MEAN-VALUE OBSERVER FOR A TURBOCHARGED SI-ENGINE

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Abstract: For air/fuel control, where the cylinder air charge (CAC) estimation is based on intake manifold pressure, it is essential to reduce the noise from measured intake manifold pressure signals while at the same time keeping the phase delays low during transients. Observers provide means of filtering without introducing large delays and therefore an observer is developed with emphasis on CAC estimation for air/fuel ratio control. It also enables model based diagnosis opportunities. The observer is based on a nonlinear mean value engine model including the intake and exhaust side together with turbine shaft speed. The observer feedback gains are determined using an extended Kalman filter. Systematic methods are presented to determine the covariance matrices for the noise and as part of that a novel method is presented to determine the state noise based on the model quality. Additional performance benefits are demonstrated when the model is augmented with one state. The observer is evaluated using real engine data with feedback from measured pressures in the intake manifold and after the intercooler. It shows very good results for CAC estimation as it suppresses intake manifold pressure noise without introducing phase delays. It also provides an accurate estimate of turbocharger speed. Therefore it is highly suitable for control and diagnosis in turbocharged SI-engines.

Keywords: Observers, automotive control, engine modeling, estimator, spark ignition engines, air/fuel ratio control

1. INTRODUCTION

The demands for better emission control, better fuel economy, and increasing legislation requirements of on-board diagnosis poses new challenges for the automotive industry. Low emissions are achieved with precise air/fuel ratio control and a three way catalyst. Good fuel economy with maintained power output can be accomplished with a downsized turbocharged engine (Guzzella *et al.*, 2000).

A key element to good air/fuel ratio control is accurate estimates of cylinder air charge (CAC). CAC is the mass of air trapped inside the cylinder per cycle. Observers are often proposed on naturally aspirated engines to provide precise CAC estimates (Jensen *et al.*, 1997; Powell *et al.*, 1998; Choi and Hedrick, 1998). These observers are less suited for use on turbocharged engines as their air-system has a more complex dynamics. The added complexity originates from the turbocharger and wastegate, which introduces a coupling between the intake- and exhaust system. This coupling influences the CAC-estimate with up to 5% (Andersson and Eriksson, 2004). Other benefits of using an observer is that it enables prediction of future signal values, estimates of non-measured signals, and also diagnosis (Massoumnia, 1986) along the air-path. The air-path is the path of the air from the air-filter until it reaches the exhaust system. These important issues, together with the fact that observers for turbocharged engines is a little studied topic, motivates this observer design investigation.

The base of the observer is a mean value engine model which is briefly described in the next section followed by a more detailed description of the observer design. In the evaluation it is demonstrated how the observer suppresses noise without introducing phase lags on the intake manifold pressure. Also it is shown how the turbocharger speed can be estimated very accurately using feedback from only two pressure signals on the intake side.

2. MEAN VALUE ENGINE MODEL

A component based mean value engine model forms the base of the observer design. The model is suitable for air-fuel control and it offers diagnosis opportunities along the air-path. Each model component relies on physically based models of the underlying engine component. The first step is to determine which components that are necessary.

In a turbocharged engine both intake and exhaust systems are tightly coupled through the turbo, and Andersson and Eriksson (2004) showed that CAC estimates is improved when the exhaust manifold pressure is included. In the CAC model, Equation (1), a coupling between the intake- and exhaust side is present that requires the following components along the air path: air filter, compressor, intercooler, throttle, intake manifold, engine, exhaust manifold, turbine, wastegate, turbocharger speed, and exhaust system.

$$\mathrm{CAC} = p_{\mathrm{im}} C_{\eta_{\mathrm{vol}}} \frac{1}{1+\frac{1}{\lambda\left(\frac{A}{F}\right)_s}} \frac{r_c - \left(\frac{p_{\mathrm{em}}}{p_{\mathrm{im}}}\right)^{\frac{1}{\gamma_e}}}{r_c - 1} V_{\mathrm{d}} \cdot \frac{1}{R_{\mathrm{im}}\left(T_{\mathrm{im}} - C_1\left(\frac{1}{\lambda}-1\right)\right)} \quad (1)$$

Consult the Appendix for a Nomenclature.

The modeling methodology of restrictions in series with adiabatic control volumes is applied. Every control volume has one pressure state and one temperature state. A general description of the model equations is given in (Eriksson *et al.*, 2002) with modifications described in (Andersson, 2003). Each state derivative is described by a nonlinear function of the states and inputs, see Equation (2). Inputs to the model are: Throttle plate angle, engine speed, wastegate opening, air/fuel ratio, and ambient conditions (pressure and temperature). Outputs are states and signals that can be derived from the estimated states such as air-mass flows and engine torque.

$$\begin{bmatrix} \dot{p}_{\mathrm{af}} \\ \dot{T}_{\mathrm{af}} \\ \dot{p}_{\mathrm{c}} \\ \dot{T}_{\mathrm{c}} \\ \dot{p}_{\mathrm{ic}} \\ \dot{T}_{\mathrm{ic}} \\ \dot{p}_{\mathrm{im}} \\ \dot{T}_{\mathrm{im}} \\ \dot{p}_{\mathrm{em}} \\ \dot{T}_{\mathrm{em}} \\ \dot{p}_{\mathrm{t}} \\ \dot{T}_{\mathrm{t}} \\ \dot{\omega}_{\mathrm{tc}} \end{bmatrix} = \begin{bmatrix} f_{p_{\mathrm{af}}}\left(p_{\mathrm{af}}, T_{\mathrm{af}}, p_{\mathrm{comp}}, \omega_{\mathrm{TC}}, p_{\mathrm{a}}, T_{\mathrm{a}}\right) \\ f_{T_{\mathrm{af}}}\left(p_{\mathrm{af}}, T_{\mathrm{af}}, p_{\mathrm{comp}}, \omega_{\mathrm{TC}}, p_{\mathrm{a}}, T_{\mathrm{a}}\right) \\ f_{p_{\mathrm{comp}}}\left(p_{\mathrm{af}}, T_{\mathrm{af}}, p_{\mathrm{comp}}, T_{\mathrm{comp}}, p_{\mathrm{ic}}, \omega_{\mathrm{TC}}\right) \\ f_{T_{\mathrm{comp}}}\left(p_{\mathrm{af}}, T_{\mathrm{af}}, p_{\mathrm{comp}}, T_{\mathrm{comp}}, p_{\mathrm{ic}}, \omega_{\mathrm{TC}}\right) \\ f_{p_{\mathrm{ic}}}\left(p_{\mathrm{comp}}, T_{\mathrm{comp}}, p_{\mathrm{ic}}, T_{\mathrm{ic}}, p_{\mathrm{im}}, \alpha\right) \\ f_{T_{\mathrm{ic}}}\left(p_{\mathrm{comp}}, T_{\mathrm{comp}}, p_{\mathrm{ic}}, T_{\mathrm{ic}}, p_{\mathrm{im}}, \alpha\right) \\ f_{p_{\mathrm{im}}}\left(p_{\mathrm{ic}}, T_{\mathrm{ic}}, T_{\mathrm{im}}, p_{\mathrm{im}}, p_{\mathrm{em}}, N, \alpha, \lambda\right) \\ f_{T_{\mathrm{im}}}\left(p_{\mathrm{ic}}, T_{\mathrm{ic}}, T_{\mathrm{im}}, p_{\mathrm{im}}, p_{\mathrm{em}}, N, \alpha, \lambda\right) \\ f_{p_{\mathrm{em}}}\left(p_{\mathrm{im}}, T_{\mathrm{im}}, p_{\mathrm{em}}, T_{\mathrm{em}}, p_{\mathrm{turb}}, N, \lambda, \alpha_{\mathrm{wg}}, T_{\mathrm{a}}\right) \\ f_{T_{\mathrm{em}}}\left(p_{\mathrm{im}}, T_{\mathrm{im}}, p_{\mathrm{em}}, T_{\mathrm{em}}, p_{\mathrm{turb}}, N, \lambda, \alpha_{\mathrm{wg}}, T_{\mathrm{a}}\right) \\ f_{p_{\mathrm{turb}}}\left(p_{\mathrm{em}}, T_{\mathrm{em}}, p_{\mathrm{turb}}, T_{\mathrm{turb}}, \omega_{\mathrm{TC}}, \alpha_{\mathrm{wg}}, p_{\mathrm{a}}\right) \\ f_{T_{\mathrm{turb}}}\left(p_{\mathrm{em}}, T_{\mathrm{em}}, p_{\mathrm{turb}}, T_{\mathrm{turb}}, \omega_{\mathrm{TC}}, \alpha_{\mathrm{wg}}, p_{\mathrm{a}}\right) \\ f_{\omega_{\mathrm{TC}}}\left(p_{\mathrm{af}}, T_{\mathrm{af}}, p_{\mathrm{comp}}, p_{\mathrm{em}}, T_{\mathrm{em}}, p_{\mathrm{turb}}, \omega_{\mathrm{TC}}\right) \end{bmatrix} \quad (2)$$

The model has a total of thirteen states and as the focus is on observer design no state reduction is performed. An important observation is that several state equations have dependencies on both intake and exhaust conditions, which shows the coupling between the intake- and exhaust side on turbocharged engines. In Equation (2) this coupling is present in for example $\dot{p}_{\mathrm{im}}$ and $\dot{\omega}_{\mathrm{tc}}$.

2.1 *Model Compared to Measured Throttle Step*

In Figure 1 the nonlinear model is compared to measured data using a throttle step at constant engine speed. One important factor in the CAC model is the intake manifold temperature T_{im} and the model describes the fast temperature dynamics in the intake manifold. This fast dynamics is not captured by the measurements due to the slow temperature sensor dynamics. The modeled pressures and turbocharger speed shows good agreement before the transient but overestimates are made as the wastegate opening is not fully known and was assumed to be in closed position. Better estimates of the states is produced with an observer that uses feedback from measurements. This raises the question of how to choose the feedback gains.

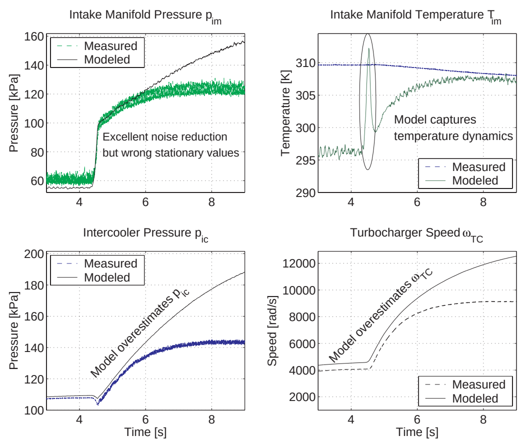

Fig. 1. Model compared to measured data during a very rapid throttle step. *Top left:* Intake manifold pressure follows measured behavior very well during the first part of the transient, but it has wrong stationary values. *Top right:* The fast intake manifold temperature dynamics is captured by the model but the slow sensor misses it completely. *Bottom left:* Pressure after intercooler is overestimated. *Bottom right:* Turbine speed tracks the measured speed very well before the transient but the speed is overestimated at the end.

3. OBSERVER DESIGN

The observer is based on a mean value model of a turbocharged SI-engine, described by Equation (2).

The observer design methodology is to first linearize the model in a set of stationary points and then design a stationary Kalman filter for these points. The stationary set of operating points are determined by an engine map. The resulting observer feedback gains are then stored in a look-up table. The gains are switched between the operating points, as in constant gain extended Kalman filters (CGEKF) (Safanov and Athans, 1978), which successfully has been used for similar applications (Jensen *et al.*, 1997; Maloney and Olin, 1998). The Kalman filter observer has the following form (Gustafsson, 2000):

$$\dot{\hat{x}} = A\hat{x} + B_u u + B_v v + K(y_m - C\hat{x}) \quad (3)$$

$$y = C\hat{x} + e \quad (4)$$

where v is the state noise, e is the measurement noise, and K is the feedback gain.

In Section 3.1 the linearizing of the model is described together with properties of the linearized system. To determine the feedback gain K by solving the Riccati-equation the covariance matrices of the state noise v and measurement noise e are needed. These are denoted Q and R respectively. A systematic method to determine Q and R is described in Section 3.3.

3.1 *Model Linearization*

Linearization is performed in the same stationary operating points as the engine is mapped. The stationary points of the model are found by simulating the model until stationary conditions are present. The inputs are selected from the map except for the throttle angle α and the wastegate opening α_{wg}. Throttle plate angle is determined by one fast controller that governs the throttle plate angle until the modeled air-mass flow is the same as measured during the mapping. A slower controller governs the wastegate opening α_{wg} to achieve the same pressure after the intercooler as the measured during the mapping.

3.1.1. *Properties of the Linearized System* The linearized system has 13 poles that all are located in the left half plane. The poles move with engine operating point and their absolute values are in the interval between –0.2 and –4500 which means that it is a stiff system.

The fast poles originate from three kinds of sources: flow restrictions (such as air filter and intercooler), throttle, and wastegate. The air filter and intercooler give fast poles when the flows are small, corresponding to low loads and speeds. For the throttle and wastegate the poles are fast when there are large pressure ratios over them.

3.2 *Feedback Signals*

There are a large number of possible feedback signal sources, but fortunately the proposed observer structure does not require any particular sensor configuration. The first approach is to measure some states directly, which can be done for pressures and temperatures. If considerable sensor dynamics is present, as for temperature sensors, a model of the sensor dynamics can be included. Other possible feedback sources are functions of states, such as measured air-mass flows. Both approaches to select feedback signals and combinations thereof can be used in the design method described here.

3.2.1. *Selected Feedback Signals* On the engine in the research laboratory two pressure signals are available which also are modeled as states: pressure after intercooler p_{ic} and intake manifold pressure p_{im}. These pressure signals are therefore selected for feedback.

3.3 *Noise Estimation*

Kalman-filter gains depends on descriptions of both measurement and state noise. A systematic method to determine the noises relying on measurements and the models quality is described next. Measurement noise and state noise are determined for each stationary operating point in the engine map.

3.3.1. *Measurement Noise* Measurement noise from the electronics should be low and as the Kalman gains depend on the ratio between the state noise and the measurement noise a low measurement noise would result in a very high feedback gain. Therefore another measurement noise definition is sought for which reflects the quality of the measured signal in each operating point.

When measured signals are used for feedback in a mean value model, the mean value of the measured signal is interesting as it describes the desired behavior of the modeled system. All deviations from the measured signals mean value is therefore considered as measurement noise. An example is shown in the top of Figure 2, where the engine pumping in the intake manifold pressure signal also are considered as measurement noise. The measured noise is calculated from stationary measurements as

$$R_i = \frac{1}{T}\int_0^T \left(\overline{y}_{\text{meas}_i}(t) - y_{\text{meas}_i}(t)\right)^2 \mathrm{d}t$$

where i is the i:th measured signal. The measured signals are assumed to be independent which results in a diagonal measurement noise matrix. In the calculations a minimum value have been used for the measurement noise R_i to make sure that R_i is not close to zero. Using this measurement noise definition, the power is correct but the noise is not white.

3.3.2. *State Noise* The state noise is a measurement of the model quality. Here the state noise is determined using the stationary model error in each operating point. This requires that the state is measured in the engine map. The stationary value of the modeled state i, is x_{state_i} and the value of the measured state i is $\overline{x}_{\text{meas}_i}$. The state noise Q_i is then:

$$Q_i = \left(\overline{x}_{\text{meas}_i} - x_{\text{state}_i}\right)^2$$

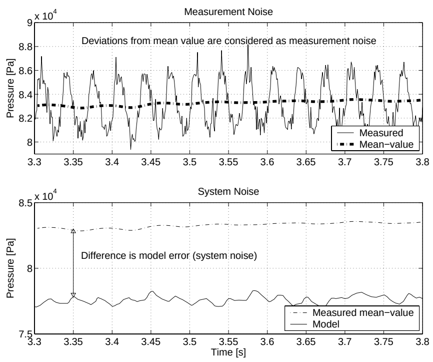

Fig. 2. During the engine mapping not only the mean value is stored but also a sequence of data measured at a high sample rate. *Top:* Measured intake manifold pressure and its mean value. Measurement noise is defined as the difference between them. *Bottom:* System noise is defined as the stationary difference between the mean value of the measured state and the modeled state.

Using this definition the state noise reflects the model quality. The state noise is assumed to be independent and the matrix is diagonal. A drawback is that the noise is not white.

3.4 *Observer Gain Calculation*

Now there exists a linearized model, estimates of state and measurement noise which means that the Riccati equation can be solved and the resulting gain can be calculated. Here there is one gain for each stationary operating point and gain switching is performed to the closest stationary operating point.

With the method proposed to determine measurement and state noise, the resulting observer feedback gains can be applied without any modifications. With other definitions of state and measurement noises, such as in (Jensen *et al.*, 1997), where engine pumping instead is included in the state noise model which resulted in observer gains had to be reduced manually.

3.4.1. *Resulting Feedback Gains* In Figure 3 some of the resulting feedback gains are shown. It is worth pointing out that:

(1) p_{ic} has low measurement noise, which results in high feedback gains to the p_{ic} state itself but also to the p_{im} state. Another consequence is that if the model predicts a too high pressure after the intercooler the feedback tries to reduce both pressure after intercooler and the intake manifold pressure.
(2) Measured p_{im} is a noisier signal, which results in lower feedback gains.
(3) The turbocharger speed is also significantly influenced by the intercooler pressure, which shows that other states are also affected.

3.4.2. *Finding the Closest Operating Point* To find the closest stationary operating point in the engine map the following procedure is used: Given the current operating point the two most important parameters in the CAC calculation is used as look-up keys: engine speed and intake manifold pressure.

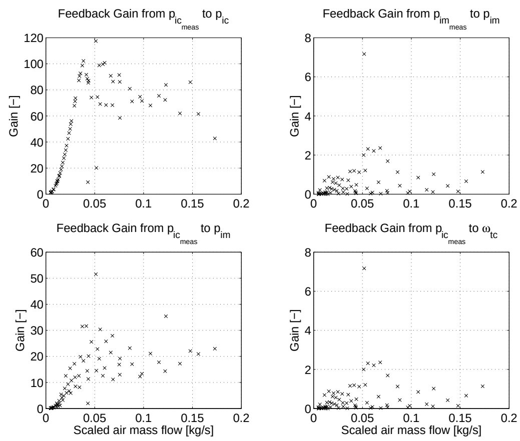

Fig. 3. Some resulting feedback gains for p_{ic} and p_{im} is shown as a function of air-mass flow. *Top left*: The gain from measured p_{ic} saturates when the wastegate opens at approximately 0.05 kg/s. *Top right*: The gain from measured intake manifold pressure is lower as the measured signal $p_{\text{im}_{\text{meas}}}$ is noisier than $p_{\text{ic}_{\text{meas}}}$. *Bottom left*: The observer tries to increase intake manifold pressure when the estimated pressure after the intercooler is too low. *Bottom right*: Here it is shown how the observer uses pressure measurements to improve other states such as turbocharger speed.

3.5 *Observer Schematic*

In Figure 4 a MATLAB/SIMULINK schematic of the implemented observer is shown. The feedback term $K(y - Cx)$ is implemented as a separate input to the engine model which enables a simple way to enable/disable the feedback by setting the on/off gain to one/zero.

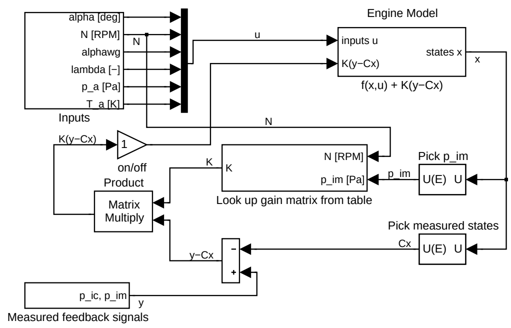

Fig. 4. The structure of the implemented observer in MATLAB/SIMULINK.

4. OBSERVER EVALUATION

The observer is tested on measured data from a turbocharged SAAB 9^5-engine (B235R) and it is capable of estimating all modeled states. In the evaluation the focus is on the intake manifold pressure which is most important for the CAC estimation. To study the observer a step in throttle position is used at 1800 RPM, the same as in Figure 1.

Figure 5 shows that the observer succeeds in filtering the intake manifold pressure and reduce the noise significantly without introducing large delays as would have been the case with ordinary causal filters. With feedback it tracks the measured data well at the end of the step, but for low intake manifold pressures it is not able to fully eliminate the stationary error.

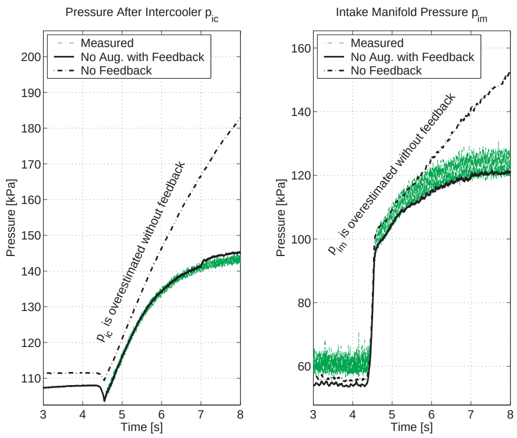

Fig. 5. *Left:* Pressure after the intercooler is overestimated by the model, but the feedback successfully reduces the stationary error. *Right:* The observer successfully reduces the noise in the measured intake manifold pressure (gray) during a step in throttle. The feedback makes the observer track measured behavior, but there are still stationary errors.

4.1 *Gains are a Compromise*

As the introduction of feedback did not eliminate the stationary error in the intake manifold pressure it is interesting to investigate the two causes. First there is a large error in estimated intercooler pressure and feedback from the measured pressure after intercooler results in a reduction in intake manifold pressure. See the lower left corner of Figure 3.

The second cause of the stationary error is more complicated and the rest of the section is devoted to this. Start by assuming:

- An isotherm model of the intake manifold pressure dynamics
- The mass-flow out of the intake manifold depends solely on the pressure $W_{\text{out}}(p) = kp$
- The flow into the intake manifold is constant W_{in}.

Now the pressure state can be written as a mass balance $\dot{p} = K(W_{\text{in}} - W_{\text{out}}(p)) = K(W_{\text{in}} - kp)$. Suppose that the stationary pressure p is too low due to a small error in k. When a feedback term is introduced it results in the following equation: $\dot{\hat{p}} = K(W_{\text{in}} - k\hat{p}) + K_{\text{obs}}(p_{\text{sensor}} - \hat{p})$. The last term will increase $\hat{p}$ but this increase in pressure will also increase $W_{\text{out}}(\hat{p}) = k\hat{p}$ which counteracts the desired increase in estimated pressure. When model errors are present it is therefore not possible to estimate correct pressure using only proportional feedback. Additionally when the feedback term is nonzero the mass balance is not fulfilled, implying that the stationary mass flow will not be correct either.

4.2 *State Augmentation*

One solution is to augment the model with one state that scales W_{out} slightly. This scaling factor is called $\Delta C_{\eta_{\text{vol}}}$ and is modeled as a slowly varying constant. It is introduced in CAC-model, Equation (1), by replacing the factor $C_{\eta_{\text{vol}}}$ with:

$$(C_{\eta_{\text{vol}}} + \underbrace{\Delta C_{\eta_{\text{vol}}}}_{\text{New state}})$$

This additional state introduces the following dynamics equation to Equation (2):

$$\Delta \dot{C}_{\eta_{\text{vol}}} = 0 \tag{5}$$

5. VALIDATION OF AUGMENTED MODEL

Using the augmented model the estimate of the intake manifold pressure converges to the measured pressure and maintains mass balance in the intake manifold. This improves the intake manifold pressure estimate considerably, as can be seen in the top left of Figure 6. This observer configuration have successfully been validated using 20 different transients in throttle, engine speed and wastegate over a wide range of engine operating points and it converged in all cases to measured intake manifold pressure.

6. SUMMARY

A mean value observer has been developed for a turbocharged SI-engine. The observer gains are determined using constant gain extended Kalman techniques and a systematic method to estimate the necessary noise matrices are also presented. The noise matrices are selected in a manner to reflect the quality of the model and measurements in a mean value sense. To improve convergence to measured data the observer is augmented with a state that adjusts the CAC to handle to model errors better. The observer have been validated over a wide range of operating points and converged in all cases to measured intake manifold pressure. It is suitable for its primary objective of estimating CAC for air/fuel ratio control as it provides excellent noise suppression and does not introduce a large phase shift. It is also suitable for diagnosis purposes as it estimates 6 pressures and 6 temperature in the engine's intake- and exhaust system together with an accurate estimate of turbocharger speed.

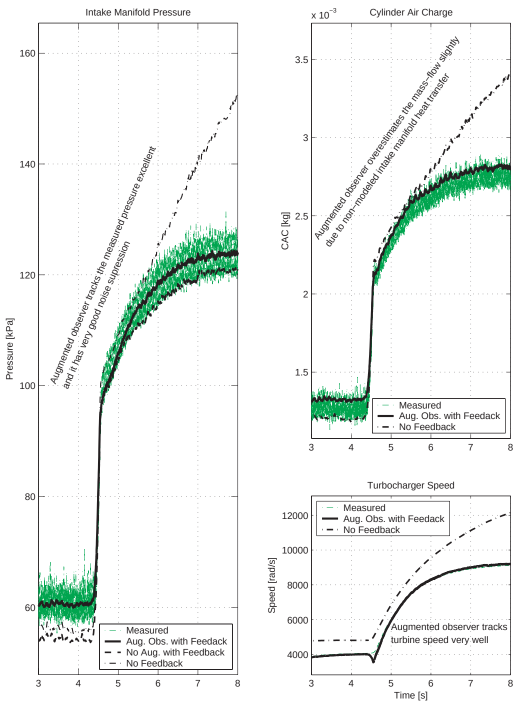

Fig. 6. *Top left:* The augmented observer (solid) with feedback from intake manifold pressure and pressure after intercooler is able to estimate the measured (gray) intake manifold pressure very well. It does not introduce a noticeable phase shift. The model without feedback is also shown for comparison together with the non-augmented observer. *Top right:* The augmented observer overestimates the CAC slightly compared to estimated CAC from measurements. The cause of the overestimate is unmodeled heat transfer in the intake manifold. *Bottom right:* With feedback from p_{im} and p_{ic} the turbocharger speed is tracked spot on, except for a small deviation during the first part of the transient.

ACKNOWLEDGMENTS

This work was financially funded by the Swedish Agency for Innovation Systems through the competence center ISIS.

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Appendix A. NOMENCLATURE

The following general nomenclature is used: W-mass flow, p–pressures, T–temperature, ω- angular velocity, and V–volume. The subscripts indicate: af–air filter, comp–compressor, ic–intercooler, im–intake manifold, em–exhaust manifold, es–exhaust system, and tc–turbocharger. Additional symbols are:

Symbol	Description
CAC	Cylinder air charge
α	Throttle angle
α_{wg}	Waste gate angle
$\hat{x}$	Estimated states
u	Inputs to the model and observer
y_m	Measured signal(s) for feedback
$C_{\eta_{\text{vol}}}$	Engine pumping parameter, similar to volumetric efficiency
$\Delta C_{\eta_{\text{vol}}}$	Offset in engine pumping parameter
C_1	Charge cooling parameter
γ_e	Ratio of specific heats on the exhaust side
λ	Normalized air/fuel ratio
$\left(\frac{A}{F}\right)_s$	Stoichiometric air/fuel ratio
V_d	Displacement volume
n_r	Number of revolutions per cycle
N	Engine speed in revolutions per second