Project report
Project 2 – TSFS09

Daniel Fahlén – danfa688@student.liu.se
Niclas Granström – nicgr354@student.liu.se

November 26, 2015

Contents

Chapter 1

Introduction

This project report deals primarily with a turbocharged engine. In an earlier the project 1, a mathematical model for a naturly aspirated engine was developed and implemented, its model parameters where identified from measured data, and the various models where validated.

In this project a turbo will be added to the engine in project 1. A mathematical model for a turbo will be developed and implemented, its model parameters will be identified from measured data, and the various models will be validated. The torbo ant the engine model from project 1 will then be put together to for a model for a turbocharged engine.

On the modelled turbo charged engine series of experiments are conducted with the aim to study the emission formation and consumption. The tool that is used for implementation is Matlab combined with Simulink.

Chapter 2

Model description

In this chapter the engine is divided into a number of components, which are then modeled separately. For each component specified input and output signals, mathematical model which describes the behavior and the parameters are determined. An overview of all input signals to the actuators and output signals from the sensors which was included in project 1 is shown in Figure 2.1 where the red signals and components are used in project 2 for the turbocharged engine.

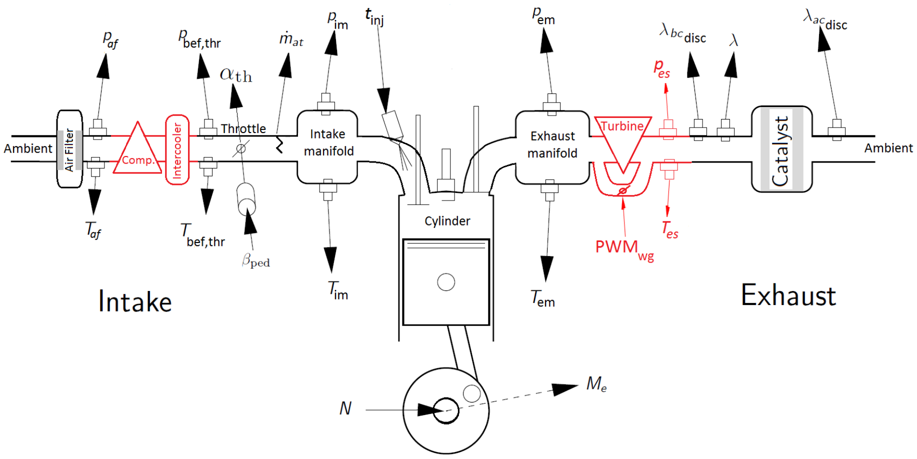

Figure 2.1: An overview of the air path with signals and components to be modelled in project 1 (shown in black) and project 2 (shown in red+black)

Mathematical models are going to be used for the modelling of following engine sub components:

- Compressor
- Turbine

The control signals which are the inputs to the engine model are:

- Accelerator pedal position (β_{ped}),

- Engine speed (N),
- Fuel injection time (t_{inj}),
- Wastegate control signal (PWM_{wg}).

The entire engine model block in Simulink should produce the following output signals

- Engine torque (M_e),
- λ measured by the discrete sensor ($\lambda_{\text{bc,disc}}$),
- Air mass flow past the throttle ($\dot{m}_{\text{at}}$)
- Intake manifold pressure (p_{im}).
- Exhaust manifold pressure (p_{em}).

2.1 Compressor

Two models for the compressor are presented here, one for the compressor air mass flow, and one for the compressor efficiency.

2.1.1 Model description

Model input signal(s): Compressor inlet temperature T_{af}, compressor inlet pressure p_{af}, the compressor rotational speed ω_{tc}, and the compressor pressure ratio Π_{c}.

Model output signal(s): The air mass flow through the compressor $\dot{m}_c$ and the compressor efficiency η_{c}.

Model: The compressor mass flow is modelled according to

$$\Pi_{c,max} = (\frac{u_2^2 \Psi_{max}}{2 c_p T_{af}} + 1)^{\frac{\gamma}{\gamma-1}}, \; u_2 = r_c \omega_{tc} \tag{2.1}$$

$$\dot{m}_{c,corr} = \dot{m}_{c,corr,max} \sqrt{1 - (\frac{\Pi_c}{\Pi_{c,max}})^2} \tag{2.2}$$

$$\dot{m}_c = \dot{m}_{c,corr} \frac{p_{af}/p_{ref,c}}{\sqrt{T_{af}/T_{ref,c}}} \tag{2.3}$$

The compressor efficiency is modelled according to

$$\eta_c = \eta_{c,max} - \chi^T Q_\eta \chi \tag{2.4}$$

$$Q_\eta = \begin{bmatrix} Q_{11} & Q_{12} \\ Q_{12} & Q_{22} \end{bmatrix}, \; \chi = \begin{bmatrix} \dot{m}_{c,corr} - \dot{m}_{c,corr@\eta_{c,max}} \\ \sqrt{\Pi_c - 1} - (\Pi_{c@\eta c,max} - 1) \end{bmatrix} \tag{2.5}$$

Parameter to find: For the flow model, Ψ_{max} and $\dot{m}_{\mathrm{c,corr,max}}$. For the efficiency model $\eta_{\mathrm{c,max}}$, $\dot{m}_{\mathrm{c,corr@}\eta_{\mathrm{c,max}}}$, $\Pi_{\mathrm{c@}\eta_{\mathrm{c,max}}}$, Q_{11}, Q_{12} and Q_{22}. Where $\dot{m}_{\mathrm{c,corr@}\eta_{\mathrm{c,max}}}$ and $\Pi_{\mathrm{c@}\eta_{\mathrm{c,max}}}$ are describing where in the map the maximum compressor efficiency $\eta_{\mathrm{c,max}}$ is, and Q_{ij} is describing how the compressor efficiency changes when moving away from this point.

Other parameters in the model: Pressure reference state $p_{ref,c}$, temperature reference state $T_{ref,c}$, radius of the compressor r_c

2.2 Turbine

Two models for the compressor are presented here, one for the turbine air mass flow, and one for the turbine efficiency.

2.2.1 Model description

Model input signal(s): p_{03}, p_{04}, T_{03}, ω_{tc}

Model output signal(s): $\dot{m}_{\text{t}}$, $\eta_{\text{t}}(\text{BSR})$

Model: Turbine flow model:

$$\text{TFP}_{\text{model}} = k_0\sqrt{1-\Pi_t^{-k_1}} \qquad \Pi_{\text{t}} = \frac{p_{03}}{p_{04}} = \frac{p_{\text{em}}}{p_{\text{es}}} \tag{2.6}$$

$$\dot{m}_{\text{t}} = \frac{p_{\text{em}}}{\sqrt{T_{\text{em}}}}\text{TFP}_{\text{model}} \tag{2.7}$$

Turbine efficiency model:

$$\text{BSR} = \frac{\omega_{\text{tc}} r_{\text{t}}}{\sqrt{2c_{\text{p,exh}}T_{\text{em}}(1-\Pi_{\text{t}}^{-\frac{\gamma_{\text{exh}}-1}{\gamma_{\text{exh}}}})}} \tag{2.8}$$

$$\eta_{\text{t}}(\text{BSR}) = \eta_{\text{t,max}}(1-(\frac{\text{BSR}-\text{BSR}_{\text{max}}}{\text{BSR}_{\text{max}}})^2 \tag{2.9}$$

Parameter to find (via measurement): k_0, k_1, $\eta_{\text{t,max}}$, BSR_{max}

Other parameters in the model: r_{t}, γ_{exh}, $c_{\text{p,exh}}$

2.3 Bmep model

In a later part of the project a model for bmep will be required, therefore such a model is presented here.

2.3.1 Model description

Model input signal(s): Intake manifold pressure p_{im}.

Model output signal(s): Brake mean effective pressure, *bmep*.

Model:

$$bmep_{\text{mod}} = -C_{\text{P0}} + C_{\text{P1}}p_{\text{im}} \tag{2.10}$$

Parameter to find (via measurement): C_{P0}, C_{P1}.

Other parameters in the model: -

Chapter 3

Turbocharger analysis and model validation

This chapter outlines and discusses how a turbocharger works. The results of parameter estimations in models of different engine components are also reported and the models are validated against measurements.

3.1 Turbocharger analysis

In this part the turbo is studied.

3.1.1 Turbo components and their purpose

The two main components of a turbo are the compressor and turbine. The compressor and turbine are mechanically coupled to each other. The turbine utilizes the enthalpy in the exhaust gas to drive the compressor. The compressor compresses the air to achieve a higher air density in the cylinder. A turbocharged engine has a drop in torque for low speeds, this is due to a region of instability in the compressor called surge. Surge is caused by a too high pressure ratio over the compressor and causes the air flow to reverse and and recover alternately which gives an oscillating behaviour for the pressure and mass flow. Another limit for the compressor is the rotational speed, since high speeds can cause mechanical damage due to high centrifugal forces. The mass flow through the compressor is limited by choke, this is when a drop in pressure ratio over the compressor does not result in an increase in mass flow. Choke is caused by sonic conditions. Another limit of the compressor operation is for low pressure ratios the compressor will act as a flow restriction. This can happen when the turbo speed is low and the engine pumps air out of the intake manifold.

3.1.2 Turbo maps and corrected quantities

The compressor- and turbine maps are measured in a gas stand. A gas stand makes it possible to control the flow of the compressor and turbine independently. The flow is controlled using three actuators. On the turbine side there are a mechanical compressor and a burner and on the compressor side there is a control valve.

The compressor map is determined by setting up a set of speed lines for those lines the the mass flow is measured from the surge line to the choke line. The inlet temperature is healed constant so tat is is close to the reference temperature, which ensures that the corrected speed for the turbine is also constant. The actuators in the gas stand are controlled to achieve this.

Corrected quantities is a simplification of some dimensionless relations that are true for the compressor and turbine. When the dimensionless relations are simplified they are no longer dimensionless and are then called corrected quantities. The corrected quantities are sometimes normalized with a reference condition or a "reference state". There are thus several different definitions of corrected quantities.

The benefit of these corrected quantities and dimensionless relation is the reduction of measurements on can achieve by using them. It is for example interest to know the turbo performance with different inlet pressures at different altitudes. Because this dependencies are given by the dimensionless relations the measurement only needs to be done for one inlet pressure.

3.1.3 Naturally aspirated engine and turbo engine

The benefits of a small engine are that it's more effective during normal use. The pleasure of driving will be affected negatively though since the engine is too small to produce high enough torque.

The large engine will give greater pleasure of driving but will not be as effective during normal use since the load will be too low.

When using a turbocharged small engine you still get (nearly) the same efficiency during normal use but with extra torque when needed. A drawback with using a turbocharged engine is that it will not be able to produce extra torque over the entire register. Another drawback is that the extra torque from the turbo will be a bit delayed because the turbo needs time to spin up.

3.1.4 Turbo engine actuators

For a turbo charged engine there are two extra actuators that does not exist in a naturally aspirated engine. Those are the wastegate valve and the surge valve. The wast gate is used to let the mass flow in the exhaust bypass the turbine. This is needed for several reasons, some examples are to limit the compressor speed to protect it from breaking, to reduce the mass flow generated by the compressor and to reduce pumping work by removing the restriction the turbine causes when the load on the engine is low.The surge valve is used to bypass the turbine. This is used to prevent surge. When the pressure ratio over the compressor becomes to high the surge valve is opened to even the pressure on both sides to prevent surge.

3.1.5 Example calculations for a compressor

Given a compressor flow ($\dot{m}_c$), compressor pressure ratio (Π_c), compressor efficiency (η_c) and compressor inlet temperature (T_{01});

(a) The compressor outlet temperature (T_{02}) can be calculated form the expression for compressor efficiency,

$$\eta_c = \frac{\Pi_c^{\frac{\gamma-1}{\gamma}} - 1}{\frac{T_{02}}{T_{01}} - 1} \Leftrightarrow T_{02} = T_{01} \frac{\Pi_c^{\frac{\gamma-1}{\gamma}} - 1}{\eta_c} + T_{01},$$

where γ is the heat capacity for air which is approximately constant.

(b) Given the temperature increase over the compressor, $\Delta T_c = T_{02} - T_{01}$, the compressor power ($\dot{W}_c$) can be calculated using the expression,

$$\dot{W}_c = \dot{m}_c c_p \Delta T_c,$$

where c_p is the heat capacity at constant pressure for air, which is approximately constant.

(c) Given the turbo speed (ω_{tc}) and the compressor power (P_c), the breaking torque (Tq_c) on the turbo shaft be calculated as,

$$P_c = \eta_c T q_c \omega_{tc} \Leftrightarrow T q_c = \frac{P_c}{\eta_c \omega_{tc}}.$$

3.1.6 Example calculations for a turbine

Given a turbine mass flow ($\dot{m}_t$), turbine pressure ratio (Π_t), turbine efficiency (η_t) and turbine inlet temperature (T_{03});

(a) The turbine outlet temperature (T_{04}) can be calculated form the expression for turbine efficiency,

$$\eta_t = \frac{1 - \frac{T_{04}}{T_{03}}}{1 - \Pi_t^{\frac{\gamma-1}{\gamma}}} \Leftrightarrow T_{04} = T_{03} - T_{03}(1 - \Pi_t^{\frac{\gamma-1}{\gamma}}),$$

where γ is the heat capacity for air which is approximately constant.

(b) Given the temperature drop over the turbine, $\Delta T_c = T_{03} - T_{04}$, the turbine power ($\dot{W}_t$) can be calculated using the expression,

$$\dot{W}_t = \dot{m}_t c_p \Delta T_c,$$

where c_p is the heat capacity at constant pressure for air, which is approximately constant.

(c) Given the turbo speed (ω_{tc}) and the turbine power (P_t), the breaking torque (Tq_t) on the turbo shaft be calculated as,

$$P_t = \frac{1}{\eta_t} T q_t \omega_{tc} \Leftrightarrow T q_t = \frac{\eta_t P_t}{\omega_{tc}}.$$

3.1.7 Throttle and wastegate control

For maximum performance the wastegate should be closed and the throttle should be controlled so the desired pressure is satisfied. This leads to a fast response time for the turbo but also a greater pumping work.

For best fuel efficiency the wastegate should be fully open. This leads to a more open throttle and less pumping work and of course a slow response time for the turbo.

3.1.8 Throttle and wastegate control example

(a) For low loads there won't be any difference because $p_{\mathrm{im}} + \Delta_{\mathrm{p_{thr}}} < p_c$. That means the wastegate will be fully open in both cases. For higher loads the situation with $\Delta_{\mathrm{p_{thr}}} = 10$ will be a little bit faster and also a little less efficient.

(b) The situation with $\Delta_{\mathrm{p_{thr}}} = 10$ will be slower and more efficient.

(c) The effects of the time delay for be more noticeable for a light press on the gas pedal (at least for high loads when the throttle is more open for the fuel-efficient variants). This means that it's easier to feel a difference in performance between the different strategies.

3.2 Model validation

In this section, the models developed in previous chapter are compared against measurement data foam a turbo map.

3.2.1 Compressor

The model parameters for the compressor models for mass flow and efficiency are estimated using a data form a turbo map. The parameters were estimated using an nonlinear least square method. The model and model parameters were then validated using measurement data from the turbo map.

Parameter(s) value: $\Psi_{\mathrm{max}} = 1.0016$, $\dot{m}_{\mathrm{c,corr,max}} = 0.1805$, $\eta_{\mathrm{c,max}} = 0.8206$, $\dot{m}_{\mathrm{c,corr@}\eta_{\mathrm{c,max}}} = 0.0842$, $\Pi_{\mathrm{c@}\eta_{\mathrm{c,max}}} = 1.9778$, $Q_{11} = 90.5045$, $Q_{12} = -6.4116$ and $Q_{22} = 0.8223$.

Measurement file: TurboMap.mat

Method: Nonlinear least square method.

Validation: The compressor mass flow validation plot is seen in figure 3.1, the different lines represent different compressor speeds ranging from 80000 rpm in the lower left corner to 170 rpm in the top right corner in the plot. It is seen in the plot that the mass flow model is better for lower compressor speeds.

In the figure 3.2 validation plot is seen. The different lines have the same interpretation here as before. It is seen in the plot that the efficiency model is the least accurate for low compressor speeds, for higher compressor speeds the model is fairly accurate.

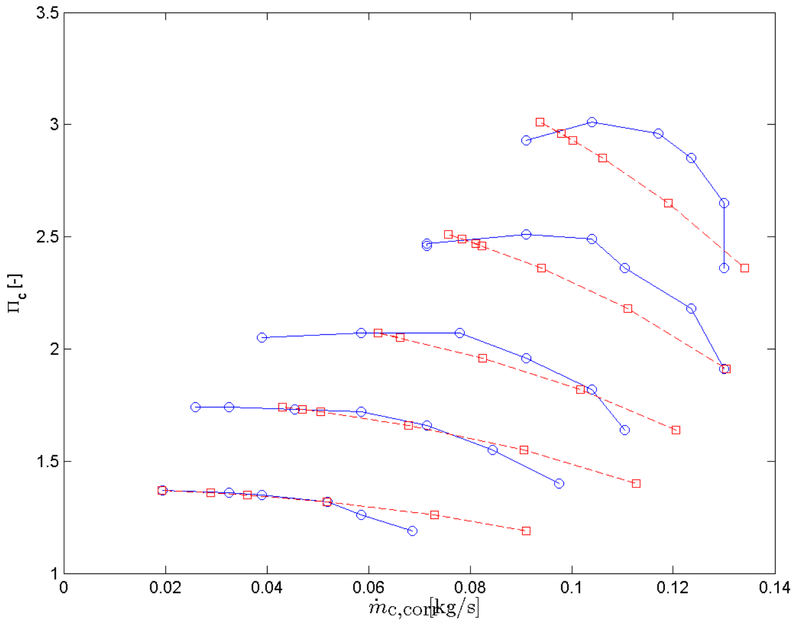

Figure 3.1: Compressor mass flow model validation. Blue: Turbo map data, Red: Modelled data.

3.2.2 Turbine

The model parameters for the turbine models for mass flow and efficiency are estimated using a data form a turbo map. The parameters were estimated using an nonlinear least-square method. The model and model parameters were then validated using measurement data from the turbo map.

Parameter(s) value: $k_0 = 0.0054$, $k_1 = 1.4506$, $\eta_{t,max} = 0.8073$, $\text{BSR}_{max} = 0.6790$

Measurement file: TurboMap.mat

Method: Non-linear least-square method

Validation: The turbine mass flow model is validated in Figure 3.3. The model is good, especially for lower pressure ratios (Π_t).

The turbine efficiency model is validated in Figure 3.4. The model is not very good for any turbine speed in the middle region for BSR. Outside that region the model fits best for 130k rpm or 150k rpm.

3.2.3 BMEP model

Parameter(s) value: $C_{P0} = 2.73 \times 10^5$, $C_{P1} = 10$

Measurement file: EngineMapTSFS09.mat

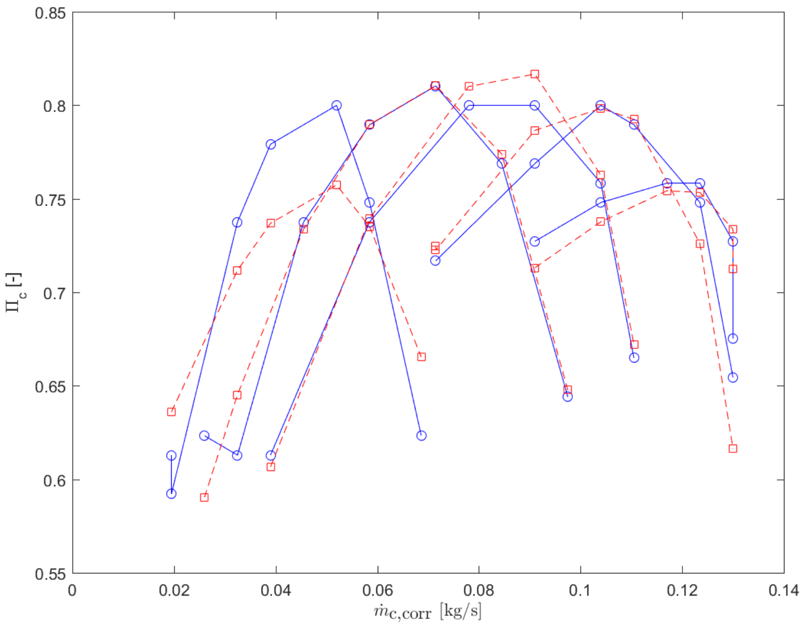

Figure 3.2: Compressor efficiency model validation. Blue: Turbo map data, Red: Modelled data.

Method: Least-square method

Validation: As seen in Figure 3.5 the model is quite good for all values of p_{im}.

3.3 Table of Parameters

All estimated parameters in the different engine sub models are summarized in table 3.1.

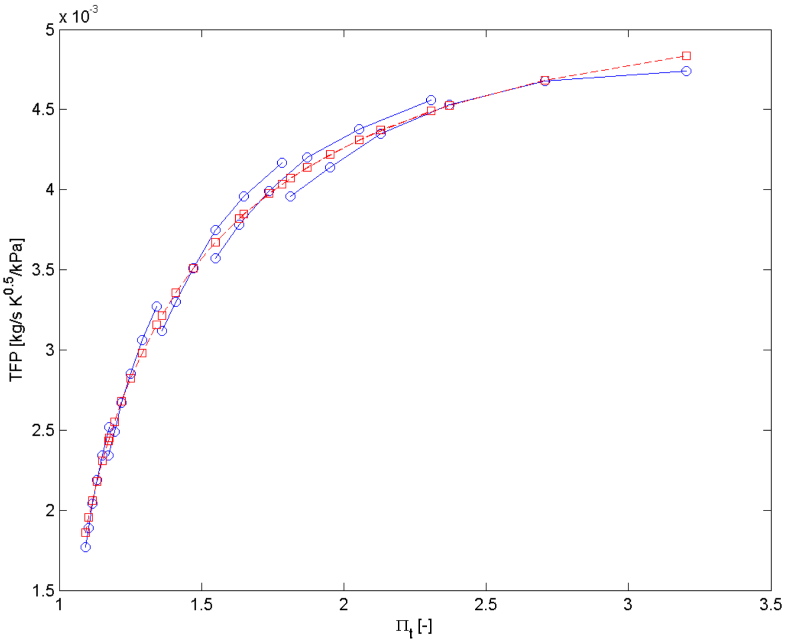

Figure 3.3: Turbine mass flow model validation. Blue: Turbo map data, Red: Modelled data.

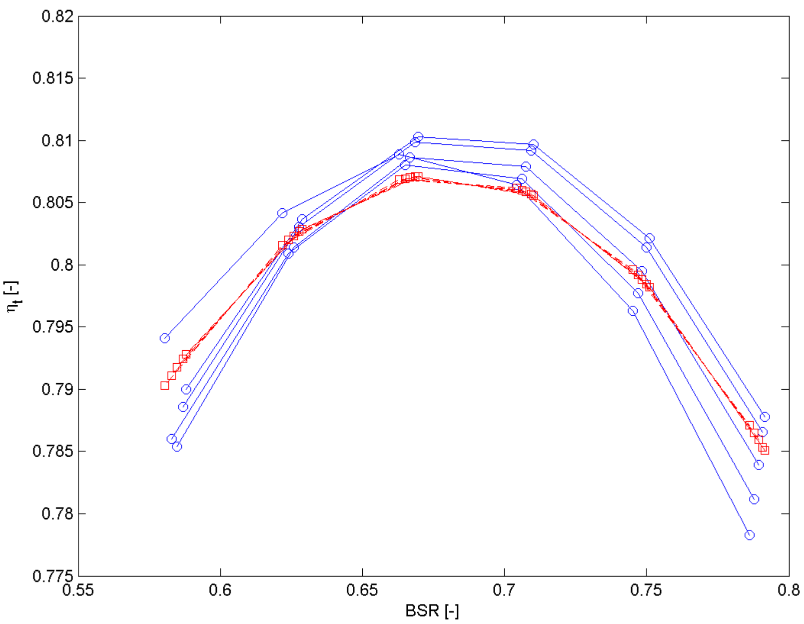

Figure 3.4: Turbine efficiency model validation. Blue: Turbo map data, Red: Modelled data.

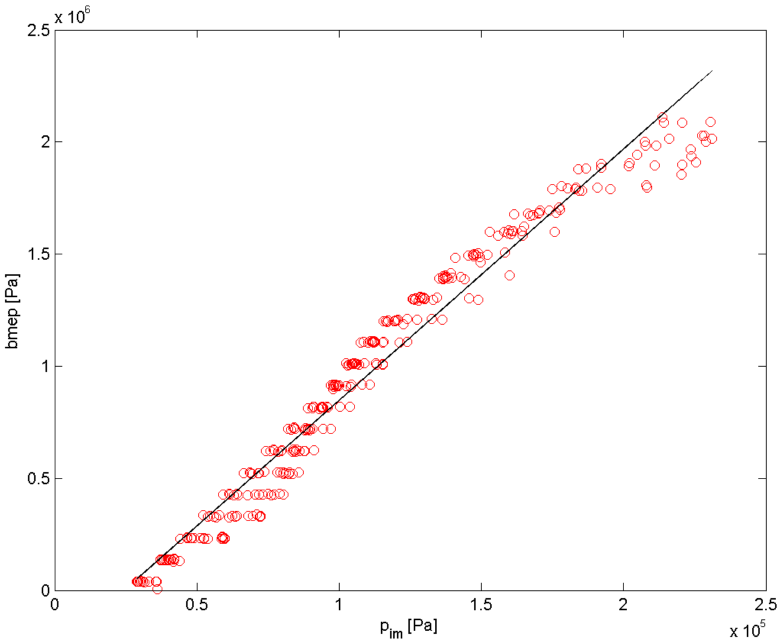

Figure 3.5: BMEP

Table 3.1: Estimated parameters in engine sub models

Component	Parameter	Value
Turbine	k_0	0.0054
	k_1	1.4506
	$\eta_{\mathrm{t,max}}$	0.8073
	$\mathrm{BSR}_{\mathrm{max}}$	0.6790
Compressor	Ψ_{max}	1.0016
	$\dot{m}_{\mathrm{c,corr,max}}$	0.1805
	$\eta_{\mathrm{c,max}}$	0.8206
	$\dot{m}_{\mathrm{c,corr@}\eta_{\mathrm{c,max}}}$	0.0842
	$\Pi_{\mathrm{c@}\eta_{\mathrm{c,max}}}$	1.9778
	Q_{11}	90.5045
	Q_{12}	-6.4116
	Q_{22}	0.8223

Chapter 4

Implementation of engine model with turbo

This chapter presents how different models for sub components of the engine with turbo are implemented in Simulink.

4.1 Compressor

Implementation: Here the simulink implementation of the compressor is presented.

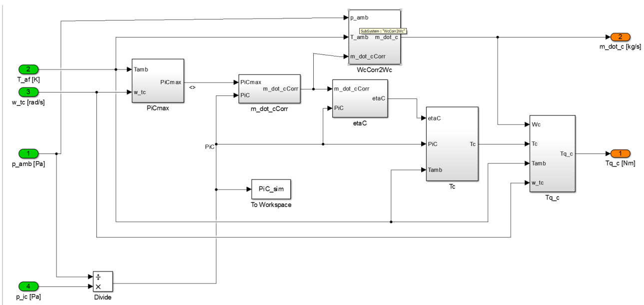

Figure 4.1: Compressor overview.

Validation: To validate the simulink implementation of the compressor model the model validation plots from earlier was used as comparison. When appropriate input data form the turbo map was used as input to the smulink implementations reasonable reasonable results was achieved. In figure 4.8 the validation of the compressor mass flow implementation is seen. The simulink model exactly matches the earlier validation plot for the model. In figure 4.9 the validation of the compressor efficiency implementation is seen. The simulink model does not exactly match the earlier model validation plot, this is due to a propagation of error form the model for

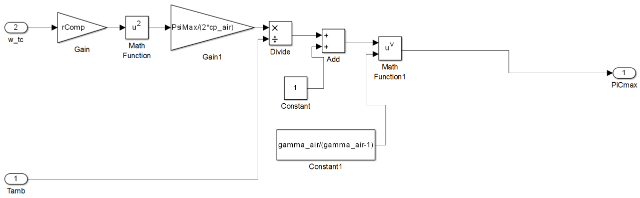

Figure 4.2: $\Pi_{c,max}$.

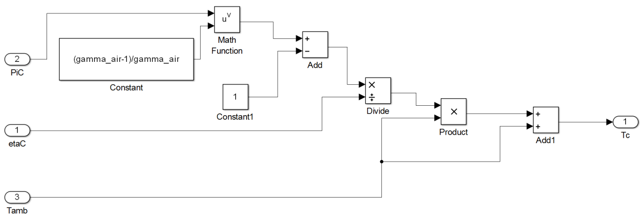

Figure 4.3: ω_{tc}.

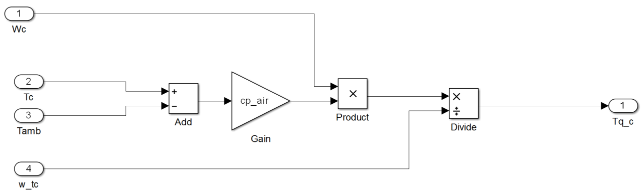

Figure 4.4: Tq_c.

compressor mass flow which is used as input to this model. The implementation is therefore considered reasonable. In figure 4.10 the validation of the torque efficiency implementation is seen. For all input data form the turbo map the torque is reasonable.

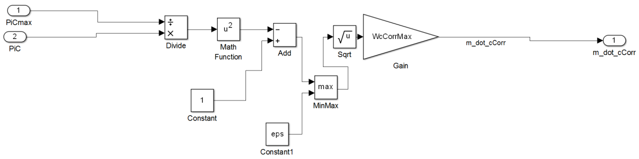

Figure 4.5: $\dot{m}_{c,corr}$.

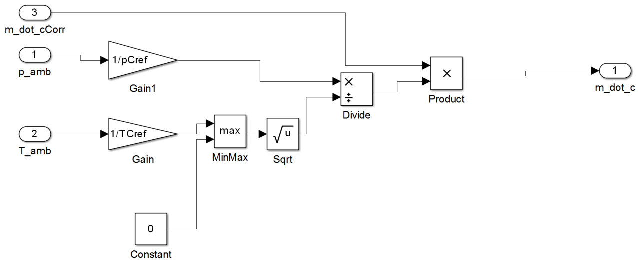

Figure 4.6: $\dot{m}_c$.

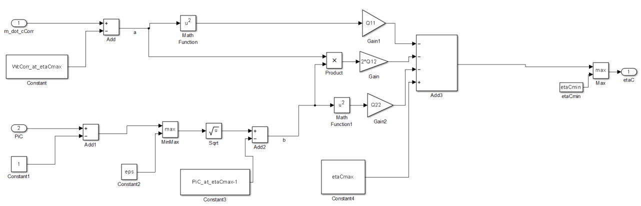

Figure 4.7: η_c.

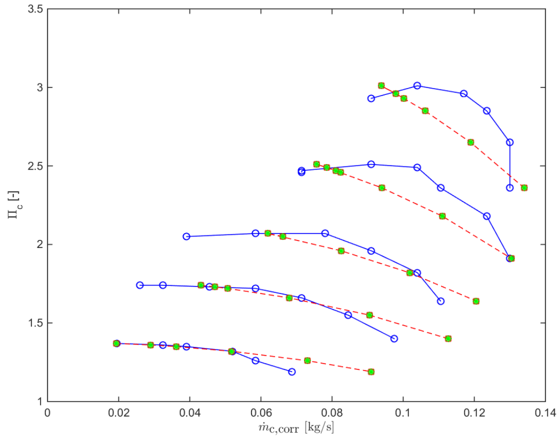

Figure 4.8: Validation of simulink compressor massflow model. Blue: Turbomap, Red: Model, Green: Simulink implementation.

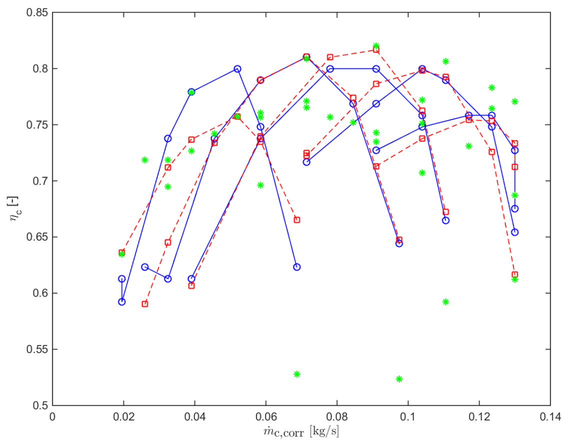

Figure 4.9: Validation of simulink compressor efficiency model. Turbomap, Red: Model, Green: Simulink implementation.

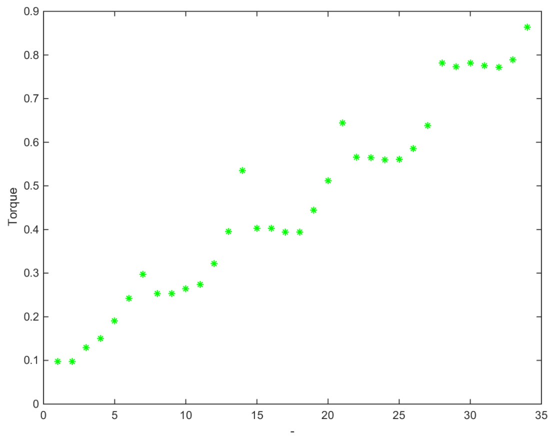

Figure 4.10: Validation of simulink compressor torque model.

4.2 Turbine

Implementation: Here the simulink implementation of the turbine is presented.

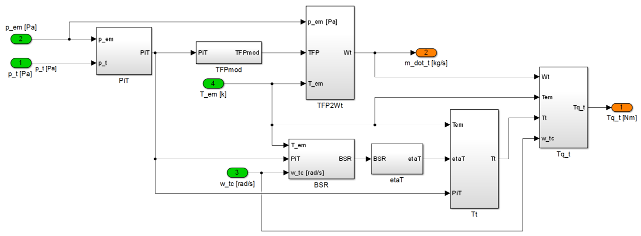

Figure 4.11: Compressor overview.

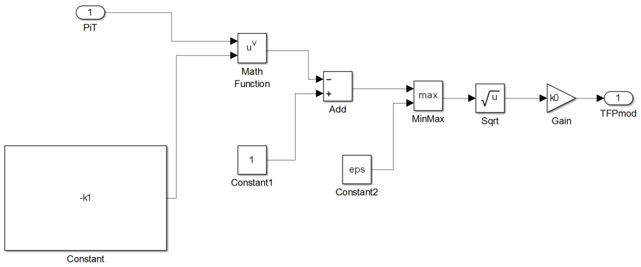

Figure 4.12: TFP_{mod}.

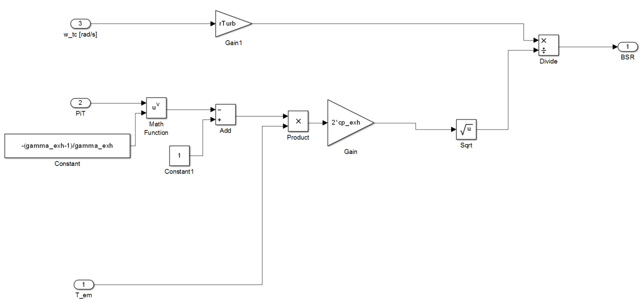

Figure 4.13: BSR.

Validation: To validate the simulink implementation of the turbine model the model validation plots from earlier was used as comparison. When appropriate input data form the turbo map was used as input to the smulink implementations reasonable reasonable results was achieved. In

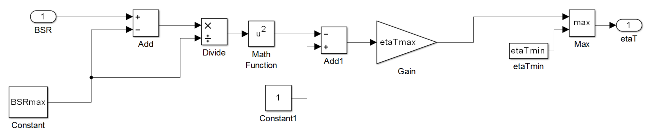

Figure 4.14: η_t.

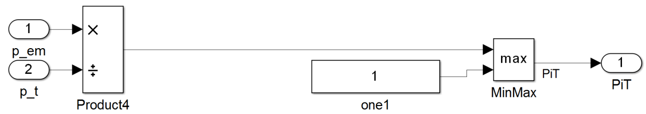

Figure 4.15: Π_t.

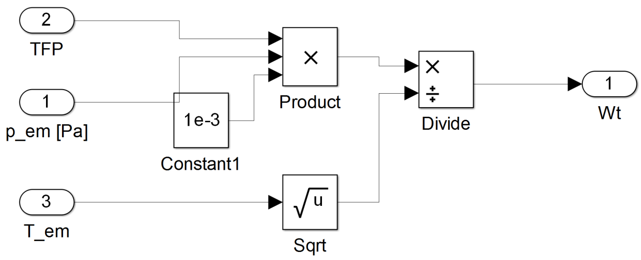

Figure 4.16: $\dot{m}_t$.

figure 4.19 the validation of the turbine mass flow implementation is seen. The simulink model exactly matches the earlier validation plot for the model. In figure 4.20 the validation of the turbine efficiency implementation is seen. The simulink model exactly matches the earlier validation plot for the model. In figure 4.21 the validation of the turbine torque implementation is seen. For all input data form the turbo map the torque is reasonable.

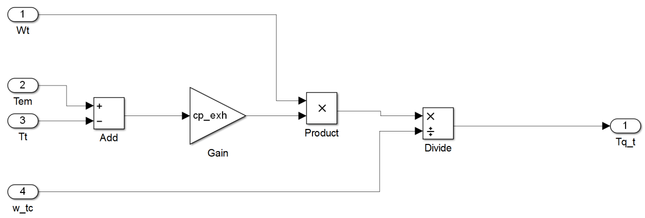

Figure 4.17: Tq_t.

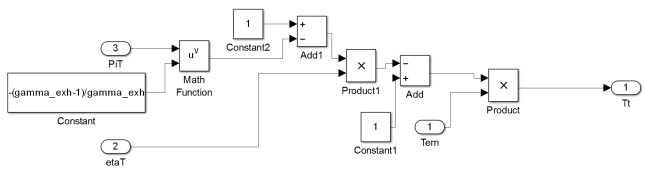

Figure 4.18: T_t.

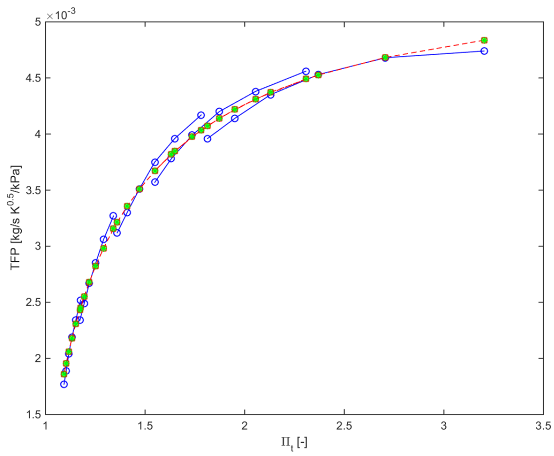

Figure 4.19: Validation of simulink turbine massflow model. Turbomap, Red: Model, Green: Simulink implementation.

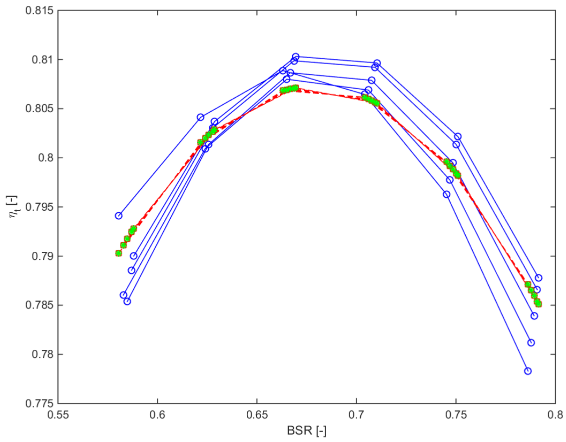

Figure 4.20: Validation of simulink turbine efficiency model. Turbomap, Red: Model, Green: Simulink implementation.

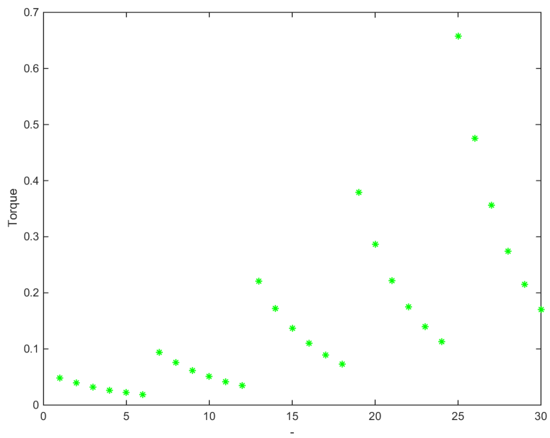

Figure 4.21: Validation of simulink turbine torque model.

4.3 Exhaust manifold

Implementation: Simulink implementation of exhaust manifold.

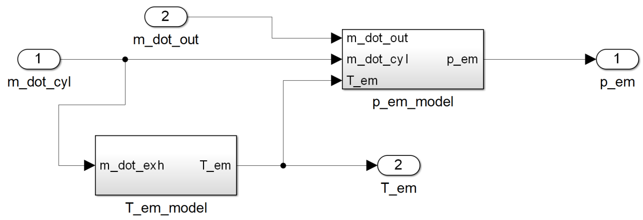

Figure 4.22: Exhaust manifold.

4.4 Exhaust flow

Implementation: Simulink implementation of exhaust flow.

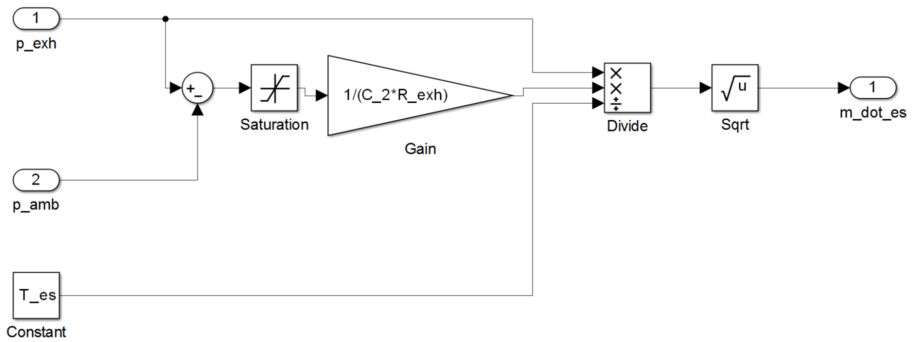

Figure 4.23: Exhaust flow.

4.5 Turbo dynamics

Implementation: Simulink implementation of turbo dynamics.

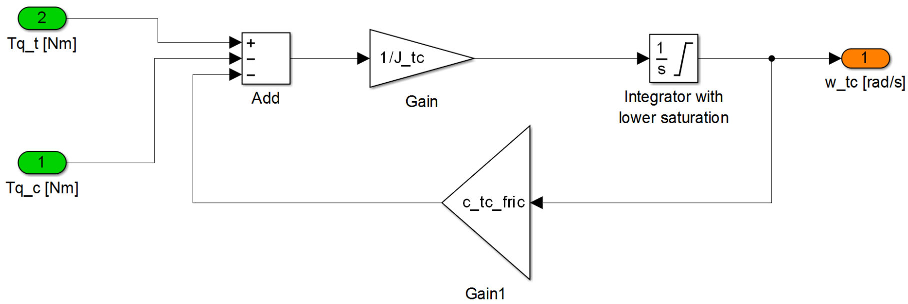

Figure 4.24: Turbo dynamics.

4.6 Complete engine model

Implementation: The entire engine simulink model with turbo is shown here.

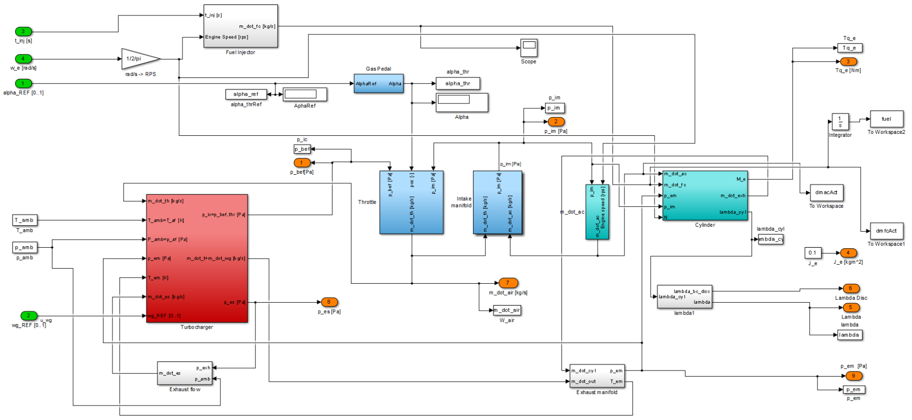

Figure 4.25: Complete engine.

4.7 Throttle Feed Forward

Implementation: The entire engine model with turbo is shown here.

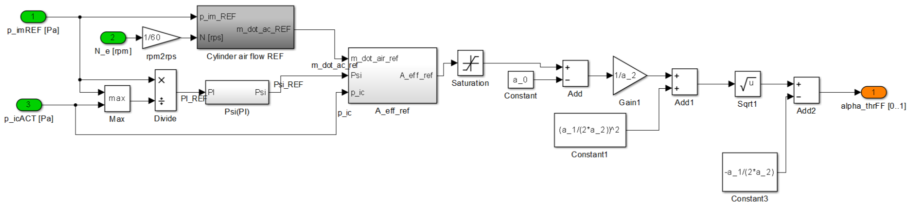

Figure 4.26: Throttle feedforward.

Chapter 5

Experiments

This chapter first presents the results of a number of experiments. The results are discussed and the plausibility is assessed.

5.1 Throttle Feedback and Feedforward

To control the intake manifold pressure a throttle controller was implemented. One feedback part and one feedforward part. The feed forward was implemented as the reverse of the intake manifold pressure from trottle position model, that was used in the engine model. The feedback is implemented as a PI controller. To determine appropriate feedback parameters, K_p and K_i, a step in gas pedal position was preformed with constant engine speed. During the step the wastegate was fully open, resulting in the throttle being the main actuator for intake manifold pressure. The result is seen in figure 5.1. The parameters was tuned to give reasonable behaviour with not too large overshoots and oscillations. The final feedback parameters was determined to be, $K_p = 1 \cdot 10^{-6}$ and $K_i = 0.1$.

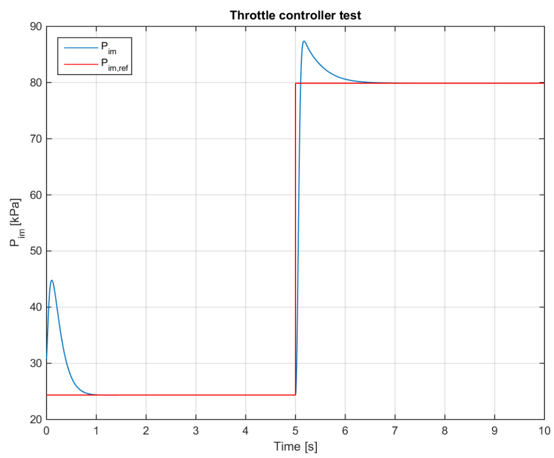

Figure 5.1: Throttle controller test, feedback and feedforward.

A second step response was preformed when the feedback controller was turned off, thus only the feedforward controlled the intake manifold pressure. The result is seen in figure 5.2. A large stationary error is clearly seen. The feedback is needed to remove this error. The reason for the stationary error is that the feedforward does not provide a perfect steady state model for the throttle position as a function of reference intake manifold pressure. It does however provide the an OK representation dynamics without the delay that the feedback delay. Therefore both feedback and feedforward is needed to accurately control the intake manifold pressure.

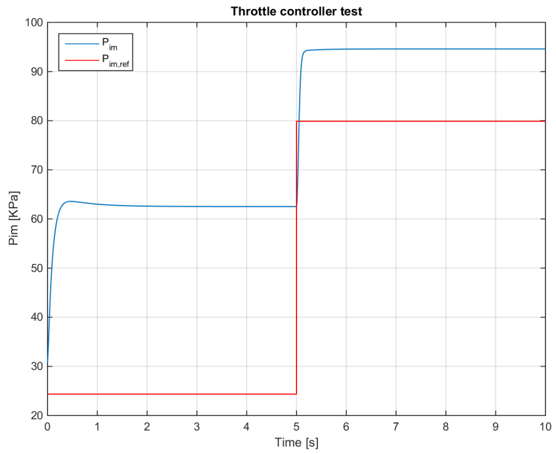

Figure 5.2: Throttle controller test only feedforward.

5.2 Wastegate Feedback

When additional boost pressure is needed the wastegate is the main actuator for intake manifold pressure. To control the wastegate a PI feedback was used. To determine the feedback parameters K_p and K_i, a step in gas pedal position was preformed with constant engine speed. The result is seen in figure 5.3.The feedback parameters was tuned to give give a reasonable behaviour with not too large overshoots and oscillations. The final feedback parameters was determined to be, $K_p = 1 \cdot 10^{-5}$ and $K_i = 5$.

When no bost pressure is need the feedback controller aims to keep the wastegate completely open. The reason for this is to reduce fuel consumption. When the wastegate is completely open, the turbine does not act as a flow restriction and the pressure in the exhaust manifold is lowered. Lowered exhaust manifold pressure reduces the pumping work in the cylinders of the engine and therefore lower fuel consumption.

5.3 Maximum torque curve

For the interpretation of the gas pedal position maximum torque curves as a function of engine speed was used, is interpolated from an engine map. To get

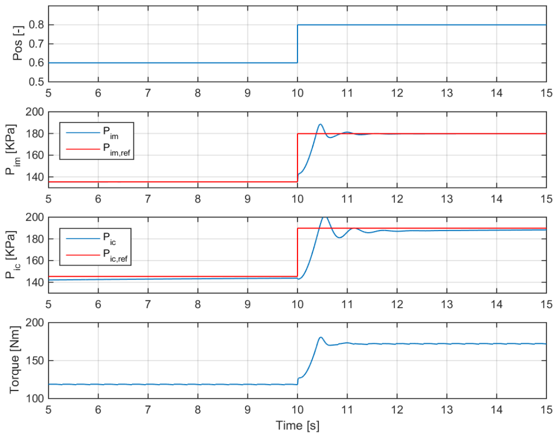

Figure 5.3: Wastegate feedback controller test.

the maximum torque curve for the modelled engine a slow ramp response in engine speed with maximum gas pedal position was preformed. The resulting torque curve is seen in figure 5.4. The difference from the interploated data en the modelled maximum torque plot could be explained if the interpolation data comes form a lager naturally aspirated engine. The interpolation data does not have the characteristic torque ramp up for low engine speeds that a turbo engine and the modelled engine has. The reduced engine friction in a smaller engine can explain the higher maximum torque in the modelled engine at working engine speeds.

In figure 5.5 the corrected mass flow in relation to the pressure ratio for the compressor, for the modelled engine as well as for the compressor map are ploted. It is seen that the engine is working within the surge region, at the left side of the compressor map and the choke region, the right side of the compressor map. It can also bee seen that at working conditions the pressure ratio maintained at a constant ratio for all engine speeds. Lower torque figures at low and high engine speeds correspond to the surge and choking regions of the compressor.

5.4 Naturally aspirated engine compared to turbocharged engine

In project 1 a lager naturally aspirated engine was modelled. Here a comparison to the modelled engine which is smaller and turbocharged is made, in terms of performance, emissions and fuel consumption is made.

In figure 5.6, an acceleration test is seen. Full throttle at forth gear was tested. It is seen that the vehicle accelerated form 70 km/h to 110 km/h in about 8.6 seconds. In project 1 the same figure was 17 seconds. A 50 % improvment.

In figure 5.7 the European drive cycle has ben run on the engine. Form this test the fuel consumption and emissions from the engine was calculated. In table 5.1 the emissions are presented for the modelled turbocharged engine.

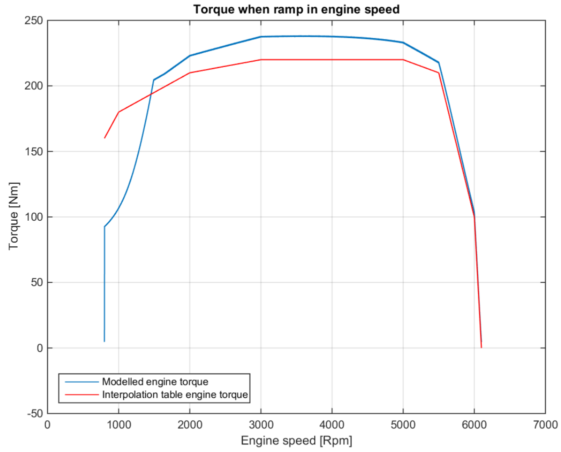

Figure 5.4: Maximum torque curve. Red: Engine map maximum torque, Blue: Modelled maximum torque.

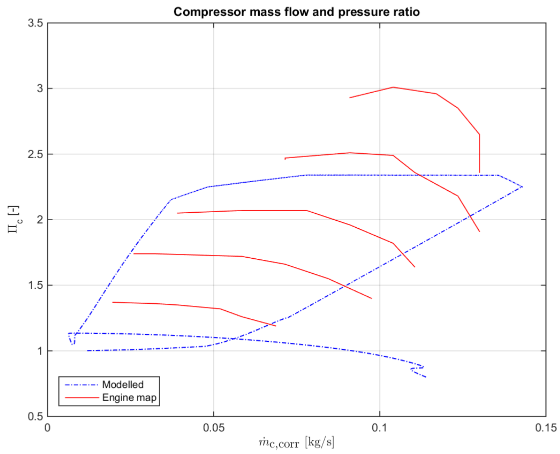

Figure 5.5: Simulation and engine map pressure ratio vs. corrected mass flow. Red: Compressor map, Blue: Model

In table 5.2 the emissions are presented for the naturally aspirated engine in project 1. It is seen in the two tables that the emissions for the turbocharged engine is higher than for the naturally aspirated engine.

From the drive cycle the fuel consumption was also calculated. For the turbocharged engine it was 5.64 [l/(100 km)]. For the engine in project 1 the fuel consumption was 6.57 [l/(100 km)]. A 15 % improvement for the turbocharged engine.

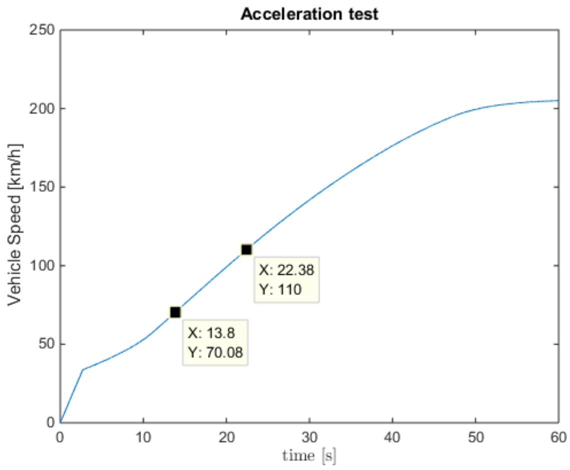

Figure 5.6: Acceleration test for the modelled engine, full throttle at forth gear.

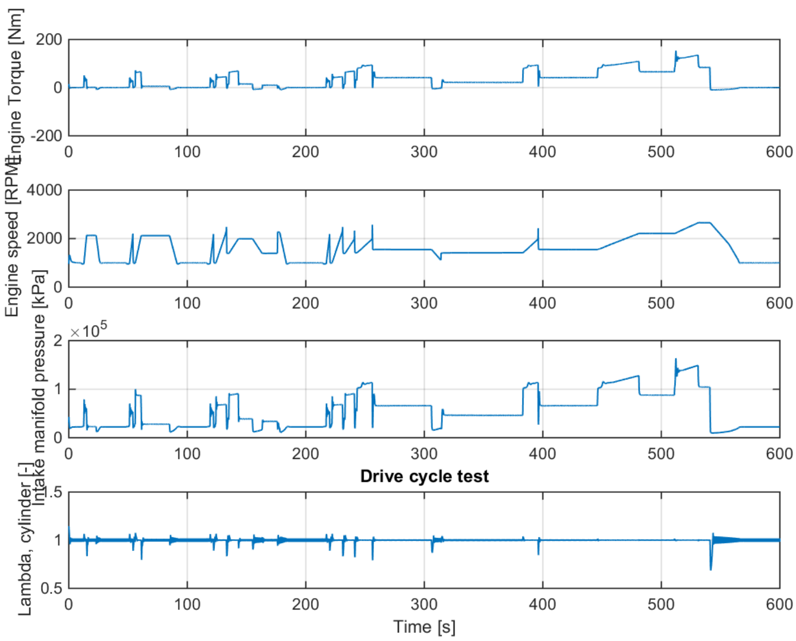

Figure 5.7: Drive cycle test for the modelled engine.

5.5 Torque for step in pedal position

An experiment was preformed where step in pedal position from ped = 0 % to ped = 100 % for a constant engine speed was preformed. Torque curve is not instant but follow a certain dynamic that corresponds to the turbo speed dynamic. At the before the step the turbo is not charged. When the step

Table 5.1: Turbocharged engine emissions

	After catalyst	EURO 3	EURO 4
CO [g/km]	0.44	2.3	1.0
HC [g/km]	0.07	0.20	0.10
NOx [g/km]	0.06	0.015	0.08

Table 5.2: Naturally aspirated engine emissions

	After catalyst	EURO 3	EURO 4
CO [g/km]	0.0	2.3	1.0
HC [g/km]	0.06	0.20	0.10
NOx [g/km]	0.0	0.015	0.08

is preformed it takes some time for the turbo to charge up and generate the mass flow needed for the desired torque. It is also seen that the throttle angle decreases when the turbo is fully charged. This is to maintain the desired pressure in the intake manifold that corresponds to the desired mass flow and torque.

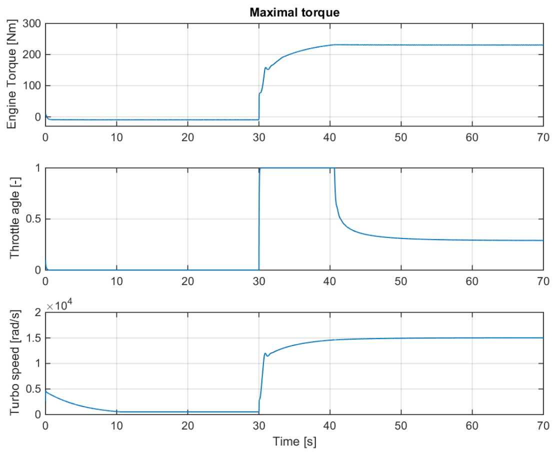

Figure 5.8: Maximal torque test a step in pedal position at constant engine speed.

Chapter 6

Conclusions

In this project an engine has been downsized and supercharged. The result is a better preforming engine for operating engine speed and lower fuel consumption for a drive cycle test. The only drawback to a bigger naturally aspirated engine are higher emissions. The emissions for the supercharged engine did however still meet the requirements for the EURO 4 standard.

Matlab code

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% Student code for project2A    %%%
%%% TSFS09 - Fordonssystem        %%%
%%% Vaheed Nezhadali 2015-10-22   %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%



figNr=1;
figpath='Figures/';

doPlot=1;
doExpFig=0;
doSimulinkFig=0;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%       Satter upp turbomotordata med antaganden      %%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%clear all; close all;
load turboMap
load EnginemapTSFS09
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Load mesurement data and parameters %%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
NcCorr = comp.NcCorr;
m_dot_Ccorr = comp.m_dot_cCorr;
p01     = comp.p01;
T01     = comp.T01;
pCref   = comp.pCref;
TCref   = comp.TCref;
PiC     = comp.PiC;
etaC    = comp.etaC;
etaCmin=min(etaC/2); %will be used in Simulink models

p04   = turb.p04;
T03   = turb.T03;
TFP   = turb.TFP;
PiT   = turb.PiT;
TSP   = turb.TSP;
etaT = turb.etaT;
p03   = p04*PiT;
etaTmin=min(turb.etaT)/2; %will be used in Simulink models
% Compressor och Turbindiameter
dComp = 56e-3;
rComp = dComp/2;
dTurb = 52.2e-3;
rTurb = dTurb/2;
cp_exh = 1.2133e+03;            % [J/(kg*K)]
gamma_exh = 1.3;                % [J/(kg*K)]

cp_air =  980.0000;
gamma_air = 1.4000;

%Calculated quantetees
Nc   = NcCorr*sqrt(T01/TCref);
m_dot_c  = m_dot_Ccorr*(p01/pCref)/(sqrt(T01/TCref));
Uc2 = rComp*2*pi*Nc/60;
```

```
m_dot_t   = TFP.*p04*1e-3.*PiT./sqrt(T03); %or  ...
    TFP.*p03*1e-3./sqrt(T03);
Nt   = TSP.*sqrt(T03);
BSR = 2*pi*Nt*rTurb./sqrt(2*cp_exh*T03* ...
    (1-PiT.^(-(gamma_exh-1)/gamma_exh)))/60;

% create matrices where every column represents the data from ...
    same turbo
% speed
m_dot_cCorr_M = reshape([m_dot_Ccorr ; NaN],7,5);
PiC_M          = reshape([PiC ; NaN],7,5);
NcCorr_M       = reshape([NcCorr ; NaN],7,5);
etaC_M         = reshape([etaC ; NaN],7,5);
Nc_M           = reshape([Nc ; NaN],7,5);
m_dot_c_M      = reshape([m_dot_c ; NaN],7,5);
Uc2_M          = reshape([Uc2 ; NaN],7,5);
% create matrices where every column represents the data from ...
    same turbo
% speed
TSP_M  = reshape(TSP,6,5);
TFP_M  = reshape(TFP,6,5);
PiT_M  = reshape(PiT,6,5);
etaT_M = reshape(etaT,6,5);
BSR_M  = reshape(BSR,6,5);
m_dot_t_M   = reshape(m_dot_t,6,5);
Nt_M   = reshape(Nt,6,5);


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Compressor modell    %%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% COMPRESSOR Mass flow model
x=[PiC Uc2];

y=m_dot_Ccorr;

% Define reasonable start values on the parameters
x0 = [1 1];

% Define the nonlinear function
f_m_dot_Ccorr_mod = ...
    @(a,x)(a(1).*sqrt(1-(x(:,1)./((x(:,2).^2.*a(2)/ ...
    (2*cp_air*T01)+1).^(gamma_air/(gamma_air-1)))).^2));
func = f_m_dot_Ccorr_mod;

par = lsqcurvefit(func, x0, x, y);
WcCorrMax = par(1);
PsiMax = par(2);

m_dot_Ccorr_mod = func(par,x);

m_dot_Ccorr_mod_M = reshape([m_dot_Ccorr_mod ; NaN],7,5);



if doPlot
    close all
    h = figure
    plot(m_dot_cCorr_M, PiC_M,'b-o',m_dot_Ccorr_mod_M, PiC_M, ...
        'r--s')
   % legend('Measured', 'Model', 'Location','northwest')
```

```
    xlabel('$\dot{m}_\textrm{c,corr}$ [kg/s]', 'interpreter', ... 'latex')
    ylabel('\Pi_c [-]')
    saveas(h,'Figures\compressor_mass_flow','png')
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% COMPRESSOR efficiency model

%par=[PiC_at_etaCmax WcCorr_at_etaCmax etaCmax Q11 Q22 Q12];
x=[PiC m_dot_Ccorr];
y=etaC;

x0=[1.977,0.08,0.8,90,-1,-6];

func=@f_etaC_mod;
par = lsqcurvefit(func, x0, x, y);

PiC_at_etaCmax = par(1);
WcCorr_at_etaCmax = par(2);
etaCmax = par(3);
Q11 = par(4);
Q22 = par(5);
Q12 = par(6);

etaC_mod=func(par,x);

etaC_mod_M = reshape([etaC_mod ; NaN],7,5);

if doPlot
    close all
    h = figure;
    plot(m_dot_cCorr_M, etaC_M,'b-o',m_dot_cCorr_M, etaC_mod_M, ... 'r--s')
   % legend('Measured', 'Model', 'Location','northwest')
    xlabel('$\dot{m}_\textrm{c,corr}$ [kg/s]', 'interpreter', ... 'latex')
    ylabel('\Pi_c [-]')
    saveas(h,'Figures\compressor_efficiensy','png')
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Turbin modell    %%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% TURBIN Mass flow model


x=PiT;
y=TFP;

% Define reasonable start values on the parameters
c0ini = 0.0052; % Max(TFP) found at Pi=inf
c1ini = 2; % From FS-book, p. 159
x0 = [c0ini c1ini];

% Define the nonlinear function
f_TFPmod = @(a,x)(a(1).*sqrt(1-1./x.^a(2)));
func = f_TFPmod;

par = lsqcurvefit(func, x0, x, y);
k0 = par(1);
k1 = par(2);
```

```
TFPmod = func(par, x);

TFPmod_M = reshape(TFPmod,6,5);

if doPlot
    close all
    h = figure
    plot(PiT_M, TFP_M,'b-o',PiT_M, TFPmod_M, 'r--s')
   % legend('Measured', 'Model', 'Location','northwest')
    xlabel('\Pi_t [-]')
    ylabel('TFP [kg/s K^{0.5}/kPa]')
    saveas(h,'Figures\turbine_mass_flow','png')
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% TURBIN efficiency model
x=BSR;
y=etaT;

% Define reasonable start values on the parameters
c0ini = 0.8; %
c1ini = 50; %
x0 = [c0ini c1ini];

% Define the nonlinear function
f_etaT_mod = @(a,x)(a(1).*(1 - ((x-a(2))./a(2)).^2));
func = f_etaT_mod;

par = lsqcurvefit(func, x0, x, y);
etaTmax = par(1);
BSRmax = par(2)

etaT_mod = f_etaT_mod(par,x)

etaT_mod_M = reshape(etaT_mod,6,5);

if doPlot
    close all
    h = figure
    plot(BSR_M, etaT_M,'b-o',BSR_M, etaT_mod_M, 'r--s')
   % legend('Measured', 'Model', 'Location','northwest')
    xlabel('BSR [-]')
    ylabel('\eta_t [-]')
    saveas(h,'Figures\turbine_efficiency','png')
end


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% BMEP model    %%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% par=[Cp0 Cp1];
% x=[EngineMap.p_im EngineMap.M_e]

bmep=EngineMap.M_e*EngineMap.engine.n_r*2*pi/EngineMap.engine.V_D;
p_im=EngineMap.p_im;

A=[-ones(length(p_im),1) p_im];

par=A\bmep;

bmep_mod=A*par
```

```

if doPlot
    close all
    h = figure
    plot(p_im, bmep,'ro',p_im, bmep_mod, 'k-')
   % legend('Measured', 'Model', 'Location','northwest')
    xlabel('p_{im} [kPa]')
    ylabel('bmep [kPa]')
    saveas(h,'Figures\bmep','png')
end
```