_1 - k_2 \tilde{u}_2 \\ \dot{x}_3 = -\dfrac{1}{\tau} x_3 + \varphi_2(x_2) + \psi_2(x_2)\tilde{u}_2 \end{cases} \tag{11}$$

where the nonlinearities are:

$$\begin{aligned} \varphi_1(x_1) &= \frac{k_1 k_c P_{ce}}{1 - p_{1e}^{\mu}}\left[\frac{p_{1e}^{\mu} - (x_1 + p_{1e})^{\mu}}{(x_1 + p_{1e})^{\mu} - 1}\right] \\ \psi_1(x_1) &= \frac{k_1 k_c}{(x_1 + p_{1e})^{\mu} - 1} \\ \varphi_2(x_2) &= \frac{P_{ce}}{\tau}\left[\frac{p_{2e}^{-\mu} - (x_2 + p_{2e})^{-\mu}}{1 - p_{2e}^{-\mu}}\right] \end{aligned}$$

$$\psi_2(x_2) = \frac{\eta_m k_t}{\tau}\left(1-(x_2+p_{2e})^{-\mu}\right)$$

The equation (11) can be written as:

$$\begin{cases} \dot{x}_1 = f_1(x_1,x_2,x_3) + g_1(x_1,x_2,x_3)\tilde{u} \\ \dot{x}_2 = f_2(x_1,x_2,x_3) + g_2(x_1,x_2,x_3)\tilde{u} \\ \dot{x}_3 = f_3(x_1,x_2,x_3) + g_3(x_1,x_2,x_3)\tilde{u} \end{cases}$$

By linearizing and discretizing around the origin, i.e. $x_1 = 0$, $x_2 = 0$, $x_3 = 0$, $\tilde{u}_1 = 0$ and $\tilde{u}_2 = 0$, the following linear model is obtained:

$$H(z) = \begin{bmatrix} h_{11}(z) & h_{12}(z) \\ h_{21}(z) & h_{22}(z) \end{bmatrix} \quad (12)$$

where $h_{11}(z)$, $h_{12}(z)$, $h_{21}(z)$ and $h_{22}(z)$ depend on the choice of the set point.

3. SUMMARY OF THE GPC STATE-SPACE APPROACH AND ITS INSTABILITY PROBLEM

Let the following discrete-time MIMO system having for input $\triangle u(k) \in \Re^q$ and output $y(k) \in \Re^s$ be:

$$\begin{cases} x(k+1) = Ax(k) + B\triangle u(k) \\ y(k) = Cx(k) \end{cases} \quad (13)$$

the vector

$$\triangle u = [\triangle u(k), \triangle u(k+1), \cdots, \triangle u(k+N_2)] \quad (14)$$

is chosen to minimize the quadratic cost function :

$$J = \sum_{j=N_1}^{N_2} [\hat{y}(k+j) - y_c(k+j)]^2 + \lambda \sum_{j=1}^{N_u} [\Delta u(k+j-1)]^2 \quad (15)$$

where $\hat{y}$ is the predicted output, y_c is the set point, N_1, N_2 and N_u refer respectively to the minimum prediction horizon, the maximum prediction horizon and the control horizon, and $\lambda \geq 0$ is the control increment weighting.
Since some state variables may be not measurable, the following observer proposed in Watanabe et al. (1991) is considered:

$$\begin{cases} \hat{x}(k+1) = A\hat{x}(k) + B\triangle u(k) + L[y(k) - C\hat{x}(k)] \\ \hat{y}(k) = C\hat{x}(k) \end{cases} \quad (16)$$

where L is the observer gain matrix. According to Elshafei et al. (1991), its equivalent representation is:

$$\hat{y} = G\triangle u(k) + MA\hat{x}(k) + ML\xi(k) \quad (17)$$

with $\xi(k) = y(k) - \hat{y}(k)$

where the matrices G and M are defined as:

$$G = \begin{bmatrix} CB & & & \\ CAB & CB & & \\ \vdots & CAB & \ddots & \\ \vdots & \vdots & \ddots & CB \\ \vdots & \vdots & \vdots & \vdots \\ CA^{N_2-1}B & CA^{N_2-2}B & \cdots & CA^{N2-Nu-1}B \end{bmatrix}$$

$$M = [\, C \;\; CA \;\; \cdots \;\; CA^{N_2-1} \,]^T \quad (18)$$

Finally the minimization of criteria (15) leads to:

$$\triangle u(k) = [G^T G - \lambda I]^{-1} G^T [y_c - MA\hat{x}(k) - ML\xi(k)] \quad (19)$$

where only the first row of $\Delta u(k)$ is considered and applied to the system (13).

3.1 GPC Instability Problems

The application of the GPC state-space approach requires close attention to the choice of the various GPC parameters N_1, N_2, N_u and λ. Indeed, these parameters considerably influence the regulation loop's stability. There are in the literature, straightforward guidelines for setting the GPC parameters, Lim et al. (1998).
The application also runs up against the system's problem related to poles and zeros outside the unit circle, Santro et al. (1998), Guemghar et al. (2005), Wang and Young (2006), Demircioglu and Karasu (2000). In the case of unstable poles, the usual solution consists in applying pole placement, Skrjanc et al. (2004), Gawthrop (2000), Santro et al. (1998), which results in stabilizing the system and setting its dynamics, before applying the GPC.
The following section presents a method to design fault-tolerant predictive controller applied to MIMO systems with unstable zeros when the GPC state-space approach is considered.

4. PROPOSED METHOD

The suggested method is based on the following stages. To simplify the presentation, it is supposed that the system is MIMO-squared ($dim\ u = dim\ y = s$).

4.1 Decoupling MIMO System

The first stage of the method is taken from the decoupling systems matrix, Fossard (1997), Mayne et al. (2000) and Bego et al. (2000). It aims to obtain independent chains of input-output subsystems.
The relative degree d_i is exactly equal to the minimum number of increments of the output $y(k)$ necessary for input $u(k)$ to appear. From (13) the i^{th} component of the output vector is defined by:

$$y_i(k+d_i) = c_i A^{d_i} x(k) + c_i A^{d_i-1} Bu(k) + \cdots \quad (20)$$

$$+ c_i Bu(k+d_i-1) \quad (21)$$

The integer d_i is characterized by the condition $c_i A^{d_i-1} B \neq 0$, where c_i is the i^{th} row of matrix C associated to output y_i. Thus, the equations relative to each y_i can be written as:

$$\begin{bmatrix} y_1(k+d_1) \\ \vdots \\ y_s(k+d_s) \end{bmatrix} = \begin{bmatrix} c_1 A^{d_1} \\ \vdots \\ c_s A^{d_s} \end{bmatrix} x(k) + \begin{bmatrix} c_1 A^{d_1-1} B \\ \vdots \\ c_s A^{d_s-1} B \end{bmatrix} u(k) \quad (22)$$

leads to:

$$Y(k+d) = \Delta_0 x(k) + \Delta_1 u(k) \quad (23)$$

The necessary and sufficient condition for decoupling the system (13) is the invertibility of the matrix Δ_1.

So, it is possible to apply to the system (13) the feedback law:

$$u(k) = \Delta_1^{-1}(\nu(k) - \Delta_0 x(k)) \tag{24}$$

where $\nu(k)$ is the input of the decoupled system. Let the decoupled system be given by the new representation:

$$\begin{cases} x(k+1) = \bar{A}x(k) + \bar{B}\nu(k) \\ y(k) = Cx(k) \end{cases} \tag{25}$$

where $\bar{A} = A - B\Delta_1^{-1}\Delta_0$ and $\bar{B} = B\Delta_1^{-1}$.
Note also that the system is finally decoupled in s independent chains of integrators as shown in (Fig. 2).

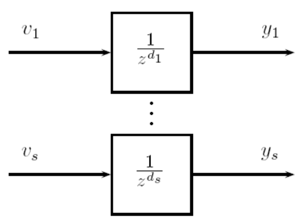

Fig. 2. Chains of decoupled input-output subsystems

4.2 Base-change Matrices

The system having now been decoupled, it is possible to fix independently dynamics of the various input-output chains. With this intention, a base-change is carried out:

$$\left\{ \xi(k+1) = \begin{bmatrix} \xi_1(k+1) \\ \vdots \\ \xi_s(k+1) \end{bmatrix} = Tx(k+1) \right. \tag{26}$$

so that:

$$\begin{cases} \xi(k+1) = \begin{bmatrix} A_1 & & \\ & \ddots & \\ & & A_s \end{bmatrix} \xi(k) + \begin{bmatrix} \beta_1 & & \\ & \ddots & \\ & & \beta_s \end{bmatrix} \nu(k) \\ y(k) = \begin{bmatrix} \gamma_1 & & \\ & \ddots & \\ & & \gamma_s \end{bmatrix} \xi(k) \end{cases} \tag{27}$$

with

$$T = \begin{bmatrix} c_1 \\ c_2 \\ \tau \end{bmatrix} \tag{28}$$

The new state-space representation is now expressed in the new base by the following equations:

$$\begin{cases} \xi(k+1) = \tilde{A}\xi(k) + \tilde{B}\nu(k) \\ y(k) = \tilde{C}\xi(k) \end{cases} \tag{29}$$

with

$$\tilde{A} = T\bar{A}T^{-1}$$
$$\tilde{B} = T\bar{B}$$
$$\tilde{C} = \bar{C}T^{-1}$$

where every triplet (A_i, β_i, γ_i) is given in the controllable canonical form.

4.3 Dynamic Modification of The Decoupled System

The determination of gain $\tilde{K}_i$ (associated to the i^{th} subsystem) by pole placement and the deduction of coefficients of the characteristic polynomial

$$\Phi(z) = z^{d_i} + \alpha_{id_{i-1}} z^{d_i - 1} + \cdots + \alpha_{i0} \tag{30}$$

leads to the new control law:

$$\nu(k) = -\tilde{K}\xi(k) + y_c = -\tilde{K}Tx(k) + y_c = -Kx(k) + y_c \tag{31}$$

with

$$K = \begin{bmatrix} \alpha_1 & & \\ & \ddots & \\ & & \alpha_s \end{bmatrix} \tag{32}$$

and

$$\alpha_i = \begin{bmatrix} \alpha_{i0} & \alpha_{i1} & \cdots & \alpha_{id_{i-1}} \end{bmatrix} \tag{33}$$

The combination of the decoupling technique with equation (31) transforms the control equation into:

$$u = -\Delta_1^{-1}(\Delta_0 + \tilde{K}T)x + \Delta_1^{-1}y_c \tag{34}$$

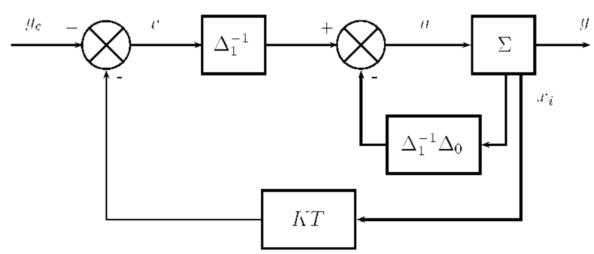

Fig. 3. Stabilization of the decoupled MIMO system

If $\breve{d} = \sum d_i = n$, the closed-loop control system shown in (Fig. 3) and the system (13) have same orders. The process (25) is thus observable and controllable.
In the opposite case ($\breve{d} < n$) the system (25) cannot represent the totality of the system (13) and the zero dynamics are stabilized. There are then $(n - \breve{d})$ unobservable modes. It is thus important to highlight them (by an adequate base-change) before carrying out the pole placement.
According to the nature of the system modes, the control law u is calculated to modify the observable or unobservable modes with or without destroying the interaction between the control laws u_i.

4.4 Finding Prediction Matrices

Once the system has been stabilized, the following stage consists in establishing the predictive control for all of the obtained Simple-Input, Simple-Output (SISO) subsystems.
The criterion to be minimized is:

$$J = \sum_{j=N_1}^{N_{2_m}} [\hat{y}_m(k+j) - y_{c_m}(k+j)]^2 + \lambda \sum_{j=1}^{N_{u_i}} [\Delta u_i(k+j-1)]^2 \quad (35)$$

where N_{2_m} and N_{u_i} correspond respectively to the prediction horizons and the control horizons for each output $m = 1, \cdots, s$ and each input $i = 1, \cdots, q$ of the system.
The control law of each subsystem is given by:

$$\begin{aligned} \triangle u_i = \; & [G_{mi}^T G_{mi} - \lambda I]^{-1} G_{mi}^T [y_{c_m} \\ & - M_{mi} A_{mi} \hat{x}(k) - M_{mi} L_{mi} \xi(k)] \end{aligned} \quad (36)$$

with

$$G_{mi} =$$

$$\begin{bmatrix} C_{mi}\tilde{B}_{mi} & & & \\ C_{mi}\tilde{A}_{mi}\tilde{B}_{mi} & C_{mi}\tilde{B}_{mi} & & \\ \vdots & C_{mi}\tilde{A}_{mi}\tilde{B}_{mi} & \ddots & \\ \vdots & \vdots & \ddots & C_{mi}\tilde{B}_{mi} \\ \vdots & \vdots & \vdots & \vdots \\ C_{mi}\tilde{A}_{mi}^{N_2-1}\tilde{B}_{mi} & C_{mi}\tilde{A}_{mi}^{N_2-2}\tilde{B}_{mi} & \cdots & C_{mi}\tilde{A}_{mi}^{N_2-N_u-1}\tilde{B}_{mi} \end{bmatrix}$$

$$M_{mi} = \begin{bmatrix} C_{mi} & C_{mi}\tilde{A}_{mi} & \cdots & C_{mi}\tilde{A}_{mi}^{N_2-1} \end{bmatrix}^T \quad (37)$$

where the triplets (A_{mi}, B_{mi}, C_{mi}) represent the new matrices of the decoupled SISO-subsystems.

4.5 Actuator and/or component failure accommodation

Let us consider the MIMO linear system (13). In the nominal case, the control law is (36). The occurrence of a fault once detected and isolated (FDI) leads to the modification of the system parameters. The parameters of B are modified when actuator failures appear and the component failure influences the parameters of matrix A. The failed system is then given by:

$$\begin{cases} x_f(k+1) = A_f x(k) + B_f \triangle u_f(k) \\ y_f(k) = C x_f(k) \end{cases} \quad (38)$$

Since the matrices of a system (13) must be re-estimated, it is proposed to use "the indirect failure accommodation method". The principle of this method is detailed in Noura et al. (1994), Sauter et al. (1998). It can also be shown as (Fig. 4). In this method, the Recursive Least Squares method (RLS) is used to compute the new state-observer parameters. Ideally, the expression of the observer (16) becomes:

$$\begin{cases} \hat{x}_f(k+1) = A_f \hat{x}_f(k) + B_f \triangle u_f(k) + L[y(k) - C\hat{x}_f(k)] \\ \hat{y}(k) = C\hat{x}_f(k) \end{cases}$$

where A_f and B_f are the matrices built by the estimated parameters. Finally the fault-tolerant control law of each subsystem is given by:

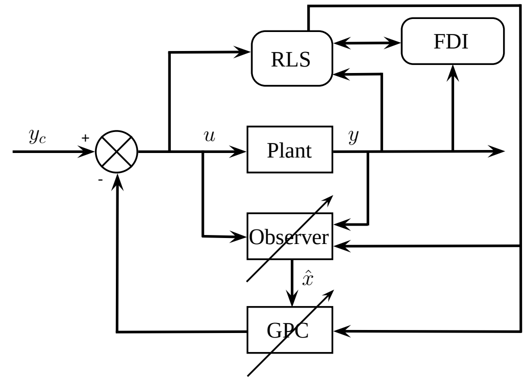

Fig. 4. Indirect failure accommodation scheme

$$\begin{aligned} \triangle u_{i_f} = \; & [G_{mi_f}^T G_{mi_f} - \lambda I]^{-1} G_{mi_f}^T [y_{c_{mf}} \\ & - M_{mi_f} A_{mi_f} \hat{x}(k) - M_{mi_f} L_{mi_f} \xi(k)] \end{aligned} \quad (39)$$

In this paper, it is assumed that only system failures can occur, consequently B remains constant.

5. SIMULATION AND RESULTS

In order to validate the proposed control strategy, simulations have been made on the engine model described in (1), (2) and (3). The model parameters k_1, k_2, k_c, k_t, k_e, τ are identified from the full-order nonlinear model at constant speed and fueling rate, Plianos et al. (2007).
From (12), the resulting linearized model is given by:

$$H(z) = \begin{bmatrix} \frac{0.2611z^2 - 0.5411z + 0.2531}{z^3 - 2.686z^2 + 2.378z - 0.6942} & \frac{-3.288z^2 + 5.611z - 2.351}{z^3 - 2.686z^2 + 2.378z - 0.6942} \\ \frac{-0.0003937z^2 - 0.01838z - 0.008045}{z^3 - 2.686z^2 + 2.378z - 0.6942} & \frac{-3.332z^2 + 5.616z - 2.312}{z^3 - 2.686z^2 + 2.378z - 0.6942} \end{bmatrix} \quad (40)$$

This transfer function describes a linear multivariable non-minimum phase and unstable system. Here, the relative degrees d_1 and d_2 of each subsystem are equal to 1.
The first base-change matrix T is given by:

$$T = \begin{bmatrix} c_1 \\ c_2 \\ \tau \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 79.0403 & -3.7107 & 100 \end{bmatrix} \quad (41)$$

τ must be independent of c_1 and c_2.
Once several base-changes have been carried out to obtain a diagonal bloc matrix, the dynamics of the system is fixed thanks to a state feedback matrix K to maintain the non-interaction between poles.
From the control point of view, the engine model can now be considered as a stabilized and decoupled system:

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} \frac{1}{z - 0.99} & 0 \\ 0 & \frac{1}{z - 0.97} \end{bmatrix} \begin{bmatrix} \tilde{u}_1 \\ \tilde{u}_2 \end{bmatrix} \quad (42)$$

The GPC-based state-space can also be applied to (42).
For performance comparison, the usual GPC-based state-space has been applied in simulation to the system (40). As illustrated in (Fig. 5) and (Fig. 6), The resulting controler is incapable of tracking the desired trajectory of x_1, as shown in (Fig. 5), although it is able to track the desired trajectory of x_2. Moreover when the system fault occurs

at $t = 25s$, it is not capable of preserving dynamic and steady-state performance.
Simulation results shown in (Fig. 7) and (Fig. 8) have been obtained by applying the GPC decoupled approach with the adequate increment weighting and horizons. The fault occurrence is starting from $t = 25s$. Figures (Fig. 7) and (Fig. 8) show explicitly the convergence of the different outputs of the system considered as decoupled. After the fault has been identified, Nourah and C. Fonte (1993), the accommodation method updates the state estimator and the controller structure.

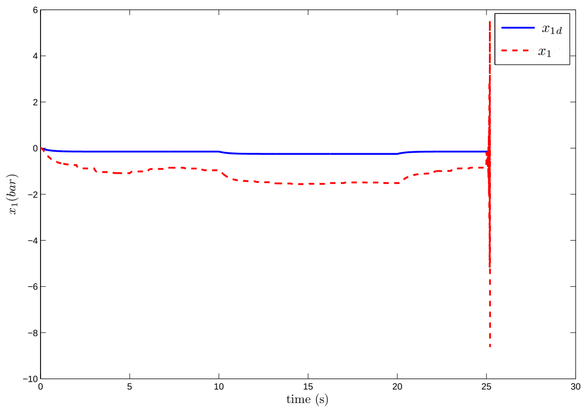

Fig. 5. x_1(bar) vs time(s)

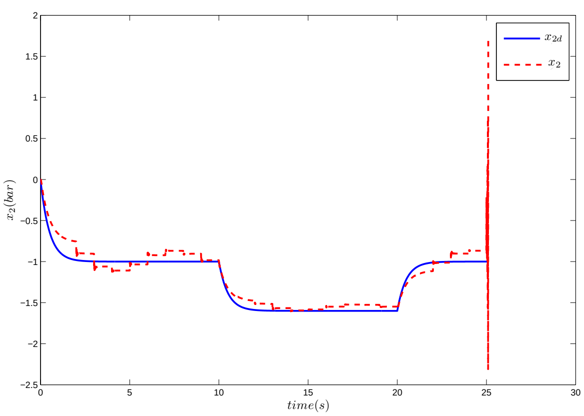

Fig. 6. x_2(bar) vs time(s)

6. CONCLUSIONS AND FUTURE WORKS

6.1 Conclusions

In this paper, a fault-tolerant predictive control strategy is proposed. It combines the state-based GPC approach with indirect failure accommodation. Under the hypothesis that the considered system can be decoupled, the controller gives considerably better performance. The proposed method dells with the closed loops of the various subsystems separately. On the one hand, it fixes independently the dynamics of each subsystem and offset the unstable zeros with decoupling law. As a result, it is

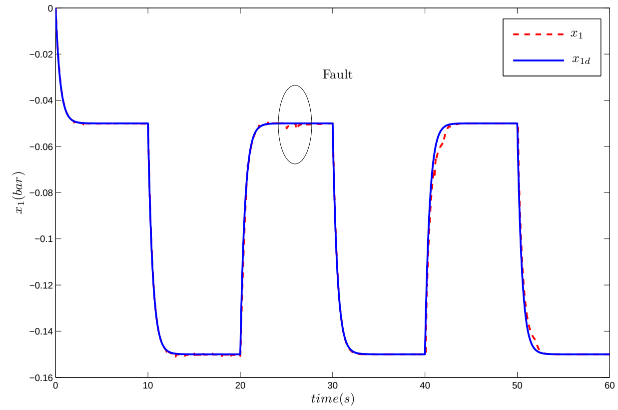

Fig. 7. x_1(bar) vs time(s)

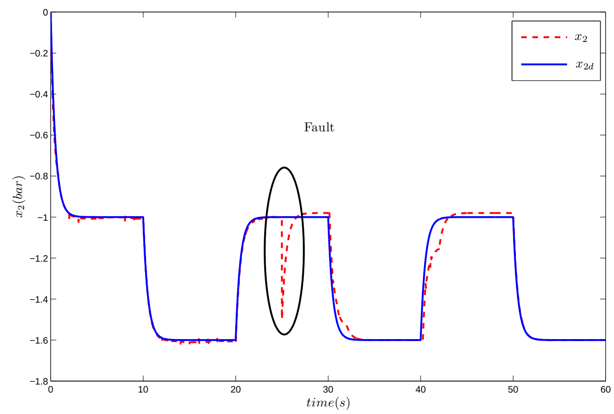

Fig. 8. x_2(bar) vs time(s)

particularly recommended for unstable multivariable non-minimum phase systems. On the other hand, it makes it possible to optimize separately the choice of the GPC parameters for each subsystem. Finally, the use of an adaptive state-observer permits the controller to accommodate actuator or/and system failures.
Applied to the model of the Diesel engine air system, the resulting predictive controller exhibits good performance in terms of trajectory tracking when a fault occurs.

6.2 Future Works

Future work will consist in applying this method to a Caterpillar six-cylinder Diesel engine (3126B).

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