

Data Driven Estimation of Exhaust Manifold Pressure by Use of In-cylinder Pressure Information

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ABSTRACT

Although the application of cylinder pressure sensors to gain insight into the combustion process is not a novel topic itself, the recent availability of inexpensive in-cylinder pressure sensors has again prompted an upcoming interest for the utilization of the cylinder pressure signal within engine control and monitoring. Besides the use of the in-cylinder pressure signal for combustion analysis and control the information can also be used to determine related quantities in the exhaust or intake manifold. Within this work two different methods to estimate the pressure inside the exhaust manifold are proposed and compared. In contrary to first principle based approaches, which may require time extensive parameterization, alternative data driven approaches were pursued. In the first method a Principle Component Analysis (PCA) is applied to extract the cylinder pressure information and combined with a polynomial model approach. In the second method an approach which uses the full pressure trace over the crank angle, also in combination with a polynomial model, is applied.

Experimental validation on a Common Rail Diesel engine in different operating conditions led to promising results, e.g. with the PCA approach the exhaust manifold pressure estimation achieved an average error of less than 1% over a wide operating range.

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INTRODUCTION

Modern Diesel combustion engines have become complex mechatronic systems with a high number of actuators, like common rail injectors, EGR and throttle valves, variable geometry turbines, and sensors. All of these components are necessary to ensure the main functionality of the engine, or in other words to provide the driver demanded torque, while maintaining high efficiency of the combustion process, in compliance with emission legislation and diagnostic functions [1]. The control tasks typically are divided into several subsystems controls, like the control of the fuel path, the air system or the exhaust aftertreatment system. To effectively address these control tasks information about the

actual state of the engine is required, either as feedback or as monitoring quantities. Moreover, many of the diagnostic functionalities in an ECU involve actual engine information. Consequently modern engines are equipped with a large amount of different sensors, for example air mass flow, temperature, pressure or lambda sensors [2]. Some sensor types, like in-cylinder pressure sensors are only used in research and development processes, due to cost reasons. These sensors can provide valuable insights into the combustion process and also be used for combustion diagnostics and control [3] or for cycle based optimization of the fuel economy [4]. Recently also production type cylinder pressure sensors have been introduced and are already used in

series production engines for the control of the combustion process to achieve low exhaust emissions [5]. Since such sensors are already implemented, it comes naturally to use their valuable information about the combustion process to estimate additional quantities, like for example the air mass flow [6], the trapped cylinder mass [7] or the pressure in connected manifolds. Another example is given in [8], where different quantities, like air mass flow or intake and exhaust pressure, are estimated based on the cylinder pressure traces. In this work wavelets are used to extract the relevant information of the pressure trace and the models are based on an artificial neural network. The discrete wavelet transformation is used to reduce the data amount which is gathered by the measurement of the cylinder pressure traces. In another works [9, 10] Principal Component Analysis [11] was used to reduce the data amount whilst maintaining the important information. In particular, it was applied to design NOx and emission models based on the in-cylinder pressure measurements and a static polynomial model. This particular approach will be adapted within this work for the estimation of exhaust manifold quantities. A similar PCA based method was used in [12] in combination with a neural network to design an estimator for NOx emissions, lambda and opacity of a HD Diesel engine.

In this work the main focus will be on the estimation of the exhaust manifold pressure of a turbocharged Diesel engine with high pressure EGR. Up to now, the exhaust pressure is often directly measured by a pressure sensor which is mounted in the exhaust manifold. The pressure information is for example necessary for EGR mass flow control, because it requires knowledge of the pressures in inlet and exhaust manifold to ensure an EGR flow in the desired direction. Moreover, the exhaust manifold pressure can also be used in model based control tasks, e.g. to provide information about the pressure difference over the turbo charger or to estimate the pumping losses due to the backpressure when the exhaust valves are open. The main influences for the cylinder pressure are the fuel amount and engine speed, which are related to the pressure inside the combustion chamber and thus during the exhaust valve opening directly connected with the manifold. Obviously also the position of the EGR valve and the guide vanes of the turbo charger have an effect on the exhaust manifold pressure, by throttling the gas flow.

The rest of this work is structured as follows: first the system and experimental setup which were used to identify and validate the models are presented. Next a brief introduction of the developed methods for the exhaust gas pressure estimation and the performed identification experiments is given. Afterwards both approaches are compared against each other and evaluated with validation measurements.

SYSTEM SETUP

For the design and evaluation of both exhaust pressure estimation methods experiments on a real combustion engine were performed. The considered engine is a 2 liter 4 cylinder Diesel engine equipped with common rail injection system, cooled high pressure EGR and a variable geometry turbine turbo charger with charge air intercooling. Besides the production standard sensors the engine is outfitted with high precision test bench equipment and of course in-cylinder pressure sensors. The in-cylinder pressure was measured in all 4 cylinders with Kistler GU13G14 sensors which were mounted instead of the glow-plugs. During the experiments the engine itself was operated at the dynamical engine test bench, see Fig 1. The pressure in the exhaust manifold was acquired with two different sensors, the production standard sensor and also a high precision water cooled Kistler indicated pressure sensor.

The indicated pressure signals from the cylinders and exhaust manifold were recorded with an AVL Indismart Gigabit, with a resolution of 0.5 CAD. Thus during one cycle of 720° crankshaft rotation 1440 samples were obtained. The offset and drift compensation of the in-cylinder pressure sensors was performed internally by the Indismart device. Further it should be mentioned that one cycle was introduced from -360° to 360° crank angle, where 0° corresponds to the top dead center before the combustion stroke.



Fig 1. Engine test bench at JKU Linz

The engine is further equipped with an open bypass ECU which was used in combination with a real time dSpace system to control the EGR valve and VGT guide vane position during the system identification and validation measurements. The direct control of those inputs was necessary to cover a wide operating range, even outside the standard engine calibration, during the experiments. Except for the cylinder pressure traces all the other signals were recorded with the dSpace system and additionally also a signal related to the current combustion cycle was transmitted to synchronize the dSpace and Indismart measurements after the experiments. Finally, it should be noted that the test cell

itself and also the intake air were fully conditioned to provide a high repeatability. A detailed overview of the whole test environment is presented in Fig 2.

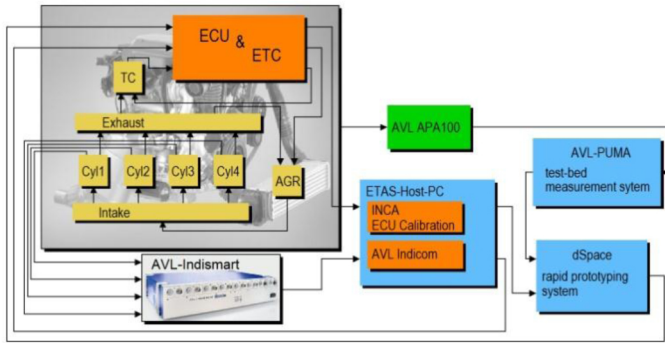


Fig 2. Experimental setup

METHODS DESCRIPTION

In order to estimate the pressure inside the exhaust manifold based on the measured in-cylinder pressure two different methods were developed:

1. PCA (Principal Component Analysis) based method
2. CA (Crank Angle) based method

The first method uses Principal Component Analysis to reconstruct the indicated pressure with a limited number of features, which are used as input for a black box polynomial model that returns the exhaust pressure as output. With this method it is only possible to determine a mean value of the pressure over a complete revolution of the crank shaft. As a consequence, the pressure oscillations inside the manifold, which occur due to gas flow dynamics and the opening and closing of the valves, cannot be estimated. Even if in practice it could be useful to use the mean of the four indicated pressures, in order to increase robustness, an advantage of this method compared to the second approach is that theoretically only the indicated pressure trace of one cylinder is necessary. The second method instead relies on the measure of every cylinder indicated pressure, and by using them as direct inputs for a black box polynomial model an accurate estimation of the pressure inside the manifold can be given, including the oscillations over the engine revolution. In the following paragraphs a detailed description of both methods will be given.

PCA Based Method

As already mentioned in the section above the indicated pressure sensor provides 1440 values during a complete revolution of the engine (1 value each 0.5° CAD). In order to obtain a reduced set of inputs for the polynomial black box model, the use of Principal Component Analysis (PCA) is suggested, since it represents a good compromise between accuracy and simplicity. Principal Component Analysis, or *Karhunen-Loève Transform*, is a method that allows to

project data on a subspace of lower dimensions, minimizing the mean square distance between the original points and their projections. Let's define P_i as a $r \times 1440$ matrix in which the measured indicated pressure values over r engine cycles are collected in vertical vectors and placed side by side. The indicated pressure signals can be written as:

$$P_i = U \Sigma V = \sum_{i=1}^r \sigma_i u_i v_i^T, \quad (1)$$

where u_i and v_i are suited orthogonal vectors, U and V are matrices composed by juxtaposing respectively u_i and v_i , and Σ is a diagonal matrix in which the values on the diagonal correspond to each singular value σ_i , $i = 1, \dots, r$. Thanks to the singular value decomposition (SVD) the singular values in the matrix Σ are sorted according to their relevance.

By selecting a reduced number $m < r$ of singular values, an approximated pressure P_{iR} can be reconstructed, with accuracy bounded by:

$$\varepsilon_j = \sum_{i=m+1}^r \sigma_i^2. \quad (2)$$

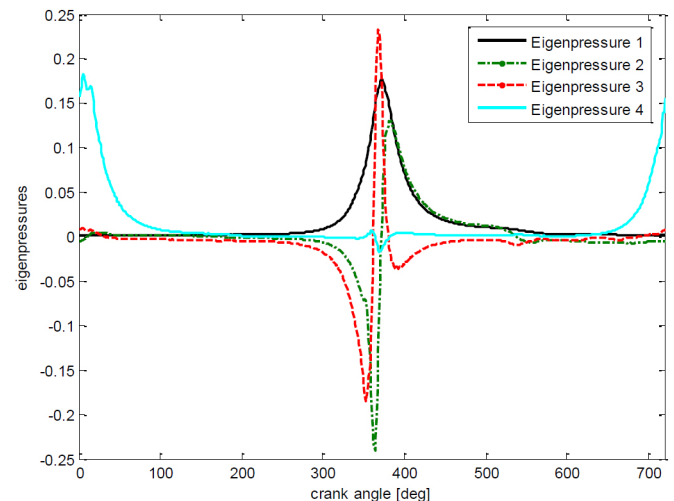


Fig 3. PCA - Eigenpressures (only the first four eigenpressures are shown)

In so doing P_{iR} is expressed as a linear combination of the first m eigenvalues or *eigenpressures*, of the data matrix P_i . As an example a selected set of the first eigenpressures is given in Fig 3. The coefficients of the linear combination are called *features*. Only a small number of features is necessary to obtain a well-defined reconstruction of P_i . In this work 10 singular values are used. This choice is motivated by the results of the singular values plot presented in Fig 4. Here it can be seen that the singular values are decreasing for the increasing feature index and that the additional information