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Determining the Initial In-Cylinder Gas State Based on Semi-Physical Models

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Abstract: Two methodologies are presented for modeling the initial in-cylinder gas state prior to the combustion. The first method is based on measured in-cylinder pressure data and allows the cylinder individual calculation of the gas mass and temperature. A physical equation for the online calculation of the polytropic exponent during the compression stroke is derived in order to receive accurate absolute pressure data from piezo based in-cylinder pressure sensors. In order to model the in-cylinder temperature an additional semi physical model is proposed to account for the heat input during the intake stroke. From the first methodology a second semi-physical model for the average in-cylinder gas mass and temperature is derived which will only need cylinder pressure data for the calibration process of the experimental model.

Keywords: cylinder, gas mass, temperature, semi-physical, model, engine, polytropic exponent

1. INTRODUCTION

The legal requirements on emission limits are continuously increasing. With the new upcoming Worldwide harmonized Light Vehicles Test Procedures (WLTC) the legal emission test cycles are highly dynamic and require optimal engine control during dynamic engine operation.

In previous work, Zydek (2015), it was shown that the dynamic engine operation can be optimized if the actuation variables of the combustion as e.g. rail pressure, injection angle and swirl flap position are not just set according to the engine operation point defined by engine speed and injection mass but also by the gas state in the cylinder just prior to the combustion. During dynamic engine operation the in-cylinder gas state is constantly changing from cycle to cycle. The emissions of NO_x and soot could be reduced and the efficiency increased if the set points for the actuation variables of the combustion were optimized for all possible initial in-cylinder gas states.

In the following, two methodologies are explained to calculate the in-cylinder gas mass and temperature. At first a more precise cylinder individual procedure with little necessary calibration effort based on in-cylinder pressure measurement is presented. From this methodology a second is derived which does not need in-cylinder pressure measurement but will require a higher amount of calibration effort.

1.1 Definition of the Initial In-Cylinder Gas State

The ideal gas law defines the thermal gas state in the cylinder:

$$p_{cyl} V_{cyl} = m_{cyl} \mathrm{R_s} T_{cyl} \tag{1}$$

The variables p_{cyl}, V_{cyl}, T_{cyl}, and m_{cyl} are the in-cylinder pressure, volume, temperature, and mass. $\mathrm{R_s}$ is the specific gas constant for air. The specific gas constant is a function of pressure and temperature but can be regarded as being constant for the beginning of the compression stroke. Since the volume of the cylinder is known, only two variables have to be determined to fully describe the thermal gas state. Additionally the air mass fraction is introduced as a third state to account for the influence of recirculated exhaust gas mass.

$$X_{air} = \frac{m_{air}}{m_{gas}} \tag{2}$$

As a result the initial gas state is defined as follows:

$$\varsigma = \begin{bmatrix} T_{cyl} & m_{cyl} & X_{cyl} \end{bmatrix}^T \tag{3}$$

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2. CALCULATION OF THE ABSOLUTE IN-CYLINDER PRESSURE

2.1 Determining the Polytropic Exponent During the Compression Stroke

In-cylinder pressure sensors based on the piezoelectric effect can measure relative pressure values only. To convert the relative pressure values to absolute ones different methodologies have been published in the past. The method often referred to was published by Hohenberg (1982). The proposed methodology is based on the assumption that a constant polytropic state change (k=const.) prevails during a limited range of the compression stroke and can therefore be described by the Poisson's relation of pressure and volume:

$$\frac{p_2}{p_1} = \left(\frac{V_1}{V_2}\right)^k \quad (4)$$

The absolute pressure

$$p = p_{\mathrm{rel}} + \Delta p_{\mathrm{off}}, \quad (5)$$

is the sum of the measured relative pressure p_{rel} and the unknown offset Δp_{off}. By inserting (5) into (4) and resolving into Δp_{off}

$$\Delta p_{\mathrm{off}} = \frac{\left(\frac{V_1}{V_2}\right)^k p_{1,\mathrm{rel}} - p_{2,\mathrm{rel}}}{1 - \left(\frac{V_1}{V_2}\right)^k}, \quad (6)$$

it is possible to calculate an estimate for the pressure offset. As proposed by Gilkey (1985) the precision of the estimated pressure offset can be improved if the pressure offset is not directly calculated by (6) but based on measured data determined by the least squares method.

When using the in-cylinder pressure data for calculating the in-cylinder gas mass, accurate pressure data in the pressure range below 10 bar is required. If precise absolute pressure data is required the assumption of a constant polytropic process no longer holds and has to be regarded as a variable polytropic process.

The heat transferred during a polytropic compression of air can be described by:

$$Q_{12} = \frac{k - 1.4}{0.4} \frac{p_1 V_1}{n - 1} \left[\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} - 1 \right] \quad (7)$$

For the polytropic compression stroke of an engine an exponent k higher than 1.4 does therefore denote that the compressed air is gaining heat. Vice versa if the polytropic exponent is smaller than 1.4 the compressed air is losing heat. The polytropic exponent k can therefore be regarded as an indicator for wall heat losses. It should therefore decrease if the in-cylinder gas temperature rises relative to the cylinder wall temperature respectively increase if the in-cylinder gas temperature falls.

Different methodologies have been presented to estimate the polytropic exponent during the compression stroke. Hart (1998) is modelling the polytropic exponent based on the coolant temperature. Klein (2009) uses an Extended Kalman Filter with Markov-2-Prozess to estimate the course of the polytropic exponent during the compression stroke. This gives good results but is computational intensive and will require the tuning of the covariance matrices.

In the following a methodology is presented which is based on a physical equation and will therefore allow the direct computation of the polytropic exponent during engine operation causing no notable computational effort.

A polytropic process is described by the Poisson's relation (4). It can be rewritten:

$$pV^{\mathrm{k}} = \mathrm{const.} \quad (8)$$

Its derivative with respect to time is:

$$\frac{dp}{dt} V^k + \kappa p V^{\kappa-1} \frac{dV}{dt} = 0 \quad (9)$$

This equation can be resolved into κ:

$$-\kappa = \frac{dp / p}{dV / V} \quad (10)$$

Therefore the polytropic exponent describes the linear relation between the relative changes of in-cylinder pressure and in-cylinder volume. Unfortunately this equation still includes the absolute pressure p which can not be measured. To eliminate p (10) can be rewritten:

$$V \frac{dp}{dV} = -\kappa p \quad (11)$$

When differentiating (11) partially with respect to V the following expression for the polytropic exponent results:

$$1 + V \frac{d\left(\frac{dp}{dV}\right)}{dp} = -\kappa \quad (12)$$

Since the derivative of dp/dV is,

$$\frac{dp}{dV} = \frac{dp_{\mathrm{rel}}}{dV} + \frac{d(\Delta p_{\mathrm{off}})}{dV} = \frac{dp_{\mathrm{rel}}}{dV} \quad (13)$$

equation (12) is now independent of the absolute pressure data and the polytropic exponent κ can directly be calculated by the measured relative pressure data. With $dp \approx \Delta p = p(\mathrm{k}) - p(\mathrm{k-1})$ and $dV \approx \Delta V = V(\mathrm{k}) - V(\mathrm{k-1})$ equation (11) can easily be implemented on a real time hardware.

Since (12) contains a second order derivative a mean polytropic exponent over a range of five to ten degrees crank