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Exhaust Manifold Pressure Estimation Diesel Equipped with a VGT Turbocharger

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Abstract

This paper develops an exhaust manifold pressure estimation method for a Diesel engine equipped with a variable geometry turbine (VGT) turbocharger. Extrapolated VGT data-maps are used directly for the estimation of the exhaust pressure using a non-iterative Newton-Raphson based method suitable for real-time applications. This approach can give more accurate estimations than traditional methods because it takes into account the turbine speed effect on the turbine mass flow rate. All this without increasing the calculation load significantly. The proposed exhaust manifold estimation can be used to relieve the exhaust manifold pressure physical sensor during engine operating conditions where its reliability is low. The estimator is evaluated in transient with two different engine cycles using a engine model validated in a benchmark as a reference.

INTRODUCTION

In the recent years, Diesel engine emissions regulations have become stricter and achieving simultaneously the emissions legislations and the demanded engine drivability has become a challenging issue. Although significant improvements have been made over the past years, there are still many challenges to address in order to meet the future emissions regulations. The introduction of sophisticated alternative combustion modes such as homogeneous charge compression ignition (HCCI), low temperature combustion (LTC) and premixed controlled compression ignition (PCCI) offers a great potential to reduce the engine emissions levels [1] [2] [3]. However, these new modes require different fueling strategies and in-cylinder conditions, thus creating the need for more complex, reliable and precise control systems and technologies.

Air-to-fuel ratio control for Diesel engines and dual-loop exhaust gas recirculation (EGR), with both high and low-pressure recirculations, are two of the traditional approaches to face the new emissions legislations. Several different control strategies have been proposed to deal with these new strategies, see e.g [4] [5] [6]. A common assumption in most works presented in the literature is that the state variables used in the controllers are measured or well known. However, the sensor's performance required by the controllers is often only achievable in engine benches by the use of expensive sensors which are not suitable for production engines.

The exhaust pressure is one of the variables typically used in Diesel engine control. However, its measurement is very difficult and expensive due to strong pressure oscillations and high temperature conditions in the exhaust manifold. In production engines, the manifold pressure measurement is not reliable in some operating conditions (for example under high exhaust manifold temperature). To deal with this issue, virtual sensors or models can be developed to estimate the exhaust pressure in order to complement or replace the physical sensors. Physical model-based estimators are specially attractive since these models work for large operating regions and allow estimating the mean value of the pressure over several engine cycles. Such a mean value is suitable for use in an engine controller for computational reasons.

Therefore, several exhaust pressure estimators have been proposed in the literature. In [7], a non-linear model-based exhaust pressure observer is proposed for a turbocharged Diesel engine. In [8], a non-linear coordinate transformation to a dimensionless model of a VGT is proposed for a single loop EGR to estimate the exhaust pressure. However, the VGT mass flow is usually approximated by a modified version of the orifice equation or a coordinate transformation (see [7] - [9]) where the effect of the turbo speed is neglected. The problem of estimating the exhaust pressure using directly the extrapolated turbine data-maps [10] [11] and taking into account the effect of the turbine speed on the turbine mass flow rate has not been found in the literature.

In this work, a model-based exhaust manifold pressure estimator is designed using a non-iterative Newton-Raphson based method. The estimation is done using directly the extrapolated VGT data-maps without neglecting the effect of the turbine speed on the turbine mass flow rate which yields a more accurate estimation of the exhaust pressure. The proposed method is not iterative and features a low calculation load, making it suitable for incorporation in a production engine controller. This estimator is intended to relieve the physical sensor when the engine operates in the conditions where the pressure sensor looses its reliability. However, this estimator can be used in various applications such as in VGT diagnosis and positioning, among others.

This paper is organized as follows: first, the engine under consideration in this work is presented. Then, the exhaust manifold pressure estimation problem formulation is introduced and a non-iterative Newton-Raphson based exhaust pressure estimation method is developed. Finally, the performance of the estimator is presented using a validated engine model as a reference.

ENGINE UNDER CONSIDERATION

The engine considered in this work is based on a modern light-duty four-cylinder Diesel 1.6 liter engine. Its schematic is depicted in Figure 1.

The engine is equipped with a variable geometry turbocharger (VGT), dual-loop EGR systems (high-pressure (HP) throttle, as well as low-pressure (LP) throttle) and exhaust-treatment systems such as Diesel particle filter and a lean NOx trap. The HP throttle is used to increase the HP-EGR rate at light load. A universal exhaust gas oxygen (UEGO) sensor is

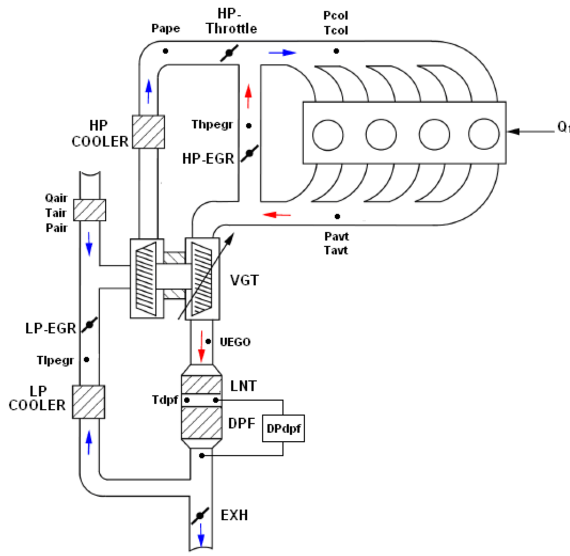

Figure 1: Schematic of the Dual-Loop EGR with VGT

installed downstream the VGT in order to avoid high-pressure at the UEGO sensor. For Diesel engines, the combustion is usually lean, which means that there is more air than the stoichmetric amount in the cylinder mixture. Therefore, the exhaust gas contains unburned air and it could be recirculated back into the intake manifold through the EGR valves. The exhaust valve EXH increases the pressure upstream the LP-EGR valve in order to increase the LP-EGR mass flow rate. The HP-EGR is used during the beginning of a cycle to obtain combustions with more elevated temperature with the purpose of heating up as fast as possible the exhaust post-treatment systems. The LP-EGR is then used instead of the HP-EGR because it is cooler, thus allowing for more mass and EGR to be introduced into the cylinder.

The measurements taken in the engine are: pressure and temperature in the intake manifold denoted p_{col} and T_{col}, pressure and temperature in the exhaust manifold denoted p_{avt} and T_{avt}, the pressure upstream the HP-throttle p_{ape}, the atmospheric pressure p_{air}, the fresh mass flow rate and temperature Q_{air} and T_{air}, the Diesel particle filter differential pressure DP_{dpf}, the exhaust oxygen proportion $UEGO$ and the HP-EGR and LP-EGR temperatures T_{hpegr} and T_{lpegr} respectively. In this work, the measurements considered are T_{avt} and DP_{dpf}. The estimations considered are: the intake gas flow rate Q_{mot}, the HP-EGR mass flow rate Q_{egrh} and the turbine speed N_t. Q_{mot} can be calculated by the speed density equation as:

$$Q_{mot} = \frac{\eta_v p_{col} N_{mot} V_d}{120 T_{col} R} \quad (1)$$

where N_{mot} is the engine's speed, V_d is the engine's volume and η_v is the volumetric efficiency usually given as an empirical function depending on p_{col}, T_{col} and N_{mot}. The estimation of the turbine speed is done using an inversion of the compressor's data-map which depends on p_{ape} and $Q_{comp} = Q_{air} + Q_{egrl}$. Q_{egrl} and Q_{egrh} are estimated separately using the results in [12]. Also, a mass flow rate measurement of Q_{egrh} can be available in the case of dual-EGR operation.

PROBLEM FORMULATION

As mentioned before, various approaches to estimate the exhaust manifold pressure p_{avt} have been addressed in the literature for different purposes such as HP-EGR mass flow rate estimation and diagnosis, among others. However, most of the approaches found in the literature approximate the VGT mass flow rate by a modified version of the orifice equation which neglects the effect of the turbine speed. In many applications, such as in [8], this seems an adequate assumption due to the behavior of the turbocharger considered. Nevertheless, this assumption can not be generalized for all the VGT because it is often found that the turbine speed has a significant effect on the turbine mass flow rate. The estimation of the exhaust manifold pressure under these conditions has not been found in the literature. Neglecting the turbine speed can result in a under-estimation or over-estimation of the exhaust manifold pressure depending on the turbine speed (see Figures 4 and 5). The problem of estimating the exhaust pressure, taking into account the effect of turbine speed, is the main concern of this work.

Let us define some important variables to be considered in this work. The turbine pressure ratio, denoted PR_t is defined as follows:

$$PR_t = \frac{p_{avt}}{p_{apt}} \quad (2)$$

where p_{apt} is the pressure downstream the turbine. As this pressure is not measured, its value can be approximated as:

$$p_{apt} = p_{air} + DP_{exh} + DP_{dpf} \quad (3)$$

where DP_{exh} is the differential pressure through the exhaust valve EXH, which can be estimated using the orifice equation and an empirical function that relates the valve sectional area with its position. The mass flow rate through the turbine is often described by extrapolated data-maps from the performance characteristics given by the suppliers in order to cover a larger operating region of the turbine [10] [11]. Usually, these data-maps are given in terms of corrected turbine mass flow rate Q_{tcorr} defined as:

$$Q_{tcorr} = Q_t \frac{p_{ref}\sqrt{T_{avt}}}{p_{avt}\sqrt{T_{ref}}} \quad (4)$$

and corrected turbine speed N_{tcorr}

$$N_{tcorr} = N_t \frac{\sqrt{T_{ref}}}{\sqrt{T_{avt}}} \quad (5)$$

where p_{ref} and T_{ref} are some given reference pressure and temperature. The three-dimensional data-maps for a VGT can be expressed in the following form:

$$Q_{tcorr} = datamap(x_{vgt}, N_{tcorr}, PR_t) \quad (6)$$

where x_{vgt} is the VGT position. The corrected turbine flow rate can be obtained for any set of inputs using look-up table techniques and trilinear interpolations as long as the inputs are contained in the defined data-map range.

Figure 2 shows how a data-map of the VGT considered in this work looks for a given VGT position. Note that in the right figure, the dependence of the turbine mass flow rate with respect to the turbine speed is significant. Clearly, not taking it into account in the exhaust pressure estimation method may introduce important inaccuracies in the result.

Let us express (6) in terms of non-corrected quantities:

$$Q_t = data\left(x_{vgt}, N_t \frac{\sqrt{T_{ref}}}{\sqrt{T_{avt}}}, \frac{p_{avt}}{p_{apt}}\right) \frac{p_{avt}\sqrt{T_{ref}}}{p_{ref}\sqrt{T_{avt}}} \quad (7)$$

Note that in (7), the mass flow rate through the turbine can be directly found using the data-map with the VGT

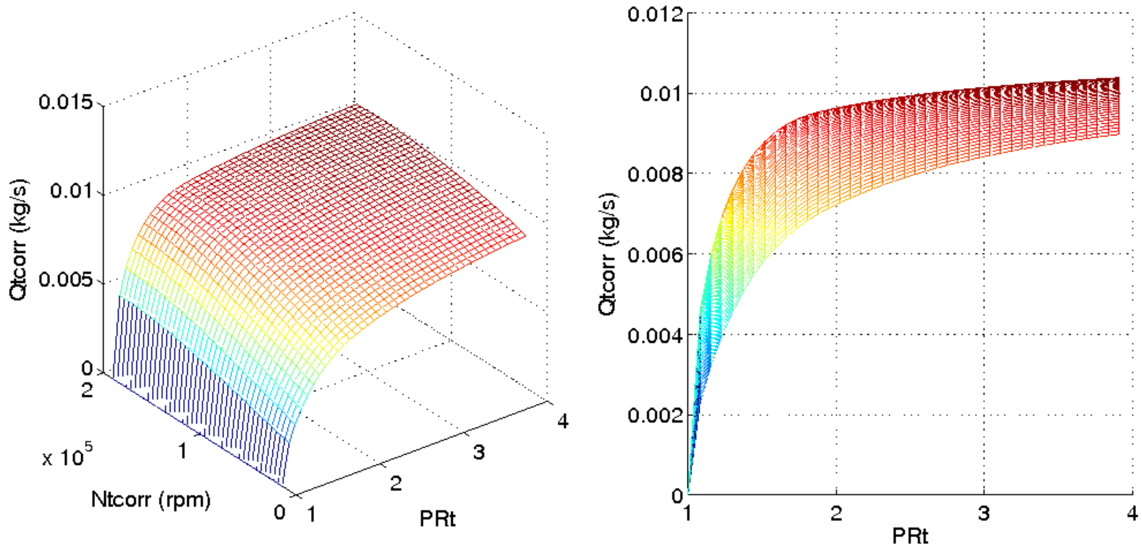

Figure 2: Turbine flow data-map for a VGT position of 65%

position, the turbine speed and the exhaust pressure. However, if the goal is to find an exhaust pressure for a given turbine mass flow rate (the inverse problem), the solution is much more complicated as can be clearly seen in (7). In the next section, a method to find the exhaust manifold pressure p_{avt} from a turbine mass flow rate using (7) is proposed.

EXHAUST PRESSURE ESTIMATION

As previously mentioned, several exhaust pressure estimators have been proposed in the literature. Mainly, three different types of approaches are found in the literature: an observer based on a non-linear dynamical model [7], a modified version of the orifice equation [13] and a non-linear coordinate transformation to a dimensionless VGT model [8]. However, existing exhaust manifold pressure estimation techniques neglect the effect of the turbine speed on the turbine mass flow rate, which is not always negligible as shown in Figure 2. Another mutual characteristic of the presented estimation strategies is the manipulation of the data-maps or the development of approximated models such as the orifice equation for describing the turbine mass flow rate, which may be time consuming and supplementary data needs to be uploaded into the vehicle controller.

In this section, an exhaust manifold pressure estimator is conceived, directly based on the traditionally used extrapolated turbine data-maps (equation (7)), without applying any reduction or manipulation on them. The benefits obtained from this approach are:

- B-1: no approximated model calibration has to be performed for estimation purposes;
- B-2: the turbine speed's effect on the mass flow rate is considered;
- B-3: the time response of the estimator can be chosen;
- B-4: it is not an iterative method, suitable for real-time applications;

In this work, a Newton-Raphson based method is used to perform the estimation of the exhaust manifold pressure. However, no iteration is done as the proposed strategy approaches the solution in time instead of defining a convergence criterion to meet every time step by means of an iteration procedure as done in the traditional Newton-Raphson algorithm. More precisely, in the proposed method, the estimation of the exhaust pressure is upgraded every time step using a non-iterative Newton-Raphson like method, assuming that the variations of the estimator's inputs are much slower than the time response of the method.

In order to introduce the proposed estimation method, consider first the traditional Newton Raphson method:

$$x^{it+1} = x^{it} - \alpha_{NR} \frac{f(x^{it})}{f'(x^{it})} \tag{8}$$

where $0 < \alpha_{NR} < 1$. The convergence criterion is usually defined by $\mid f(x^{it}) \mid < \epsilon$ where f is a well-behaved function and $f(x^*) = 0$, x^* being a root of

f. Note that the derivative of f with respect to x has to be calculated in order to update x^{it}. Evaluating this derivative is not always an easy task, as shown later. The parameter α_{NR} sets the convergence speed, the smaller the value, the slower the convergence. However, as α_{NR} decreases, the robustness of the method increases, a property that is considered in the proposed method. The Newton-Raphson method is an iterative method whose convergence can not be always guaranteed. Also, the amount of iterations to reach the solution is unknown, which is undesirable for real time implementation in a vehicle controller.

A gradient based method (such as the NR method) is a good approach to solve an equation like (7) because, as seen in Figure 2, the turbine mass flow rate data-map is typically convex downward which permits to approach the solution using the information given by the derivative [10]. However, as previously said, the NR algorithm is not convenient for this application as the amount of iterations at every time step is unknown and the convergence is not guaranteed due in this case, to numerical limitations of the engine controller. Consider the following method to upgrade every time step (without iterations) the estimation of the turbine pressure ratio inspired in the NR algorithm:

$$\hat{PR}_t^{n+1} = \hat{PR}_t^{n} - \alpha_t \frac{f_t(\hat{PR}_t^{n})}{f_t'(\hat{PR}_t^{n})} \tag{9}$$

where $\hat{PR}_t^{n+1}$ is the estimation of the turbine pressure ratio at the next time step, $\hat{PR}_t^{n}$ is the estimation at the actual time step, n denotes the time step and α_t is equivalent to α_{NR}. Let us define the function f_t in terms of the pressure ratio $\hat{PR}_t$:

$$f_t = Q_t - data\left(x_{vgt}, N_t\frac{\sqrt{T_{ref}}}{\sqrt{T_{avt}}}, \hat{PR}_t\right)\frac{\hat{PR}_t p_{apt}\sqrt{T_{ref}}}{p_{ref}\sqrt{T_{avt}}} \tag{10}$$

f_t will be zero when the pressure ratio estimation error equals zero. Evaluating the derivative with respect to $\hat{PR}_t$ is not an easy task. Calculating it analytically gives a large expression and a data-map having the derivative with respect to PR_t has to be built and stored in the real-time controller. Usually it is more efficient to approximate f_t' in a way not only to avoid the calculation of the derivative, but also save linear algebra work and matrix storage. The price of such an approximation is that the method converges more slowly. However, the overall cost of the solution is significantly less expensive [14]. Consider the following secant based upgrade function:

$$\hat{PR}_t^{n+1} = \hat{PR}_t^{n} - \alpha_t \frac{\delta PR\, f_t(\hat{PR}_t^{n})}{f_t(\hat{PR}_t^{n} + \delta PR) - f_t(\hat{PR}_t^{n})} \tag{11}$$

where δPR is a defined small change of pressure ratio to approximate the derivative of f_t. The schematic presented in Figure 3 describes the proposed method.

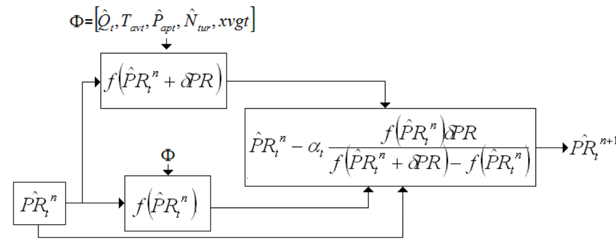

Figure 3: Proposed method schematic

As seen in 3, it is only required to carry out twice the trilinear interpolation using the turbine data-maps at each time step. Then, using the results obtained, (11) allows obtaining the value of the estimated turbine pressure ratio in the next time step. The estimation of the exhaust manifold pressure is then obtained by:

$$\hat{p}_{avt}^{n} = \hat{PR}_t^{n} p_{apt} \tag{12}$$

The estimator can be initialized using a measurement of p_{avt} if available or using a predefined value in order to reach the exhaust pressure as fast as possible. However, it is not essential to initialize the estimator close to the solution as long as p_{avt}^0 is inside the data-map range. The parameter α_t can be fixed between 0 and 1 to set the desired convergence speed of the estimator. The greater α_t, the faster the convergence but the lesser the robustness. Note that the calculation load is the same at every time step which is very convenient when working with real-time applications.

ESTIMATOR RESULTS

In this section, the performance of the estimator is evaluated using an engine model validated in a benchmark as a reference. A comparison with respect to an orifice-based estimation method is performed with the purpose of illustrating the gain in the estimation accuracy when the turbine speed in taken into account. The reference model validation has been done using 147 engine operating conditions at steady-state and in transient conditions using the

NMVEG cycle as well as with two additional engine cycles. An accuracy better than 10% (with respect to the benchmark measurements) has been obtained for most of the operating conditions, which allows considering the model to be representative of the engine. The estimator evaluation is done using two different engine cycles. Figures 4 and 5 show the results obtained with $\alpha_t = 0.02$, $\delta PR = 0.01$ and sampling time of 5 ms.

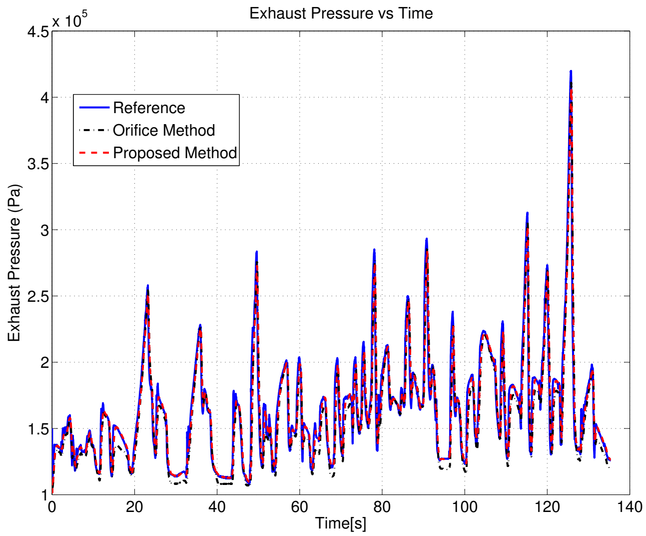

Figure 4: Exhaust manifold pressure estimation (Cycle 1)

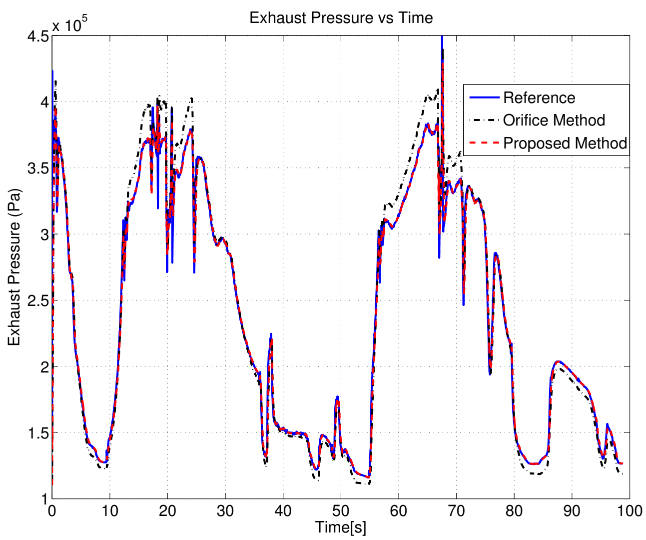

Figure 5: Exhaust manifold pressure estimation (Cycle 2)

As depicted in Figures 4 and 5, it can be seen that the proposed estimator rapidly reaches the reference. The orifice-based method presents an inaccurate response at some engine operating conditions due to the effect of the turbine speed on the mass flow rate. The estimation error corresponding to Figure 5 is given in Figure 6, which shows how the estimation error converges towards zero under strong transient conditions.

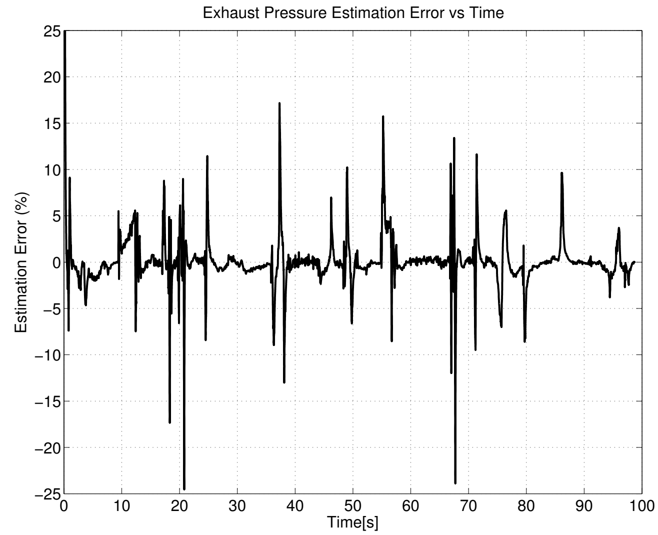

Figure 6: Exhaust manifold pressure estimation error (Cycle 2)

In order to illustrate the effect of α_t on the pressure estimation, a response comparison with three different values of α_t is performed. Figure 7 presents in detail the results obtained (a zoom in at a strong transient).

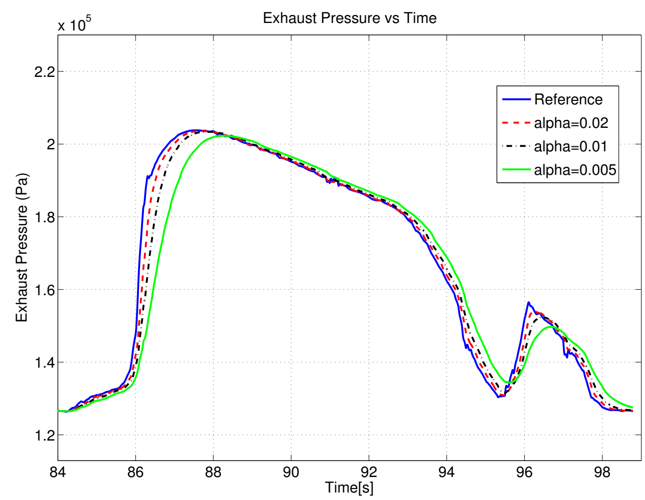

Figure 7: Response comparison between different α_t

As depicted in Figure 7, when α_t is increased, the estimator response becomes faster. Nevertheless, it is important to take into account that as α_t increases, the robustness of the estimator decreases. For this application, the value $\alpha_t = 0.02$ has shown to be a good choice for the exhaust manifold pressure estimation.

CONCLUSIONS

In this paper, an exhaust manifold pressure estimator is designed using directly the variable geometry turbine mass flow rate data-maps and a modified Newton-Raphson based method. This iteration-free estimator takes into account the effect of the turbine speed on the turbine mass flow rate which allows achieving more accurate pressure estimations. A very interesting feature of the method is that no model calibration has to be performed for the estimator, the only parameter to choose is α_t that permits adjusting the convergence speed and the robustness of the estimator. The exhaust pressure estimator has been evaluated using, as a reference, a model previously validated with experimental measurements. The results show the good agreement of the estimator with respect to the reference model.

The next step in this work is to perform an experimental validation of the estimator in an engine benchmark and the eventual the implementation in a production engine. A natural extension of this work could be the improvement of the VGT positioning algorithms based on the exhaust pressure estimation method.

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