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NCGPC with dynamic extension applied to a Turbocharged Diesel Engine

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Abstract: This paper presents a control design method applied to diesel engines equipped with a Variable Geometry Turbocharger (VGT) and an Exhaust Gas Recirculation (EGR) valve. The objective of this control is to reduce gas pollution to the fixed rate norms imposed by Euro v and Euro vi, Arnold et al. [2006] (Transport and E. E. Federation [2004] and Umweltbundesamt [2003]) without loosing the torque power of the controlled Turbocharged Diesel Engine (shortly, TDE). To achieve this, we propose to control Air Fuel Ratio (AFR) and EGR Fraction. But these variables are not accessible for measurements, Jankovic et al. [2000]. Therefore the gas pressure in the intake manifold and the compressor mass flow rate are preferred. Those outputs, however, lead to a non-minimum phase system. To avoid this, another choice of outputs is proposed which, together with a dynamic extension, yields a linearizable system with trivial zero dynamics, to which we apply Nonlinear Continuous-time Generalized Predictive Control. Simulation results are presented to highlight efficiency of the controller.

1. INTRODUCTION

In order to comply with more constraining antipollution standards, Arnold et al. [2006] (see Transport and E. E. Federation [2004] and Umweltbundesamt [2003] therein) and Cook et al. [2007], automobile constructors introduce in some diesel engines two actuators: the EGR valve and the VGT. The former permits recirculation of exhaust gas into the intake manifold while the latter the compensation of the amount of fresh air due to the important amount of recirculated exhaust gas in the intake manifold. But some drawbacks have to be underlined: an important reduction of the amount of fresh air leads to an increase in particulate emissions and possibly visible smoke whereas a low amount of EGR fraction leads to an increase in NO_x emissions. For this, a stoichiometric mixture (which is a mixture that contains chemically exact mass of air to burn all the fuel injected) is preferred in the cylinder. For Diesel fuel, the stoichiometric AFR is around 14.6, Jankovic et al. [2000].

To render these two actuators more efficient, during the diesel engines combustion, several control design methods have been proposed: Constructive Lyapunov control design, Jankovic et al. [2000], Indirect passivation, Larsen et al. [2000], Passivation, Larsen and Kokotovic [1998], Polynomial control, Ayadi et al. [2004], Dynamic feedback linearization, Plianos and Stobart [2007], Optimal nonlinear Control, Plianos et al. [2007], Predictive Control, Otner and del Re [2007] and Ferreau et al. [2007].

In this paper, we propose unconstrained Nonlinear Continuous-time Generalized Predictive Control NCGPC to control both actuators, that is, to track desired values of them.

The paper is organized as follows: Section 2 presents the full seventh-order and the reduced third-order TDE models while Section 3 unconstrained NCGPC of a MIMO-square system. In Section 4, the application to TDE is presented. Simulation results are presented in Section 5 to demonstrate the effectiveness of this approach applied to the extended fourth-order TDE model.

2. DIESEL ENGINE DESCRIPTION

Many models of diesel engines have been proposed since the early 60's (Borman [1964], Ledger et al. [1973]). For sake of simplicity, we use the model proposed and validated through experiments in Jankovic et al. [2000].

2.1 Full order TDE model

The full-order TDE model is a seventh-order one described as follows in Jankovic et al. [2000]. The change of masses of gas in the intake and exhaust manifolds is derived as

$$\begin{aligned} \dot{m}_1 &= W_c + W_{egr} - W_e \\ \dot{m}_2 &= W_e - W_{egr} - W_t + W_f. \end{aligned}$$

Similarly, the change of the pressures in the intake and exhaust manifolds is obtained from the first law of thermodynamics as:

$$\dot{p}_1 = \frac{\gamma R}{V_1}(W_c T_c + W_{egr} T_{egr} - W_e T_1)$$

$$\dot{p}_2 = \frac{\gamma R}{V_2}((W_e + W_f) T_e - W_{egr} T_2 - W_t T_2).$$

Because of a lean combustion, the exhaust from the engine is not entirely burned gas. Then, the dynamics of fractions of burned gas F_1 and F_2 respectively in the intake and exhaust manifolds are derived as

$$\dot{F_1} = \frac{W_{egr}(F_2 - F_1) - W_c F_1}{m_1}$$

$$\dot{F_2} = \frac{W_e[15.6(1 - F_1) + (AF + 1)F_1]/(AF - 1) - W_e F_2}{m_1}.$$

The dynamics $\dot{\omega}_{tc}$ of the turbocharger are derived from Newton's second law:

$$\dot{\omega}_{tc} = \frac{1}{J_{tc}\omega_{tc}}(\eta_m P_t - P_c).$$

The nomenclature of the variables is as follows:

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

2.2 Reduced order TDE model

In the sequel, the parameters of the model k_1, k_2, k_c, k_e, k_t, τ and η_m are identified from the seventh-order mean value nonlinear model of TDE at a constant speed of 1600 rpm and a fueling rate of 7.2 kg/h. In order to simplify the studied system, the seventh-order TDE model is reduced to a third-order model one, under the specific following hypothesis, Jankovic et al. [2000]:

- the fractions of intake and exhaust manifolds burned gas, F_1 and F_2, are difficult to measure and then they are not considered in the model,
- for the same reasons the intake and exhaust burned gas masses fraction, m_1 and m_2, are ignored,
- the turbocharger dynamics are modelled as a first-order lag power transfer with a time constant τ.

Neglecting the external disturbance W_f yields the following third-order model:

$$\begin{aligned} \dot{p_1} &= k_1(W_c + u_1 - k_e p_1) + \frac{\dot{T_1}}{T_1}p_1 \\ \dot{p_2} &= k_2(k_e p_1 - u_1 - u_2) + \frac{\dot{T_2}}{T_2}p_2 \\ \dot{P_c} &= \frac{1}{\tau}(\eta_m P_t - P_c), \end{aligned}$$

where the compressor (resp. turbine) air mass flow is related to the compressor (resp. turbine) power as follows:

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

$$\left(\text{resp. } P_t = k_t\left(1 - \frac{1}{p_2^\mu}\right)u_2\right). \tag{2}$$

Despite the fact that the real inputs are EGR valve and VGT openings, the considered inputs are, in this study, for sake of simplicity, $u_1 = W_{egr}$ and $u_2 = W_t$.

In the sequel, $\dot{T_1}$ and $\dot{T_2}$ are assumed to vanish because their corresponding measured signals T_1 and T_2 have very slow variations. This gives, Jankovic et al. [2000]:

$$\begin{aligned} \dot{p_1} &= k_1(W_c + u_1 - k_e p_1) \\ \dot{p_2} &= k_2(k_e p_1 - u_1 - u_2) \\ \dot{P_c} &= \frac{1}{\tau}(\eta_m P_t - P_c). \end{aligned} \tag{3}$$

Replacing W_c and P_t by their expressions (1) and (2) and denoting $K_0 = \frac{\eta_m}{\tau}k_t$ yields the system:

$$\dot{x} = f(x) + g_1(x)u_1 + g_2(x)u_2, \tag{4}$$

where

$$f(x) = \begin{bmatrix} k_1 k_c \dfrac{P_c}{p_1^\mu - 1} - k_1 k_e p_1 \\ k_2 k_e p_1 \\ -\dfrac{P_c}{\tau} \end{bmatrix}, \tag{5}$$

$$g_1(x) = \begin{bmatrix} k_1 \\ -k_2 \\ 0 \end{bmatrix} \text{ and } g_2(x) = \begin{bmatrix} 0 \\ -k_2 \\ K_0\left(1 - p_2^{-\mu}\right) \end{bmatrix}. \tag{6}$$

2.3 Vector output choice

The output of to-be-controlled variables consists of the input manifold pressure p_1 and the compressor mass flow rate W_c instead of the AFR and EGR fraction because the latter are not measurable in a vehicle, Jankovic et al. [2000]. The choice of p_1, as the first component of the vector output, is motivated by the fact that if one controls the amount of fresh air in order to have a stoichiometric mixture with the exhaust recirculated gas, the control of EGR fraction is consequently done. The AFR can be deduced from the following relation $AFR = (1-F_1)(W_c + W_{egr}/W_f)$, Jankovic et al. [2000]. We thus consider the nonlinear system (3) (equivalently, (4)-(6)) with the vector output:

$$y = \begin{bmatrix} p_1 \\ W_c \end{bmatrix} \tag{7}$$

and the goal is to track desired constant values p_{1d} of p_1 and W_{cd} of W_c. In the sequel, we suppose that all the components (p_1, p_2, P_c) of the state x are accessible for measurements and, moreover, that they belong to the set Ω, Jankovic et al. [2000], defined by

$$\begin{aligned}\Omega = \{(p_1, p_2, P_c) : 1 < p_1 < p_1^{max},\\ 1 < p_2 < p_2^{max}, 0 < P_c < P_c^{max}\},\end{aligned} \tag{8}$$

where the maximal values $p_1^{max}, p_2^{max}, P_c^{max}$ follow from physical limits of the TDE.

3. UNCONSTRAINED NONLINEAR CONTINUOUS-TIME GENERALIZED PREDICTIVE CONTROL NCGPC

Consider the square-MIMO $(m \times m)$ nonlinear system

$$\begin{aligned}\dot{x} &= f(x) + \sum_{j=1}^{m} g_j(x) u_j\\ y &= (h_1(x), \ldots, h_m(x))^t,\end{aligned} \tag{9}$$

where $x \in R^n$, $u \in R^m$ and $y \in R^m$ are the vectors state, control, and output, respectively.

To simplify the exposition, the standard geometric notation for Lie derivatives is used in this paper. For a real-valued function h on R^n and a vector field f on R^n, the Lie derivative of h along f at $x \in R^n$ is given by:

$$L_f h(x) = \sum_{i=1}^{n} \frac{\partial h}{\partial x_i}(x) f_i(x).$$

Inductively, we define

$$L_f^k h(x) = L_f L_f^{k-1} h(x) = \frac{\partial L_f^{k-1} h}{\partial x}(x) f(x),$$

with $L_f^0 h(x) = h(x)$.

3.1 Vector relative degree

A system of the form (9) has a vector relative degree $(\rho_1, \cdots, \rho_m)$ if:

(i) for any $x \in R^n$

$$L_{g_j} L_f^k h_i(x) = 0,$$

for all $1 \le i \le m$, all $1 \le j \le m$, and all $0 \le k < \rho_i - 1$;

(ii) the $m \times m$ matrix (decoupling matrix)

$$A(x) = \begin{bmatrix} L_{g_1} L_f^{\rho_1 - 1} h_1(x) & \cdots & L_{g_m} L_f^{\rho_1 - 1} h_1(x) \\ \vdots & & \vdots \\ L_{g_1} L_f^{\rho_m - 1} h_m(x) & \cdots & L_{g_m} L_f^{\rho_m - 1} h_m(x) \end{bmatrix} \tag{10}$$

is nonsingular for all $x \in R^n$ (see, e.g., Isidori [1995]).

3.2 Unconstrained NCGPC

The goal is to find a control law such that the output $y(t)$ of the system (9) tracks asymptotically a given reference signal $\omega(t)$. Unconstrained predictive control consists of deriving a control law by minimizing a receding horizon performance index, in a finite prediction horizon time without taking into account constraints on the vectors state, input and output. The receding horizon performance index is given as

$$J = \sum_{i=1}^{m} J_i, \tag{11}$$

with the expression of J_i equal to, Demircioglu and Gawthrop [1992],

$$J_i = \frac{1}{2} \int_0^{T_i} [\hat{e}_i(t + \tau_i)]^2 d\tau_i,$$

where

$$\hat{e}_i(t + \tau_i) = \hat{y}_i(t + \tau_i) - \hat{\omega}_i(t + \tau_i).$$

Above, T_i is the prediction horizon time corresponding to the i-th component of the vector output, $\hat{y}_i(t + \tau_i)$ and $\hat{\omega}_i(t + \tau_i)$ denote, respectively, the i-th component of the predicted vector output and that of the vector reference signal for any τ_i belonging to $[t, t + T_i]$.

Finally, the vector control law is derived under the following conditions, Chen [2001]:

$A1$: the zero dynamics exist and are asymptotically stable;

$A2$: all states are available for measurements;

$A3$: the system has a vector relative degree $(\rho_1, \cdots, \rho_m)$;

$A4$: the vector output $y(t)$ and the vector reference signal $\omega(t)$ are sufficiently many times continuously differentiable with respect to time.

3.3 Error Prediction

In order to predict the error between the vector output and vector reference, one uses the Taylor series development at time $t = \tau_i$, up to a chosen order $l_i > \rho_i$. Note that this order of development is important for stability of the closed-loop system, Chen et al. [1999] and Chen et al. [2003]. We then have the following relation:

$$\hat{e}_i(t + \tau_i) = \sum_{k=0}^{l_i} e_i^{(k)}(t) \frac{(t + \tau_i - t)^k}{k!} + R_i(\tau_i),$$

where $R_i(\tau_i)$ represents higher order terms (h.o.t.) of $\hat{e}_i(t+\tau_i)$. Rewriting the expression $\hat{e}_i(t + \tau_i)$ in a matrix form and neglecting the h.o.t., leads to:

$$\hat{e}_i(t + \tau_i) = \mathbf{t}_i(\tau_i) \mathbf{e}_i, \tag{12}$$

where $\mathbf{t}_i(\tau_i) = \left[1 \;\; \tau_i \;\; \ldots \;\; \frac{\tau_i^{l_i}}{l_i!} \right]$ and

$$\mathbf{e}_i = \begin{bmatrix} y_i^{(0)} - \omega \\ y_i^{(1)} - \dot{\omega} \\ \vdots \\ y_i^{(\rho_i)} - \omega^{(\rho_i)} \\ y_i^{(\rho_i+1)} - \omega^{(\rho_i+1)} \\ \vdots \\ y_i^{(\rho_i+r_i)} - \omega^{(\rho_i+r_i)} \end{bmatrix} + \begin{bmatrix} 0_{i(\rho_i \times 1)} \\ D_i(x, \bar{u}^{r_i}) \end{bmatrix}.$$

The terms $D_i(x, \bar{u}^{r_i})$ above, depending on x and $\bar{u}^{r_i} = (u, \dot{u}, \ldots, u^{(r_i)})$, result from successive derivations of the i-th component of the vector output y. The integer $l_i = \rho_i + r_i$ is the order of development in Taylor series of the i-th error component and r_i the order of derivation of the vector control law, see Chen et al. [2003].

Denote by M_i the matrices

$$M_i = \int_0^{T_i} \mathbf{t}_i(\tau_i)^t \mathbf{t}_i(\tau_i) d\tau_i,$$

of dimension $(l_i + 1) \times (l_i + 1)$ and by M_i' (resp. M_i'') $(r_i + 1) \times (l_i + 1)$ matrices (resp. $(r_i + 1) \times (r_i + 1)$ matrices) resulting from simplifications of the matrix M_i during the minimization of the receding horizon performance index (11), see Chen [2001]. Define the matrix

$$B = diag\{M''_1, \cdots, M''_m\}^{-1} diag\{M'_1, \cdots, M'_m\},$$

and denote by $L_{[j]}$ its j-th row. Finally, put $W = [\omega_1, \ldots, \omega_1^{(l_1)}, \ldots, \omega_m, \ldots, \omega_m^{(l_m)}]^t$ and

$$\bar{Y} = [h_1, \ldots, L_f^{l_1} h_1, \ldots, h_m, \ldots, L_f^{l_m} h_m]^t.$$

Now the vector control law $u = u(x(t), t)$ is defined by

$$u = (A(x(t)))^{-1} \begin{bmatrix} L_{[1]}(B) \\ \vdots \\ L_{[(m-1)(r_i+1)+1]}(B) \end{bmatrix} \left[W(t) - \bar{Y}(x(t)) \right],$$

where $A(x)$ is the decoupling matrix (10), supposed to be invertible (assumption (A1)). Observe that the choice of the rows $L_{[j]}(B)$ of B implies that the right hand side of the above formula depends on $x(t)$ and t only (and not on u and its time derivatives).

4. APPLICATION TO DIESEL ENGINE

The control design method presented above is now applied to the reduced order model of TDE. First, the vector relative degree is calculated and then the zero dynamics are examined. It turns out that they are unstable. We thus propose a new choice of to-be-controlled output which leads to a system that is exactly linearizable via a dynamic extension and possesses trivial zero dynamics. Finally, a vector control law is calculated for the dynamically extended system.

4.1 Vector relative degree

For the third-order model TDE (4)-(6) and (7), the vector relative degree exists and equals $(\rho_1, \rho_2) = (1, 1)$ for all $(p_1, p_2, P_c) \in \Omega$. The decoupling matrix is:

$$A(x) = \begin{bmatrix} k_1 & 0 \\ -\dfrac{\mu k_c k_1 P_c p_1^{\mu-1}}{(p_1^\mu - 1)^2} & -K_0 k_c \dfrac{p_2^{-\mu} - 1}{p_1^\mu - 1} \end{bmatrix}.$$

The sum of the vector relative degree's components is equal to 2 which is less than 3, the dimension of the state space of system (4)-(6). Therefore one-dimensional zero dynamics exist. An examination of their stability is necessary before deriving the vector control law.

4.2 Zero dynamics

Since the goal is to track the reference signal $(\omega_1, \omega_2)^t$, which consists of desired fixed values p_{1d} and W_{cd} of the respective components of the output $y = (p_1, W_c)^t$, define

$$y_d = [\, p_1 - p_{1d}, W_c - W_{cd} \,]^t.$$

The zero dynamics are obtained by applying the control annihilating identically the vector output $y_d(t)$ and thus are given by

$$\dot{p_2} = k_2 W_{cd} \left[1 - \frac{(p_{1d}^\mu - 1)}{\eta_m k_t k_c (1 - p_2^{-\mu})} \right], \qquad (13)$$

which are unstable. Indeed, (13) has a single equilibrium point $p_{2e} = \left[1 - \frac{p_{1d-1}}{\eta_m k_t k_c} \right]^{-\frac{1}{\mu}}$ and the eigenvalue of the linearization of (13) at p_{2e} is positive (see Fig. 1 and 2). To avoid dealing with unstable zero-dynamics, we propose another choice of outputs and a dynamic extension.

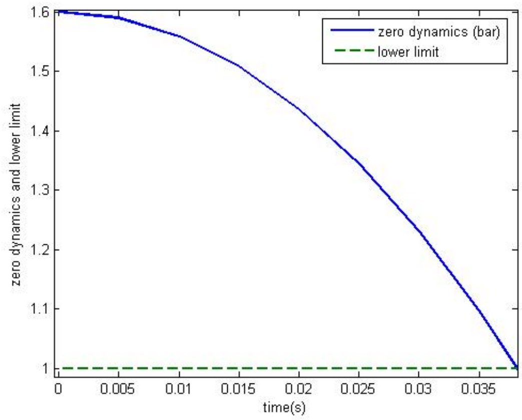

Fig. 1. Third-order TDE with $p_{20} = 1.6$ bar: unstable zero dynamics (escaping in finite time towards $p_1 = 1$)

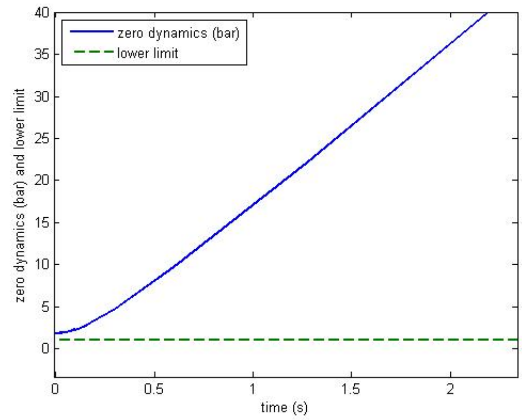

Fig. 2. Third-order TDE with $p_{20} = 1.8$ bar: unstable zero dynamics (going towards $+\infty$ with an asymptotically constant velocity)

4.3 Change of the vector output and Dynamic Extension of TDE

Change of the vector output. We will overcome the problem of unstable zero dynamics by changing the output (7) such that the modified system has trivial zero dynamics. This can be achieved by keeping the first component $y_1 = p_1$ (or $y_{1d} = p_1 - p_{1d}$) and choosing the second output component $y_2 = h(x)$, where $x = (p_1, p_2, P_c)$, such that, indeed, $L_{g_2} h = 0$. Resolving this equation gives

$$h(x) = P_c + \frac{K_0}{k_2} \left[p_2 - \frac{1}{1-\mu} p_2^{1-\mu} \right],$$

and thus we consider the new output $\tilde{y}(t)$ of to-be-controlled variables defined by

$$\tilde{y}(t) = \begin{bmatrix} p_1 \\ P_c + \dfrac{K_0}{k_2} \left[p_2 - \dfrac{1}{1-\mu} p_2^{1-\mu} \right] \end{bmatrix}. \qquad (14)$$

In the next subsection we will show that the system (4)-(6) with the output (14) has, indeed, trivial zero dynamics.

As we specified, our problem is to track desired constant values p_{1d} of p_1 and W_{cd} of W_c. A natural question is thus how to reformulate the problem in terms of the components of the new output $\tilde{y}$, given by (14), in order to achieve a solution of the original tracking goal. Notice that W_c, P_c, and p_1 are linked via the relation $W_c = P_c \frac{k_c}{p_1^{\mu}-1}$ and hence the desired tracking values p_{1d} and W_{cd} determine uniquely the desired value P_{cd} of P_c via

$$W_{cd} = P_{cd} \frac{k_c}{p_{1d}^{\mu} - 1}.$$

Notice that given any fixed p_{1d} and P_{cd}, there exists a unique point $x_e = (p_{1e}, p_{2e}, P_{ce})$, satisfying $p_{1e} = p_{1d}$ and $P_{ce} = P_{cd}$, and unique control values $u_e = (u_{1e}, u_{2e})$ such that the right hand side of (4)-(6) has an equilibrium at x_e when the controls are evaluated at u_e. We will define the desired tracking value h_d of h, the second component of the new output $\tilde{y}$ (given by (14)), as

$$h_d = h(x_e) = P_{cd} + \frac{K_0}{k_2}\left[p_{2e} - \frac{1}{1-\mu} p_{2e}^{1-\mu}\right].$$

Now a crucial observation is that when the new output $\tilde{y}(t)$ tracks asymptotically the constant value (p_{1d}, h_d) and the overall system approaches the equilibrium point x_e, then the original output $y(t)$ tracks asymptotically the desired values (p_{1d}, W_{cd}), see Dabo et al. [2008] for more details.

Dynamic Extension of TDE. In this section we will follow notions of geometric nonlinear control (see, e.g., Isidori [1995]). The system (4)-(6) with the output (14) has the decoupling matrix

$$\tilde{A}(x) = \begin{bmatrix} k_1 & 0 \\ -\dfrac{\mu k_c k_1 P_c p_1^{\mu-1}}{(p_1^{\mu}-1)^2} & 0 \end{bmatrix}, \tag{15}$$

which is not invertible, and thus the system has no a vector relative degree. We can, however, construct a suitable dynamic extension with a well defined relative degree. To this end, put $z = u_1$, $\dot{z} = v_1$ and apply the new vector control $[v_1, v_2]^t$, where $v_2 = u_2$. This yields the following nonlinear system:

$$\begin{aligned} \dot{p_1} &= k_1(W_c + z - k_e p_1) \\ \dot{p_2} &= k_2(k_e p_1 - z - v_2) \\ \dot{P}_c &= \frac{1}{\tau}(\eta_m P_t - P_c) \\ \dot{z} &= v_1. \end{aligned} \tag{16}$$

The extended system (16) with the output (14) has the vector relative degree equal to $(\rho_1^e, \rho_2^e) = (2, 2)$ and the invertible decoupling matrix

$$A^e(x) = \begin{bmatrix} k_1 & k_1 k_c K_0 \dfrac{1-p_2^{-\mu}}{p_1^{\mu}-1} \\ K_0(p_2^{-1}-1) & \mu k_2 K_0 (z - k_e p_1) p_2^{-\mu-1} + \dfrac{K_0}{\tau}(p_2^{-\mu}-1) \end{bmatrix}. \tag{17}$$

The system is thus dynamically I-O decouplable and has trivial zero dynamics (since the sum of the components of its vector relative degree is $\rho_1^e + \rho_2^e = 2 + 2 = 4$, the dimension of the state space of the extended system). Notice that the original system (4)-(6), with the output (14), has trivial zero dynamics too because the latter does not depend on invertible endogenous feedback.

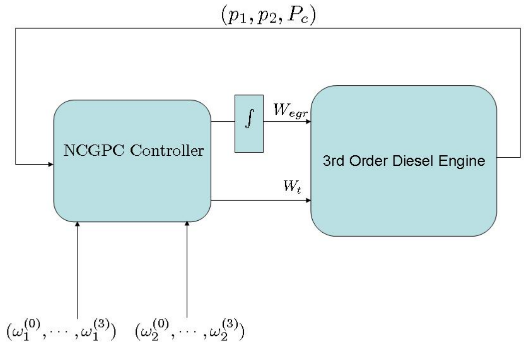

Fig. 3. NCGPC controller with dynamic extension

Another way of looking at the extension procedure that we propose is to observe that the system (3) (equivalently, (4)-(6)) is not static feedback linearizable because the distribution $D = span\{g_1, g_2\}$ is not involutive. It is, however, flat, Fliess et al. [1995] (that is, dynamic feedback linearizable) since any 3-dimensional system with noninvolutive distribution $D = span\{g_1, g_2\}$ is so and the components p_1 and h, given by (14), of the new output $\tilde{y}$ are actually flat outputs (linearizing outputs of the system (4)-(6)).

4.4 Vector control law for TDE

In this section we apply the NCGPC control, described in Section 3, to the extended system (16) with the output (14). As we have just checked, the assumptions (A1) and (A3) are satisfied (indeed, the vector relative degree is $(\rho_1^e, \rho_2^e) = (2, 2)$ and the zero dynamics are trivial) and so are (A2) and (A4). We choose $l_1 = l_2 = 3$ and the predictive horizons $T_1 = 2, T_2 = 1$. As the reference signals ω_1 and ω_2 we take smooth concatenations of three constant values 1.87×10^5 bar, then 1.33×10^5 bar, and 1.87×10^5 bar again (for ω_1) and 6.98×10^5 (no physical unit), then 5.01×10^5, and 6.98×10^5 again (for ω_2). The control law is

$$u(x(t), t) = (A^e(x(t)))^{-1} \begin{bmatrix} L_{[1]}(B) \\ L_{[3]}(B) \end{bmatrix} \left[W(t) - \bar{Y}(x(t))\right],$$

where $h_1 = p_1$, $h_2 = h$, $W = (\omega_1, \ldots, \omega_1^{(3)}, \omega_2, \ldots, \omega_2^{(3)})^t$, and $\bar{Y} = (h_1, \ldots, L_f^3 h_1, h_2, \ldots, L_f^3 h_2)^t$; one calculates $L_{[1]}(B) = [\,3.75\ 3\ 1\ 0\ 0_4\,]$ and $L_{[3]}(B) = [\,0_4\ 15\ 6\ 1\ 0\,]$, where $0_4 = [\,0\ 0\ 0\ 0\,]$.

5. SIMULATION RESULTS

Simulation results are carried out via Simulink with the version V 7.0 of Matlab. Fig. 4 and Fig. 5 show the effectiveness of the NCGPC controller.

6. CONCLUSION

The technique of Nonlinear Continuous-time Generalized Predictive Control NCGPC is applied to a 3-dimensional model of Turbocharged Diesel Engine TDE. To avoid dealing with unstable zero dynamics of that model, we

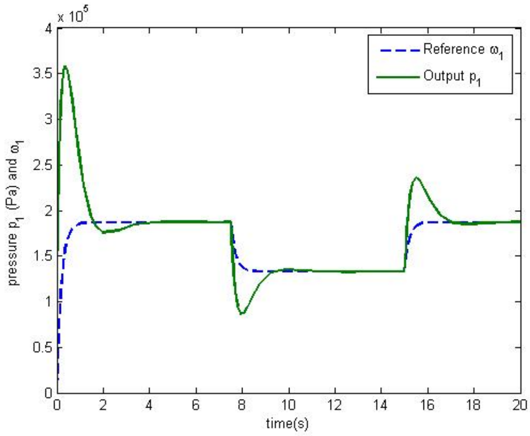

Fig. 4. Extended TDE model: output p_1 and reference ω_1

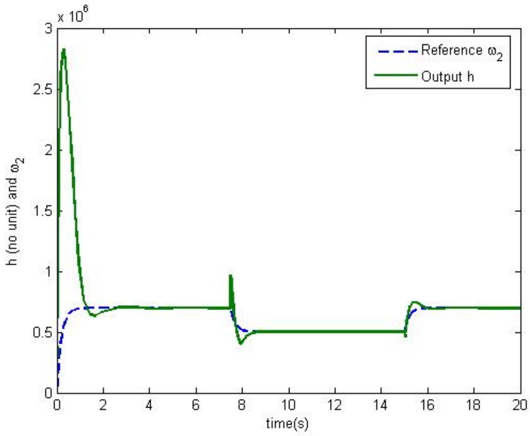

Fig. 5. Extended TDE model: output h and reference ω_2

propose a new choice of outputs such that the modified system has trivial zero dynamics. Then we construct a dynamic extension in order to have a well defined vector relative degree. Therefore the extended system satisfies all hypothesis ($A1$)-($A4$) of Chen [2001] and the NCGPC can be applied. The fact that the extended system is (dynamically) linearizable and has trivial zero dynamics considerably simplifies calculation and implementation of the NCGPC controller. Future works will aim at comparing NCGPC controller and Exact Dynamic Linearization applied to Turbocharged Diesel Engine TDE.

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