2001-01-0262

Air-to-Cylinder Observer on a Turbocharged SI-Engine with Wastegate

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ABSTRACT

Observers for air mass flow to the cylinder is studied on a turbocharged SI-engine with wastegate. A position change of the wastegate influences the residual gas mass and causes the volumetric efficiency to change, which produces a transient in the air mass flow to the cylinder. Two standard methods of estimating air-to-cylinder are investigated. A new nonlinear air-to-cylinder observer is suggested with two states: one for intake manifold pressure and one for the offset in in-cylinder air mass compared to expected through the volumetric efficiency. The observers are validated on intake manifold pressure data from a turbocharged spark ignited production engine with wastegate.

INTRODUCTION

The growing demand for lower emission spark ignition engines requires good control of air/fuel ratio since the three-way catalyst has a very narrow operating region with good conversion efficiency of hydrocarbons, carbon monoxide and nitrogen oxides. To keep the conversion ratio high, the air fuel ratio must be kept within a few percent of stoichiometric [1].

Turbocharged spark ignition engines are getting more popular since the engine can be made smaller and therefore have lower fuel consumption [2]. To control the power to the turbine, these engines are commonly equipped with a wastegate. It governs the amount of gases passed through the turbine. More gases through the turbine result in more power to the compressor and a higher exhaust pressure. Air mass to cylinder depends on the pressure ratio between the exhaust manifold pressure and the intake manifold pressure [1, 3]. A change in exhaust manifold pressure will therefore require a change in injected fuel to maintain the air/fuel ratio.

On SI engines the air mass flow is governed by the throttle and the injected fuel mass is calculated based on the amount of air mass to the cylinder. The air mass flow to the cylinder is not directly measurable and therefore many strategies to estimate it have been proposed. The strategies combine the use of air mass flow sensor, throttle plate angle, pressure and temperature sensors in the air intake system.

The two most common principles to calculate air mass to cylinder will be addressed here, first the measured air mass flow, and second the speed density principle.

Measured Air Mass Flow Principle

One principle to base the fuel calculations on is the measured air mass flow. On the research engine, the air mass flow sensor is located close to the air filter. The air mass flow to the cylinder will differ from the measured during transients since the volume between the sensor and the cylinder is considerable and the resulting pressure dynamics in the intake system due to filling/emptying. This dynamics is excited when the wastegate is operated due to a change in air mass flow to the cylinder. In Figure 1 the dynamics of the air system is shown when the wastegate is operated during constant speed of the engine. If the air mass flow sensor is used to calculate injected fuel there will be approximately a 5% error during the operation of the wastegate due to the filling/emptying dynamics of the intake system.

Speed-Density Principles

The speed-density methods use volumetric efficiency, engine speed, and intake manifold pressure and temperature to determine the air mass flow to cylinder. Speed-density methods have the advantage of estimating the air to the cylinder which do not suffer from the sensor dynamics of the air mass flow sensor [4] or the filling and emptying dynamics of the intake manifold [1]. To reduce noise, due to standing waves and engine pumping, in the intake manifold pressure signal, observers for mean intake manifold pressure have been proposed [4, 5].

A standard method is to map the volumetric efficiency and compensate it for density variations in the intake manifold [1]. In Figure 2 the change in volumetric efficiency is shown when the wastegate is opened and closed. When the wastegate opens the exhaust pressure drops rapidly and there are less residual gases in the cylinder. More air can then enter the cylinder which increases the volumetric efficiency. In the lower plot of Figure 2 a 3% increase in η_{vol} is present as the conditions stabilize at 14

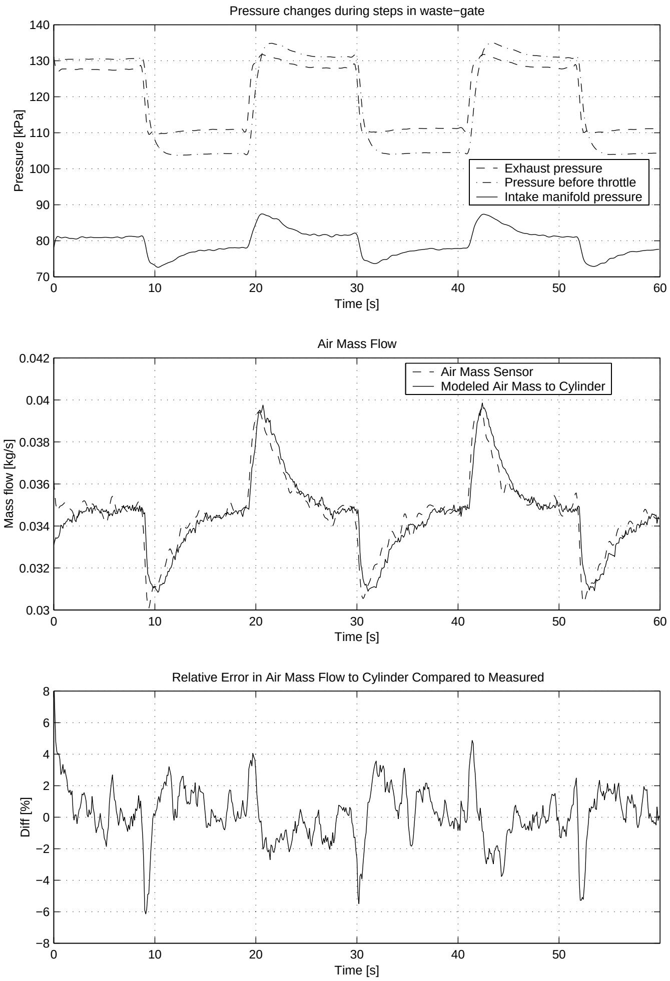

Figure 1: Measurements of the impact on measured air mass compared to estimated air mass to cylinder using the suggested two-state observer. *Top:* Pressure changes in exhaust system, intake system before throttle, and intake manifold pressure during manual operation of the wastegate. Wastegate is opened at 9, 30, and 52 seconds. It is closed at 19.5 and 41 seconds. During the test the engine speed was held constant. *Center:* Measured air mass flow, $\dot{m}_{\mathrm{a}_{\mathrm{sensor}}}$, from the sensor and calculated air mass flow to cylinder $\dot{m}_{\mathrm{ac}} = \eta_{\mathrm{vol}}\left(N, p_{\mathrm{man}}\right) \frac{p_{\mathrm{man}} V_d N}{2 R_{\mathrm{man}} T_{\mathrm{man}}}$. *Bottom:* The deviations from 0, in the relative difference $100\left(1 - \frac{\dot{m}_{\mathrm{a}_{\mathrm{sensor}}}}{\dot{m}_{\mathrm{ac}}}\right)$, is due to the filling and emptying dynamics of the intake system. Using the air mass flow sensor results in a 5% error compared to actual air mass to cylinder during the transient of the wastegate step.

and 37 seconds. Speed-density methods must therefore rely on feed-back from the oxygen sensor to compensate for the change in η_{vol}. The considerable transport delay and the sensor dynamics delay the detection of the change in air mass to cylinder which pose problems when using the oxygen sensor.

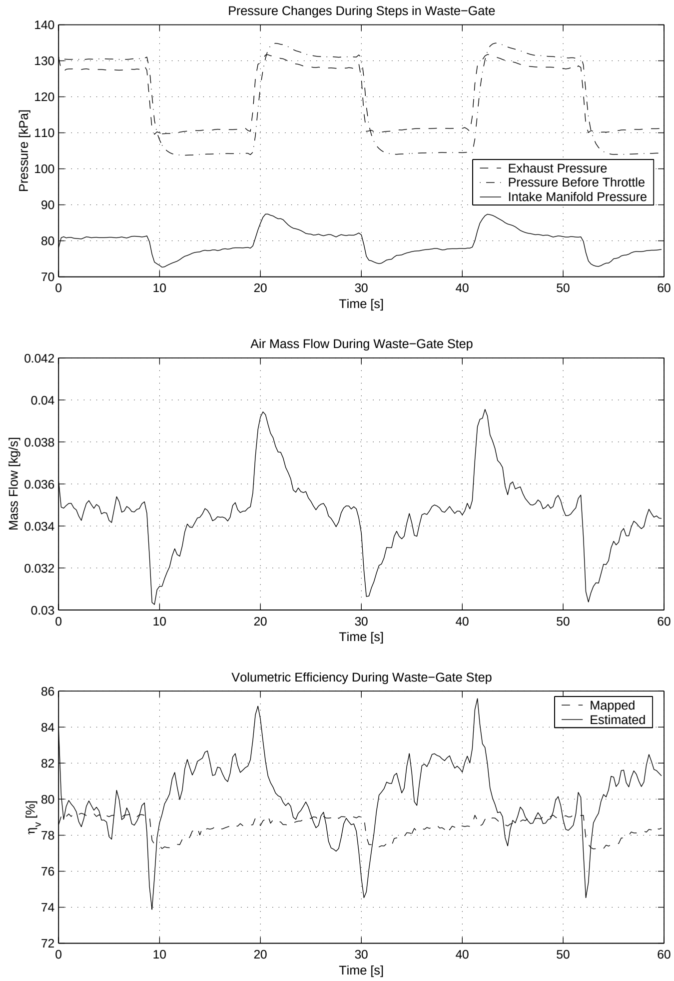

Figure 2: When the wastegate position have been changed the volumetric efficiency is affected. *Top:* Pressure changes in exhaust system, intake system before throttle, and intake manifold pressure during manual operation of the wastegate. Wastegate is opened at 9, 30, and 52 seconds. It is closed at 19.5 and 41 seconds. During the test the engine speed was held constant. *Center:* Measured air mass flow, $\dot{m}_{\mathrm{a}_{\mathrm{sensor}}}$. As the wastegate is opened the air mass flow decreased momentarily until the air mass controller has opened the throttle more. The throttle controller tries to maintain a constant air mass flow. *Bottom:* Calculated and estimated volumetric efficiency during the wastegate step. The volumetric efficiency increases as the pressure ratio $\frac{p_{\mathrm{exh}}}{p_{\mathrm{man}}}$ decreases. During the transients the estimated volumetric efficiency is not valid.

Outline of the work

The two standard methods described above for determining the air mass flow to the cylinder can not fully handle changes in air mass flow due to changes in the wastegate position. A strategy for estimating the air mass flow into the cylinder is developed. A change in wastegate position changes the exhaust back pressure which in turn influence the intake manifold pressure through the air mass flow to the cylinder. The strategy for estimating the air mass flow to the cylinder thus relies on: a fast pressure sensor in the intake manifold, sensors in the intake manifold and before the throttle, as well as a model for the intake system.

TEST SETUP

The measurements were performed on a 2.3 dm^3 turbocharged SAAB spark ignition engine with wastegate and drive-by-wire system. The engine is connected to an asynchronous Dynas 220 NT dynamometer, which is operated at constant speed mode. A PC controls the dynamometer and a research engine management system called Trionic 7 controls the engine. The engine management unit is connected to a PC in the control room using a CAN-bus. From the control room it is possible to control the throttle and the wastegate. The later was also manually operated with a handle.

The engine is equipped with additional pressure sensors produced by Kristall. The models 4293A2 and 4293A5 was used. Pressure sensors was placed before the throttle, in the intake manifold, and in the exhaust manifold before the turbine. There are also extra temperature sensors Heraeus ECO-TS200s, type PT200, in the intake manifold and between the intercooler and the throttle and in the exhaust manifold close to the turbine.

All measurements were performed with a VXI-instrument HPE 1415A from Hewlett-Packard. Engine mapping was performed with a sampling frequency of 10 Hz and the signals were low-pass filtered at 5 Hz to avoid aliasing. The engine mapping was performed from 1000 RPM up to 4800 RPM in steps of approximately 500 RPM. The lower limit was due to severe vibrations at higher loads. The engine was run 25 seconds in each engine point before a 5 second sampling was started. The median of the sampled data was then stored for 114 engine operating points.

Step response experiments where performed with the same instrument HPE 1415A and a sampling frequency of 1 kHz was used. Anti-alias filters were disabled due to the damping and delay introduced by the filter.

AIR INTAKE SYSTEM MODELING

In order to calculate the air mass flow to the cylinder using an observer the air intake system is modeled. A summary of available sensors and a system overview is given in Figure 3.

The intake manifold model is described in three steps; air mass flow into the manifold, air mass flow to the cylinder, and finally the intake manifold pressure dynamics is described. For description of the subscripts and symbol names, please see the nomenclature at the end.

Air Mass Flow Into the Intake Manifold

On the modeled engine the sensor for air mass flow is located after the air filter and the volume between the intake manifold and the sensor is considerable. The filling and emptying dynamics of the volume acts like a low pass filter and adds on to the

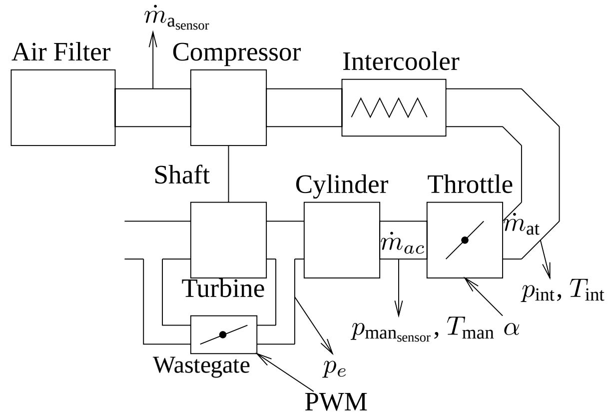

Figure 3: The air flow after the air-filter is measured by a hot-film air mass sensor, $\dot{m}_{a_{\text{sensor}}}$. The intercooler cools the air and there are sensors for pressure, p_{int}, and temperature T_{int}. The throttle is operated by setting the angle of the throttle plate, α. In the intake manifold there is one production pressure sensor, $p_{\text{man}_{\text{sensor}}}$. The wastegate can be controlled by a pulse width modulated (PWM) signal or manually.

sensor dynamics. To improve the estimation of air mass flow into the intake manifold, a throttle model is used. The air mass flow through the throttle, $\dot{m}_{\text{at}}$, is modeled as an isentropic flow through a restriction [1], described by Equation (1). The $\Psi\left(p_r\right)$ governs the flow through the restriction depending on the pressure ratio p_r, Equation (3). The function $Q\left(\alpha\right)$ is a product of the area $A\left(\alpha\right)$, and discharge coefficient $C_d\left(\alpha\right)$ [6] and it is fitted in least square sense to mapped engine data. In Figure 4 the result of the modeled $Q\left(\alpha\right)$ is shown. A systematic relative error present in the bottom right corner of Figure 4. The relative error is negative for small p_r and positive for large p_r which indicates that $Q\left(\alpha\right)$ could be slightly improved by including p_r, which is supported in [7].

$$\dot{m}_{\text{at}} = \frac{p_{\text{int}}}{\sqrt{R_{\text{man}}T_{\text{int}}}} Q\left(\alpha\right)\Psi\left(\frac{p_{\text{man}}}{p_{\text{int}}}\right) \tag{1}$$

$$Q\left(\alpha\right) = A\left(\alpha\right)C_d\left(\alpha\right) = Q\left(\alpha\right) = e^{c_2\alpha^2+c_1\alpha+c_0} \tag{2}$$

$$p_r = \frac{p_{\text{man}}}{p_{\text{int}}} \tag{3}$$

$$\Psi\left(p_r\right) = \begin{cases} \sqrt{\frac{2\gamma}{\gamma-1}\left(p_r^{\frac{2}{\gamma}} - p_r^{\frac{\gamma+1}{\gamma}}\right)} & \text{for } p_r > \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} \\ \sqrt{\frac{2\gamma}{\gamma-1}\left(\left(\frac{2}{\gamma+1}\right)^{\frac{2}{\gamma-1}} - \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}\right)} & \text{otherwise} \end{cases}$$

In Equation (1) both the pressure p_{int} and the temperature T_{int} before the throttle is needed. Measurements can be used since the dynamics of p_{int} and T_{int} is considerably slower than p_{man}, due to the substantially larger volume of the system before the throttle and to the slow dynamics of the compressor. They are also subjected to lesser pumping noise.

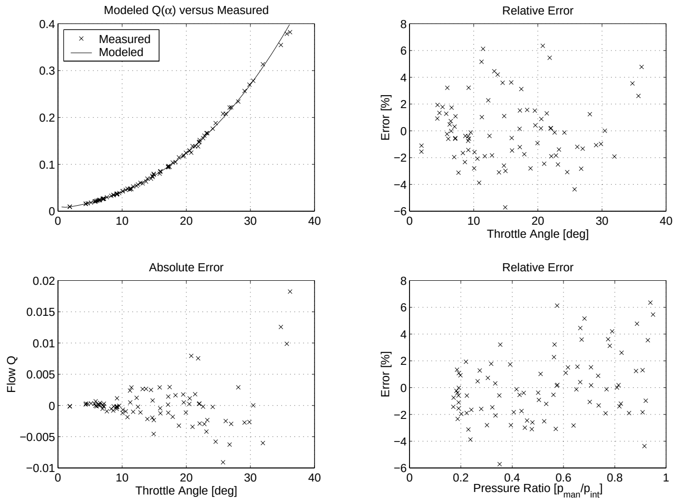

Figure 4: Comparison of measured and calculated $Q(\alpha)$. The fit is within 6% for most points. The absolute and relative error is shown as a function of throttle angle and note that the errors are spread equally around zero except for large α. In the bottom right corner the relative error as a function of pressure ratio is shown.

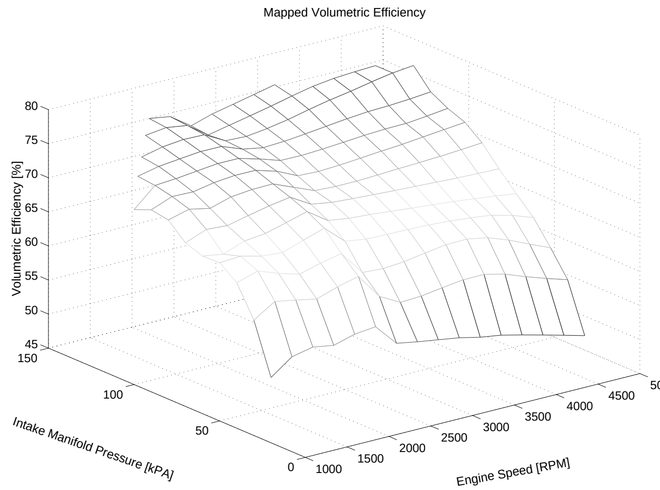

Figure 5: Mapped volumetric efficiency, η_{vol}, of the engine.

Air Mass Flow into Cylinder

A standard method of estimating air to cylinder [1, 3] and a time continuous version [8] is discussed in their capability of handling wastegate steps. From the discussion a new interpretation of air mass to cylinder is presented at the end.

Air Mass to Cylinder Using Mapped Volumetric Efficiency A standard method to calculate air mass flow into the cylinder is to use the volumetric efficiency of the engine η_{vol} [1, 3]. The volumetric efficiency is mapped at steady-state as a function of engine speed N and mean intake manifold pressure p_{man} [1]. For the engine used, the volumetric efficiency map is shown in Figure 5. The air mass flow to the cylinder is then written as

$$\dot{m}_{\text{ac}_{std}}(N, p_{\text{man}}, T_{\text{man}}) = \eta_{\text{vol}}(N, p_{\text{man}}) \frac{p_{\text{man}} V_d}{R T_{\text{man}}} \frac{N}{2} \tag{4}$$

On a turbocharged engine with wastegate, the exhaust manifold pressure changes when the wastegate is operated. A higher exhaust manifold pressure results in more residual gases which decreases the air mass flow into the cylinder. The mapped η_{vol} will give a certain in cylinder air mass provided intake manifold pressure, temperature, and engine speed. When the wastegates position is changed the residual gas mass also changes and the mapped η_{vol} does not properly describe the air mass flow into the cylinder, as shown in Figure 2. Other sources that influence the air mass to cylinder is ambient air moisture, or a change of fuel etc.

Integration of η_{vol} A day to day variation in η_{vol} of a few percent was reported in [8]. Their solution to the problem was to use an integrator that estimates the change in η_{vol} called $\Delta\eta_{\text{vol}}$. This approach leads to correct estimation of air mass to cylinder during steady-state conditions. A time lag is introduced while integrating η_{vol} to the new value after the transient.

$$\dot{m}_{\text{ac}_{ts}} = (\eta_{\text{vol}} + \Delta\eta_{\text{vol}}) \frac{p_{\text{man}} V_d N}{R_{\text{man}} T_{\text{man}} n_r} \tag{5}$$

Air Mass Flow to Cylinder With Offset Estimation The result of a change in volumetric efficiency is that the air mass in the cylinder changes. Suppose the in cylinder air mass offset, compared to the expected through η_{vol}, is called m. The air mass flow to the cylinder can then be written as

$$\begin{aligned}&\dot{m}_{\text{ac}}(N, p_{\text{man}}, T_{\text{man}}, p_{\text{exh}}, (A/F), \ldots) = \\ &\qquad \dot{m}_{\text{ac}_{std}}(N, p_{\text{man}}, T_{\text{man}}) - m(p_{\text{exh}}, (A/F), \ldots) \frac{N}{2}\end{aligned} \tag{6}$$

In Equation (6) the in cylinder air mass offset m is sensitive to the exhaust manifold pressure, the air/fuel ratio, and other sources such as model errors. The offset m can be estimated by the air-to-cylinder observer described later.

Intake Manifold Pressure Dynamics

To model pressure dynamics the gas is assumed to be ideal and the molar mass of the gas constant. Using the ideal gas law, mass conservation, and assuming constant temperature T_{man} in the intake manifold, the pressure change inside the volume of the intake manifold with the volume V_{man} can be written, with $C = \frac{R_{\text{man}} T_{\text{man}}}{V_{\text{man}}}$, as

$$\frac{\mathrm{d}p_{\text{man}}}{\mathrm{d}t} = C(\dot{m}_{\text{at}} - \dot{m}_{\text{ac}}) \tag{7}$$

In Equation (7) $\dot{m}_{\text{ac}}$ can be any of the described air to cylinder flows. Since the molar mass of the gas inside the intake manifold is assumed to be constant and therefore R_{man} is also constant. These are standard assumptions and the model is described in [9]. There is actually some temperature dynamics in the intake manifold during pressure transients and this have been investigated by [10] but it is neglected in this study.

The gas inside the intake manifold is mainly air and some residual gases which flow back into the intake manifold during intake valve opening. There is also some fuel which is injected close to the intake valve shortly before the intake valve opens. The effects of fuel vaporization in the intake manifold on air mass to cylinder is disregarded since: 1. The fuel mass is a small fraction of the total mass in the intake manifold and 2. The fuel dynamics adds unnecessary complexity during transients [11, 12].

AIR TO CYLINDER OBSERVERS

An observer for air mass to cylinder based on speed density principle needs the mean intake manifold pressure and the engine speed. Measured intake manifold pressure have to be filtered to reduce the noise from engine pumping and standing waves [4]. Drawbacks of filtering the pressure signal are the effects of the filter dynamics. Observers are therefore often proposed since they can filter the signal and predict manifold pressure during transients. Here a comparison is made of a nonlinear observer using proportional feedback [4] and a nonlinear observer using pure integration [8]. From the comparison a modified nonlinear observer is developed which takes advantage of the strengths of both structures and better suits the conditions in a turbocharged spark ignition engine with wastegate.

Observer with Proportional Feedback

A constant gain extended Kalman filter (CGEKF) [13] for the intake manifold pressure, Equation (7), with proportional feedback from the intake manifold pressure sensor, was suggested in [4]. This methodology resulted in the following observer for the intake manifold pressure

$$\frac{\mathrm{d}\hat{p}_{\text{man}}}{\mathrm{d}t} = C\left(\dot{m}_{\text{at}} - \dot{m}_{\text{ac}_{std}}\right) + K_{\text{obs}}\left(p_{\text{man}_{\text{sensor}}} - \hat{p}_{\text{man}}\right) \tag{8}$$

Tuning When K_{obs} was calculated in Equation (8), the variance of the state noise of $\hat{p}_{\text{man}}$ was assumed to be the first harmonic of the pumping noise. The variance of the measurement signal $p_{\text{man}_{\text{sensor}}}$ was measured with the engine off but with ignition and dynamometer on. No dependence between the measurement variance and the state variances is assumed. K_{obs} depends on the current state of the engine (N, p_{man}) and is stored in a table.

Properties How does this type of observer handle the effects of a wastegate step? As shown in Figure 2 the volumetric efficiency changes slightly during the wastegate step. Suppose the offset in volumetric efficiency is $\Delta\eta_{\text{vol}}$. The observer converges when $\frac{\mathrm{d}\hat{p}_{\text{man}}}{\mathrm{d}t} = 0$ and this occurs when either $\dot{m}_{\text{at}} = \dot{m}_{\text{ac}}$, which is the case when the volumetric efficiency is correct, or when there is a stationary error in pressure. An approximation of the pressure error due to a small offset $\Delta\eta_{\text{vol}}$ in volumetric efficiency is given in Equation (9).

$$\begin{aligned}&(p_{\text{man}_{\text{sensor}}} - \hat{p}_{\text{man}}) = \\ &-\frac{C}{K_{\text{obs}}}\left(\underbrace{\dot{m}_{\text{at}} - \eta_{\text{vol}}\frac{\hat{p}_{\text{man}}V_d N}{R_{\text{man}}T_{\text{man}}n_r}}_{\approx 0} - \Delta\eta_{\text{vol}}\frac{\hat{p}_{\text{man}}V_d N}{R_{\text{man}}T_{\text{man}}n_r}\right) \approx \\ &\frac{C}{K_{\text{obs}}}\Delta\eta_{\text{vol}}\frac{\hat{p}_{\text{man}}V_d N}{R_{\text{man}}T_{\text{man}}n_r}\end{aligned} \tag{9}$$

If the offset $\Delta\eta_{\text{vol}}$ is small the approximation in Equation (9) is valid and the steady-state pressure error corresponds to a small error in the estimated air mass flow $\Delta\dot{m}_{\text{ac}}$.

$$\Delta\dot{m}_{\text{ac}} = -\frac{K_{\text{obs}}}{C}\left(p_{\text{man}_{\text{sensor}}} - \hat{p}_{\text{man}}\right) \tag{10}$$

Since the estimated air mass flow is used to calculate injected fuel mass there will be a small error in the air/fuel ratio. If the engine is equipped with feedback from an oxygen sensor this error in air/fuel ratio will be detected and compensated for. Unfortunately there is a delay until the mixture is combusted and transported to the sensor.

Observer with Integration of η_{vol}

A method capable of handling offsets in volumetric efficiency was developed in [8]. It is based on pure integration of the η_{vol} to cancel the steady-state error. A minor modification have been made to make the method time continuous. The method is derived as a first order approximation of the pressure change $\Delta p_{\text{man}} = p_{\text{man}_{\text{sensor}}} - \hat{p}_{\text{man}}$ caused by a deviation $\Delta\eta_{\text{vol}}$ in the volumetric efficiency, Equation (11).

$$\frac{\partial p_{\text{man}}}{\partial \eta_{\text{vol}}} = -\frac{n_r R_{\text{man}} T_{\text{man}} \dot{m}_{\text{at}}}{\eta_{\text{vol}}^2 N V_d} \tag{11}$$

$$\Delta\eta_{\text{vol}} = -\frac{1}{\frac{\partial p_{\text{man}}}{\partial \eta_{\text{vol}}}}\Delta p_{\text{man}} \tag{12}$$

Tuning The convergence rate of the estimation of $\Delta\eta_{\text{vol}}$ in Equation (12) was controlled by a scaling factor L_1 introduced in Equation (14). No systematic tuning method for L_1 was presented in [8].

$$\frac{\mathrm{d}\hat{p}_{\text{man}}}{\mathrm{d}t} = C\left(\dot{m}_{\text{at}} - \dot{m}_{\text{ac}_{ts}}\right) \tag{13}$$

$$\frac{\mathrm{d}\Delta\eta_{\text{vol}}}{\mathrm{d}t} = -\frac{1}{L_1}\frac{\eta_{\text{vol}}^2 N V_d}{R_{\text{man}} T_{\text{man}} \dot{m}_{\text{at}} n_r}\left(p_{\text{man}_{\text{sensor}}} - \hat{p}_{\text{man}}\right) \tag{14}$$

Properties In Equation (13) $\dot{m}_{\text{ac}_{ts}}$ is calculated using Equation (5). This observer structure does not suffer from a steady-state error but problems was reported during intake manifold pressure transients since the observer updated $\Delta\eta_{\text{vol}}$ incorrectly. To solve this problem the adaption was turned off during large pressure transients. Another problem with this structure is that the mapped η_{vol} was not compensated for temperature variations in the intake system. The suggested correction factor $\Delta\eta_{\text{vol}}$ is additive and temperature variations are multiplicative [1]. After a pressure transient there will be an offset in estimated pressure until the observer have integrated the new $\Delta\eta_{\text{vol}}$.

Observer With Air Mass Flow Estimation

The constant gain extended Kalman filter have fast convergence but suffers from a steady-state error when the volumetric efficiency changes which is the case under wastegate steps. The second method using integration of η_{vol} does not have any stationary errors but on the other hand it does have problems with pressure transients.

Wastegate steps at constant engine speed causes an offset in η_{vol} since the $\frac{p_{\text{exh}}}{p_{\text{man}}}$ changes. The difference in volumetric efficiency compared to the mapped results in a change in in-cylinder air mass Δm. If this is assumed to be slow varying it can be estimated using a constant gain extended Kalman filter, see Equation (15b). The information of m can then be used in the calculation of air to cylinder, see Equation (6).

$$\frac{\mathrm{d}\hat{p}_{\text{man}}}{\mathrm{d}t} = -C\eta_{\text{vol}}\frac{\hat{p}_{\text{man}}NV_d}{R_{\text{man}}T_{\text{man}}n_r} + \frac{N}{n_r}m + C\dot{m}_{\text{at}} + K_1\left(p_{\text{man}_{\text{sensor}}} - \hat{p}_{\text{man}}\right) \tag{15a}$$

$$\frac{\mathrm{d}m}{\mathrm{d}t} = K_2\left(p_{\text{man}_{\text{sensor}}} - \hat{p}_{\text{man}}\right) \tag{15b}$$

Tuning Equation (15a) is linearized and the observer gains K_1 and K_2 are determined by applying Kalman filtering technique. The covariance matrices are calculated as follows. Pressure state variance is assumed to be the first harmonics of the intake manifold pumpings. In measurements the amplitude of the pumpings are less or approximately equal to 10% of the mean intake manifold pressure resulting in a variance of $\frac{1}{2\cdot 10}p_{\text{man}}$. The variance of the in cylinder air mass offset m is based on calculated residual gas variance when the exhaust pressure varies sinusoidal. Peak to peak amplitude is the exhaust pressure difference the wastegate is closed and when it is fully opened. In the later case the exhaust pressure is approximately equal to the ambient pressure at our research laboratory. Residual gas mass is calculated using the approximative model in [1]

$$x_r = \left(1 + \frac{T_r}{T_{\text{man}}}\left(r_c\left(\frac{p_{\text{man}}}{p_{\text{exh}}}\right) - \left(\frac{p_{\text{man}}}{p_{\text{exh}}}\right)^{(\gamma-1)/\gamma}\right)\right)^{-1} \tag{16}$$

$$T_1 = T_r r_c x_r\left(\frac{p_{\text{man}}}{p_{\text{exh}}}\right) \tag{17}$$

$$m_r = \frac{x_r}{1-x_r}\frac{p_{\text{man}}V_d}{R_{\text{man}}T_{\text{man}}}\left(1 + \frac{1}{\lambda\left(\frac{A}{F}\right)_s}\right) \tag{18}$$

In Equations (16,17,18) the following values where used $T_r = 1400$, η_{vol} is taken from the engine map, and $\lambda = 1$. Only simulations was used to calculate the variance of m_r. Intake manifold pressure and air mass offset are assumed to be independent. There is a dependency between intake manifold pressure and in cylinder mass offset but this is neglected. The same measurement noise was used as in the calculations of the feedback gain in the observer with only proportional feedback.

Properties Convergence rate can be set by the the proportional feedback and the integrating part cancels the stationary error since Equation (15b) is only zero when the estimated pressure is equal to the measured. A systematic tuning method also exists which makes use of a standard methodology. The rate of convergence depends on the covariance matrices where all but the mass offset variance is measurable.

AIR-TO-CYLINDER OBSERVER VALIDATION

The observer was validated using wastegate steps. To achieve wastegate steps of high amplitude a manual control device was used instead of the production vacuum control actuator. In Figure 6 a comparison of the proportional feedback [4], the integrated η_{vol} [8] and the new 2-state observer is shown. The pure integration observer [8] was tuned manually.

Estimated air mass to cylinder in Figure 6 looks similar for all observers, but since the intake manifold pressure differs from the measured for the proportional feedback observer there is a difference in air mass flow to cylinder. No steady-state error is present for the integrated η_{vol} nor the 2-state observer, but the 2-state observer converges faster due to its additional proportional feedback from the intake manifold pressure. The observer using only proportional feedback does not handle the changes in volumetric efficiency when the wastegate is operated with a steady-state pressure error as a result.

CONCLUSIONS

Observers for estimating air mass flow to the cylinders, for control of air/fuel ratio, have been studied on a turbocharged spark ignition engine with wastegate. The effects of changed wastegate setting on air-to-cylinder seems to be a little studied topic. Here, it was shown that some methods were unable to estimate the system state even at stationary conditions and further, of course, dynamic behavior.

To better describe the air-to-cylinder an observer was developed. It features an additional state for the difference between the air-to-cylinder mass and the expected air-to-cylinder mass. The expected air-to-cylinder mass is based on the volumetric efficiency. Constant gain extended Kalman filter theory was used to tune the observer and it showed good agreement with measurements of intake manifold pressure during a step in wastegate. Further there was stationary agreement with measurements of intake manifold pressure and of air mass flow into the intake manifold.

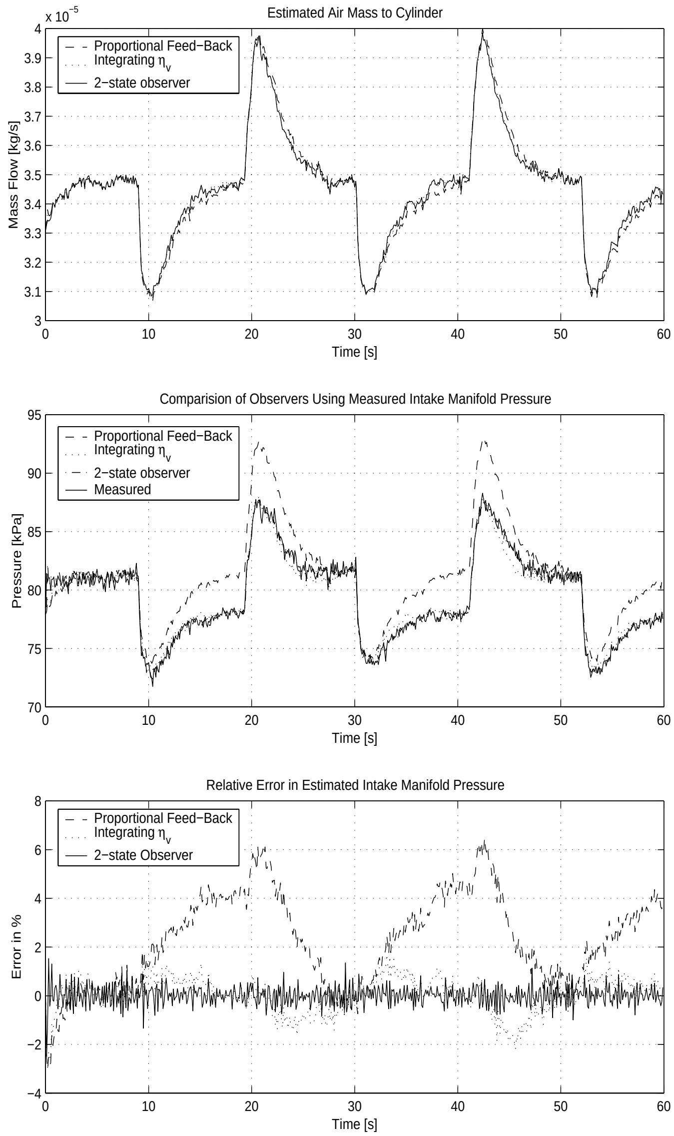

Figure 6: Steps in wastegate is used to compare the observers. It is opened at 9, 30, and 52 seconds and closed at 19.4 and 41 seconds. *Top:* The estimated air mass to cylinder differs with approximately 5% during the wastegate steps. *Center:* The integration of η_{vol} gives almost as good result as the 2-state observer in observed intake manifold pressure. *Bottom:* The observer using only proportional feedback shows good accuracy in estimated intake manifold pressure when the wastegate is closed. When the wastegate is opened the intake manifold pressure is overestimated by the proportional feedback observer due to the increase in volumetric efficiency not captured by the static map.

ACKNOWLEDGMENTS

This work was financially funded by the Swedish National Board for Industrial and Technical Development.

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NOMENCLATURE

Symbol	Description
p_{man}	Intake manifold pressure
T_{man}	Intake manifold temperature
η_{vol}	Volumetric efficiency
$\Delta\eta_{\text{vol}}$	Offset in volumetric efficiency
R_{man}	Specific gas constant in the intake manifold
p_{int}	Pressure before throttle
T_{int}	Temperature before throttle
α	Throttle angle
$A(\alpha)$	Effective throttle area
$C_d(\alpha)$	Discharge coefficient for the throttle
$Q(\alpha)$	A fitted function to the measured product of area and discharge coefficient
$\dot{m}_{\text{at}}$	Air mass flow through throttle
$\dot{m}_{\text{ac}}$	Air mass flow to cylinder
$\dot{m}_{\text{ac}_{std}}$	Air mass flow to cylinder using mapped volumetric efficiency
$\dot{m}_{\text{ac}_{ts}}$	Air mass flow to cylinder using mapped volumetric efficiency with integration of the offset $\Delta\eta_{\text{vol}}$
p_{exh}	Exhaust manifold pressure
m	Air mass flow offset $m = \dot{m}_{\text{ac}_{std}} - \dot{m}_{\text{at}}$
γ	Ratio of specific heats
x_r	Residual gas fraction
m_r	Residual gas mass
T_r	Temperature of residual gases
r_c	Compression ratio of the engine
T_1	Temperature of air/fuel charge at start of compression
L_1	Time constant in [8]
λ	Normalized air/fuel ratio
$\left(\frac{A}{F}\right)_s$	Stoichiometric air/fuel ratio
V_d	Displacement volume
V_{man}	Volume of intake manifold
C	Intake manifold filling/emptying constant $C = \frac{R_{\text{man}} T_{\text{man}}}{V_{\text{man}}}$
n_r	Number of revolutions per cycle
N	Engine speed i revolutions per second