Control design for diesel engines using a Modelica model

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Abstract

The Modelica language supports reusable components throughout the design process. Using the Functional Mock-up Interface, system model built by reusable components can be transferred to different platforms. This can be done in a straightforward manner and makes it possible for different engineering divisions to use the same Modelica models.

In this thesis, it is displayed how a Modelica model of a diesel engine can be used for control design. The diesel engine model is a multiple input and multiple output system. It is also nonlinear and has a higher order than most control design algorithms are able to handle in a numerically robust manner.

In this thesis the following approach was used to be able to control the system. Design-of-Experiment is used to analyze the variation of the dynamics of the system in the operating range of the engine. The Functional Mock-up Unit is linearized and the number of states are reduced.

The controller used consists of nine multivariable Linear-Quadratic-Gaussian (LQG) controllers spread out over the operating range of the engine. Using a gain scheduler the different LQG controllers are connected.

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Contents

1. Introduction

As computers become more powerful, so do the state-of-the-art platforms for technical calculations. The platforms are for example Excel, MATLAB, Dymola, ANSYS and Python. They can handle larger and more complex models than before. Some areas of the platforms has dropped behind. For example, information exchange of dynamic models from one computational platform to another was standardized as late as in 2010 [FMI standard, 2015].

Information exchange is the means of moving a model to another platform. Since each platform becomes more complex and specialized, the need for such a standard was great. This new standard resulted in more complex and better-described models being available in MATLAB, which has well-developed toolboxes in, for example, control and optimization.

Some control methods cannot be applied on large complex models. This is why Modelon has devoted resources to develop a toolbox for simplification and analysis of models, called Functional Mock-up Interface Toolbox.

In this thesis a Dymola model of a diesel engine is transferred from Dymola using Functional Mock-up Interface (FMI) into MATLAB, where the model is analyzed using Modelon’s toolbox and later controlled.

The model in Dymola is described using the Modelica language. The Modelica language is open-source language developed by the Modelica Association. It is an object-oriented modelling language, which is used for model-based development. The association has an open-source standard library that covers the most ordinary components in mechanical, electrical, thermal and fluid system. The model in this thesis is designed using Modelon’s Engine Dynamics Library.

One important features of a model-based development is that the model can be modified easily and the design environment is unanimous through different functionality groups in the company. Model-based development makes it possible for different functionality teams in the company to share the same system model, but different model parts. For example, the model design team might have a simple control mock-up and a complex system model, while the control team uses a complex controller and a simple system model. This could reduce the simulation time in development of the product.

1.1 Context

The development of more energy-efficient engines is one of today’s most important goals for the vehicular industry. Legislators are constantly lowering the limits of emission, and the price of fuel is increasing over a longer perspective. The combustion engine process can be improved significantly. For example, less than 10% of the maximum engine power is utilized on average. Another example is that the efficiency of the tank-to-wheel process is less than 18% for an actual passenger car [Guzzella and Onder, 2010].

To make engines more efficient the combustion process is controlled even tighter. For example the engine can be stopped when the vehicle stops. It is also possible to try to control the variable valve timing or the electronic throttle, which is a quite new approach [Guzzella and Onder, 2010]. This is not only good for the fuel economy, but also for the environment. The four most important control loops for Spark Ignition (SI) engines according to Guzzella and Onder are:

- The fuel-injection feed.
- The air/fuel ratio feedback loop.
- The ignition angle feedforward loop.
- The knock feedback loop.

These control loops exist in most processes connected to the engine, for example secondary air injection and idle speed control of the piston [Guzzella and Onder, 2010]. The control process for diesel engines is easier than for SI engines. To have a higher torque output in diesel engines, it is possible to change the air/fuel ratio, while for SI engines the three-way catalyst principle is used to apply a higher torque. What does complicate the process for a diesel engine is the turbocharged unit, which is not purely an air/fuel ratio process [Bosch, 2004].

To make use of new technology companies require a standardized method of applying them on a platform for development where it is easy and cheap to test new ideas. Dymola is such a platform, which Modelon has implemented a library of processes for the purpose of simulating different processes in an easy manner.

Xin discusses the system design of diesel engines and how this emerging technical field will affect the vehicular product development. This development can be divided into four sections: performance, durability, packaging and cost [Xin, 2011]. It is hard to meet all these demands simultaneously, but to do it requires a good model in an early stage of the product development. It is also good to enable an independence between different parts of the system. This is to make it possible to change the parts of the system without having to change the whole system.

Model-based engineering, such as Design of Experiment (DoE), is one of the keys in today's product development [Henningsson et al., 2014]. This is due to the fact that DoE is cheap and reduces the product cycle. When comparing implementing something in a computer and testing it versus implementing a process in the physical world and testing that, it is of course cheaper and easier to implement a system in a computer when it is done in a standardized manner.

Using the diesel engine model and Modelon's FMI Toolbox for MATLAB, the model is linearized using DoE and control of the process can be done. This workflow results in first having a complex model with many variables and later obtaining a model with less variables, but the reduced system still describes the system in a good approximation.

1.2 Control objectives

The performance variables to be controlled are emissions and efficiency of the engine. Emission is highly regulated by the legislators, see Sec. 2.1. Efficiency is chosen as a control objective to reduce the consumption of fuel. The control objectives are met using the control variables Exhaust Gas Recirculation (EGR) and Variable-Geometry Turbocharger (VGT). The measured variables are temperature of the exhaust ($T_{exhaust}$), flow of air ($flow_{air}$), pressure in the inlet (p_{inlet}), temperature of the inlet air (T_{inlet}) and speed of the turbocharger ($N_{turbine}$). The inputs of the user are regarded as disturbances. Figure 1 displays a block diagram of the correlation between the signals. All this results in the following control objectives:

1. Soot should be avoided.
2. The set-points of the user should be followed.
3. The turbocharger speed should not surpass a maximum limit.

4. The temperature of the exhaust should be in an interval, were the SCR is able to operate as it should.
5. The pressure in the inlet should be higher than a soft limit.

The goal is to find a controller that satisfies all these demands.

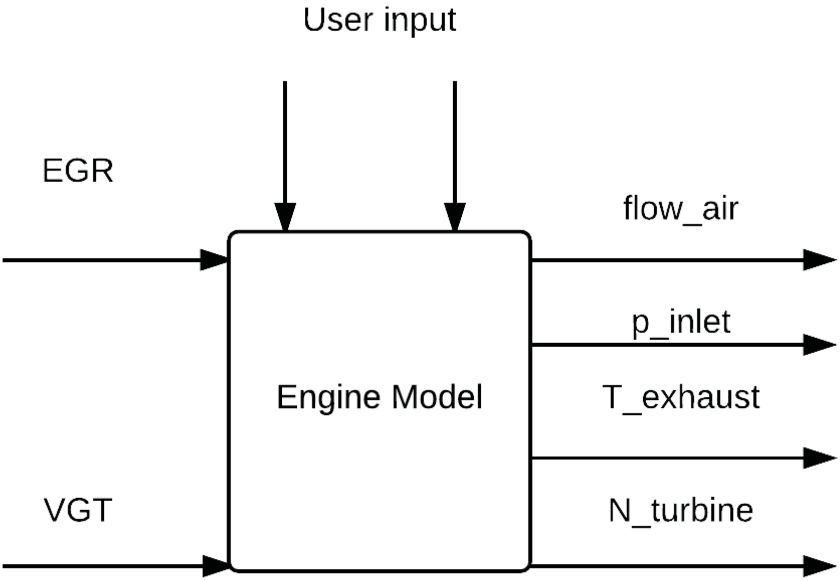


Fig. 1. The correlation between the signals used to solve the control problem.

1.3 Goals of the thesis

The ambition with the thesis is to give an example of a workflow where a real process is approximated using the Modelica languages in Dymola, which is commonly used platform for model design. An information exchange is then done using Modelon's Funtional mock-up interface toolbox (FMIT). The information exchanged is done with the platform MATLAB, which is a commonly used platform by control engineers. In MATLAB the control of the diesel engine system is performed.

The workflow gives a good example on how FMI standard models can be reused, by different functionalities of the company without any compromises in performance.

1.4 Outline of thesis

The thesis outline is as follows. Chapter 2 describes background of methods, tools and theories, which are used later in the paper. The chapter is divided into model, robust design analysis and control aspects. Chapter 3 describes the workflow of the paper, what work has been done during the thesis and what was already done before the thesis. In Chapter 4 the system is analysed and the nonlinearities of the system are revealed. The diesel engine system is analysed in Chapter 5. The control design is done Chapter 5, and a control configuration is presented. In Chapter 6 discussion are made and in Chapter 7 conclusions are drawn.

2. Background

In this chapter, the background will be presented, which will be later used to solve the control problem. The model will first be presented. Later the robust design analysis and control theory will follow.

2.1 Diesel engine

In this section the model diesel engine model will be explained. The model will have simplifications. For example, losses in temperature during the process steps, in the turbine, are disregarded. The model as stated earlier is a diesel combustion engine, the attributes of such a diesel engine system is explained in this section.

Internal combustion engine

The purpose of a combustion engine is to produce mechanical power from a chemical energy source. The term internal, in internal combustion engine, originates in the energy being released inside the engine. There are two main internal combustion engine types: Spark-Ignition (SI) and Compression-Ignition (CI) [Heywood, 1988].

The most common modern passenger cars today have SI engines. On the other hand, most heavy-duty vehicles are usually equipped with CI engines [Guzzella, 2010]. CI engines are also used to produce electricity [Johansson, 2003].

The CI engine can be driven on different types of fuel. The diesel engine does not have the problem of the knock effect, as the SI engine has [Heywood, 1988]. The CI engine is superior to the SI engine with respect to fuel consumption. The diesel engine has many other advantages compared to SI engines as well. Xin (2011) points out the following:

- Lower fuel consumption and CO_2 emission (due to high compression ratio)
- Higher power (CI engines can have a high level of turbocharging. SI engines also require auto-ignition, which results in that CI engines can use wider cylinders).

- Higher torque at low speeds (the high level of turbocharging allows CI engines to burn more fuel and therefore acquire higher torque than SI engines)
- Lower emission of CO and HC (because of the high level of air in the air-fuel mixture).

A problem with CI engines is that if there is not enough air (oxygen) in the air/fuel ratio soot may occur [Guzzella, 2010].

Today many diesel engines are equipped with Exhaust Gas Recirculation (EGR) and Variable-Geometry Turbocharger (VGT) (see section 2.1), to make the combustion process more efficient. Many after-treatment systems have also been implemented, due to legislations of emission limits.

Combustion

This section will describe the combustion of hydrocarbons. The combustion process can be described as fuel and air transformed into heat and exhausts. One of the most important aspects in the combustion process is the ratio between flow of air and flow of fuel.

$$\frac{\dot{m}_a}{\dot{m}_f} = \frac{A}{F} \tag{2.1}$$

The stoichiometric combustion ratio flow is defined as the ratio between flow of air and flow of fuel in a stoichiometric combustion:

$$\frac{\dot{m}_{as}}{\dot{m}_{fs}} = \left(\frac{A}{F}\right)_s \tag{2.2}$$

Compression ignition engines often have a constant flow of air and changes the flow of fuel to handle the power needed. The flow ratio can be compared to the stoichiometric combustion ratio flow. This will produce a number, lambda.

$$\lambda = \frac{\left(\frac{A}{F}\right)}{\left(\frac{A}{F}\right)_s} \tag{2.3}$$

To be able know how much flow of air is needed to provide a stoichiometric combustion, the following chemical reaction has to be balanced [Johansson, 2003]:

$$\begin{aligned} C_aH_b + \lambda \mathrm{n}_{\mathrm{O}_2,r}(O_2 + 3.773N_2) \\ = n_{C_aH_b}C_aH_b + n_{CO_2}CO_2 + n_{H_2O}H_2O + n_{CO}CO + n_{H_2}H_2 \\ + n_{O_2}O_2 + n_{N_2}N_2 + n_{NO}NO + n_{NO_2}NO_2 \end{aligned}$$

For diesel in our case, a and b which is the number mol of carbon and hydrogen have the value of 12 and 23. The pressure is calculated using the Ideal gas law and volumetric efficiency:

$$p_{inlet} = \frac{RT_{inlet}n}{V_{cyl} \cdot \eta_v} \tag{2.4}$$

where $\eta_v$is the volumetric efficiency, R is Reynolds number, T_{inlet} is the temperature in the inlet, V_{cyl} is the total volume of the cylinders, n is the chemical amount and p_{inlet} is the pressure of the inlet.

Exhaust gas recirculation (EGR)

EGR is used to control the NO_x emission in a combustion process. A part of the exhaust gas is recirculated in the engine in a controlled manner. This makes the fraction of exhaust in the fresh air that enters the combustion chamber a control variable. It is possible to cool the exhaust air to reduce the temperature in the combustion chamber [Guzzella and Onder, 2010].

A negative influence of the EGR on the process is when reducing the combustion rate it also makes the combustion process less stable and therefore harder to control. The emission of hydrocarbon may increase when the EGR ratio becomes large. When the EGR ratio is large the combustion temperature is often higher, the air/fuel ratio becomes lower and full combustion does not always occur. The positive effects of the EGR system can be summarized as [Heywood, 1988]:

- Reduced pump work because the pressure is higher in the outlet than in the inlet of the diesel engine system.
- The temperature of the process is more constant (less fresh air to heat-up and slower combustion process)
- A reduction of the combustion temperature, the processes has less emission (less variations in the combustion process)

Variable-geometry turbocharger (VGT)

The volume of air in the cylinder is limited by the pumping power of the engine. Therefore engines have a limited maximum torque, which they can supply. The engine can supercharge to force a larger airflow into the cylinder. In this case, the turbocharger consists of a compressor and a turbine mounted on the same shaft. According to Guzzella and Onder (2010), the exhaust gas can be used to boost the pressure in the intake, thereby also controlling the amount of air flowing into the cylinder even better, see figures 2 and 3.

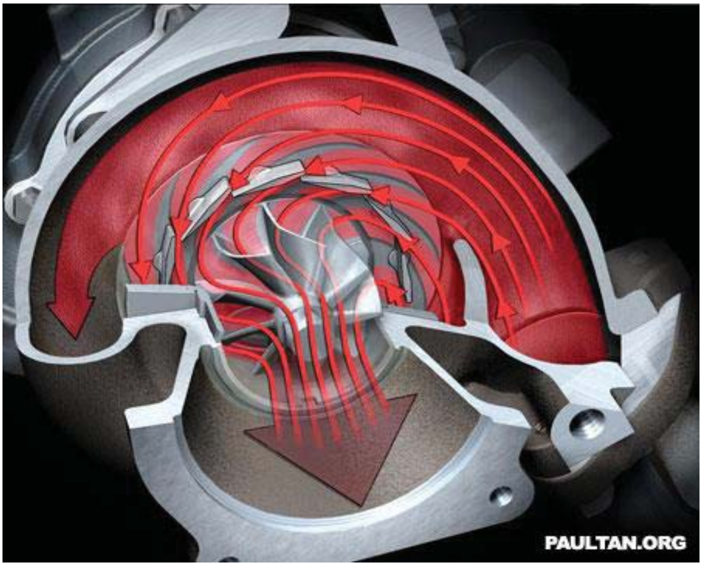


Fig. 2. Turbine reducing the flow using VGT valve. Source: [Tan, 2006]

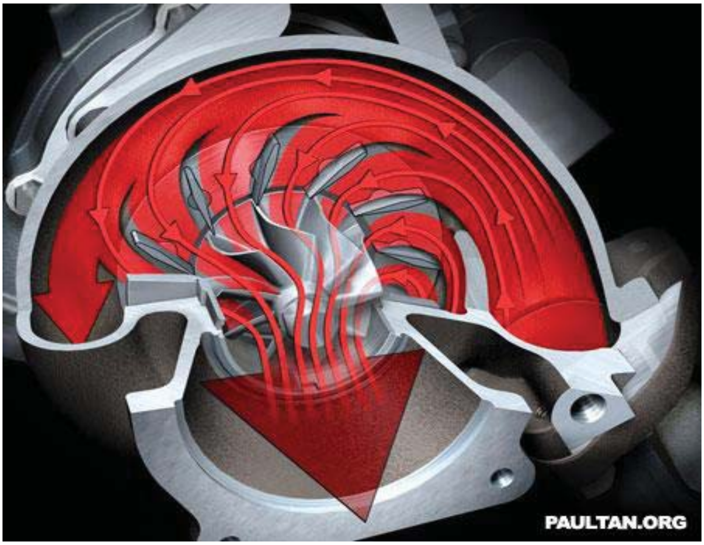


Fig. 3. Turbine with open VGT valve. Source: [Tan, 2006]

Modelica engine model

The engine model used in this thesis is found in Engine Dynamics Library from Modelon [Modelon, 2015]. The engine model is a Modelica model, which in Dymola has the following configuration, see figures 4 and 5. The model is a mean-value diesel engine model. The engine model represents a four-stroke engine with six cylinders with a 13 dm^3 total displaced volume and has a total compression ratio of 16. The engine is equipped with a high-pressure EGR loop, throttle for the EGR loop and for the air intake. It also has a charged air cooler and an EGR cooler. The combustion energy-conversion efficiency, exhaust gas temperature, volumetric efficiency and emissions are calculated using table-based maps.

The internal main dynamical effects are produced by thermal masses of the cylinder blocks and pipes walls, moment of inertia of the cylinder flywheel and turbo.

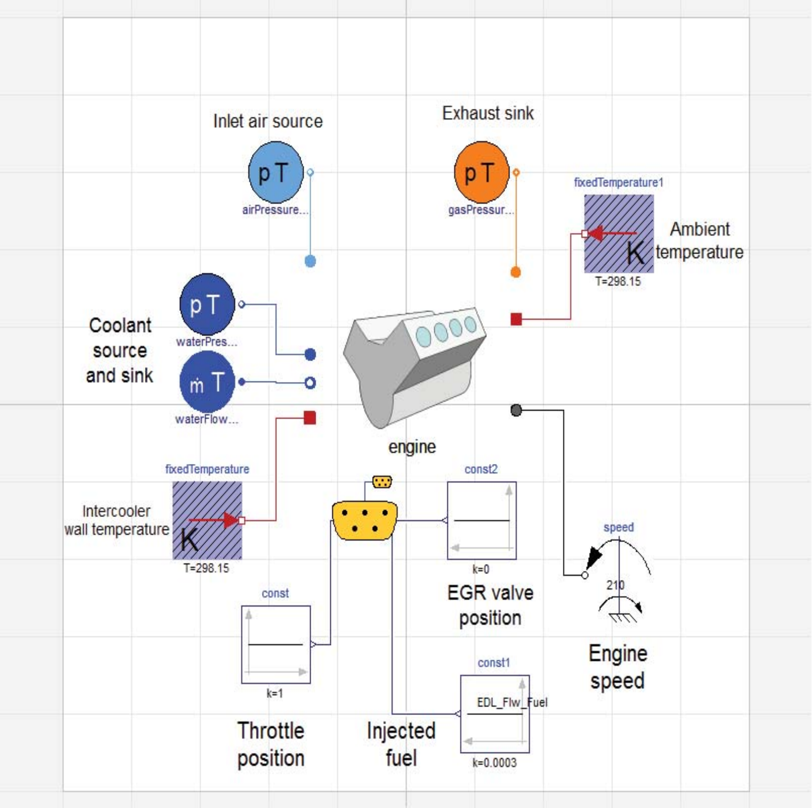


Fig. 4. The diesel engine in Engine Dynamics Library with inputs engine speed, throttle position, injected fuel and EGR valve position. Source: [Modelon AB, 2015]

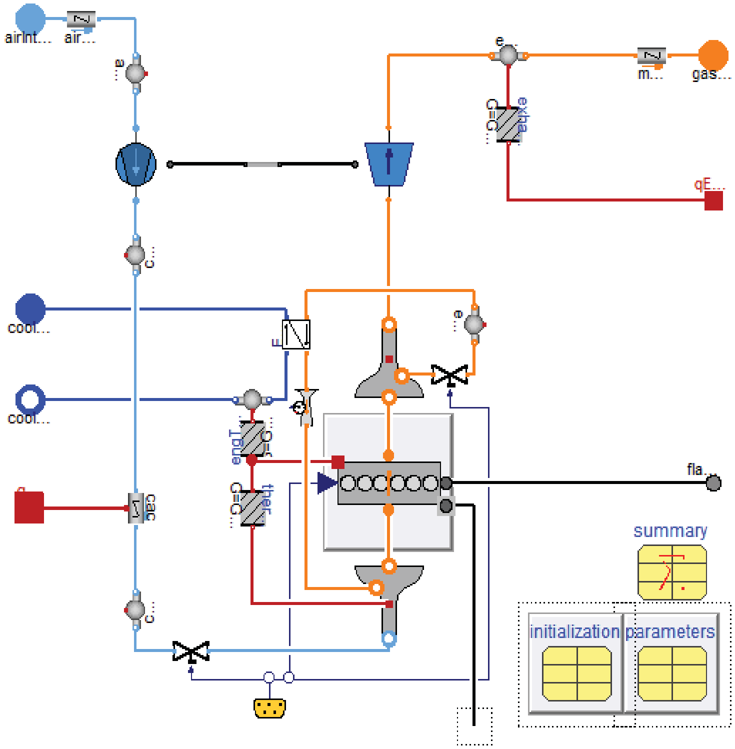


Fig. 5. The “inside” of the diesel engine in Engine Dynamics Library. The light blue line is air from the intake, the red lines are heat-transfer lines, the dark blue line is the cooling recirculation and the orange lines are the exhausts. Source: [Modelon, 2015]

Diesel engine control

Legislators have set high demands on the engines to hold low emission levels and fuel consumption. This fact makes it necessary to equip the diesel engine system with a good controller [Guzzella and Onder, 2010]. When controlling the diesel engine system there are many challenges for the control design. A problem with engines is the variation of the components because of serial manufacturing. This fact limits the amounts of sensors a system can have. It also makes the tolerances of the system wider. There are other difficulties with controlling an engine. For example, there are nonlinearities in the system, which causes difficulties [Henningsson, 2012].

There are no universally applicable methods for control of nonlinear dynamical system. A common means of handling nonlinear systems is to linearize the system. Then you can regard the system as a linear system, which are better understood. Another way of handling the nonlinearities is to use feedback around the nonlinearity of the system [Åström, 2006].

There are other problems that make the engine hard to control when applied to a vehicle. The diesel engine system is hard to control due to the real-time demands that are imposed on the controller. There are also technical problems in CI engines. Xin (2011) list the following problems:

- Heterogeneous mixtures of air-fuel resulting in smoke.
- Lower engine rated speed. SI engines have limits of 6000-7000 rpm, whereas CI engines have a limit of 2000-4000 rpm. This is because of limits in combustion speed.
- Low power density, compared with the SI-engine, due to the limits in the rated power and speed.
- Hard to cold start, when comparing with the SI-engine.

All these disadvantages must be considered in the design and should not be increased due to the design of the control system.

Control system

An important design challenge of the diesel engine system is to reduce emission of pollutants as well as the fuel consumption. Low emissions, which the legislators want to achieve, require high air ratio or EGR. High air ratio and EGR reduces the power density, which increases the fuel consumption. A partial solution to this problem has been to a have high-pressure fuel system, after treatment, electronic control and low sulphur fuel [Xin, 2011].

There are many measurable variables that could be used for feedback when controlling the diesel engine system [Xin, 2011]:

- Velocity and acceleration
- Force and torque
- Energy and energy rate
- Fluid flow (for example pressure, temperature)
- Noise (for example exhaust noise, combustion noise)

Through these measured variables the following performance variables could be derived, namely in our case emission and efficiency. Performance variables are often high-level variables.

The high-level variable emission is not easy to predict in simulation. The foremost problem is determining the mixture of the composition of the air/fuel mixture, the temperature and the pressure inside the combustion chamber. The conditions inside the combustion chamber are not homogenous either. To solve the problem it is common to rely on maps based on experiments. To enable the use of maps, the conditions in the chamber most be slowly varying. Of course this sort of modelling will give a rough approximation [Guzzella and Onder, 2010]. In the diesel engine from the Engine dynamics library the volumetric efficiency is mapped and also the fuel mean effective pressure. Then an equation system is applied to produce the high-level variables.

2.2 Software

This section explains the software and workflow used to:

- Build the model (Dymola, Modelica and the different libraries).
- Perform the information exchange (Functional Mock-up Interface).
- The platform used to design the controller and test the system controller and diesel engine.

Modelica

Modelica is used as physical-modeling tool. It is also known for its applications in reusability of models earlier created. The Modelica language supports an environment, which is both diagram layer and a text layer. These layers are equivalent in what they describe. In the diagram it is easy to draw connections between different components and the text layer is good to state equations in. The main purpose of the language is to describe differential, algebraic and discrete equations and the connections with other components. There are different objects that can be described in Modelica for example function, simulation models, packages or partial models. Some Modelica models can only be simulated if a symbolic index reduction is performed on the system. Therefore the system should be able to transform to state-space form in a locally numerical interpretation [Aronsson, 2014].

Dymola

The modelling environment Dymola provides the user with is a powerful tool of simulation. The features of Dymola are [Dassault, 2015]:

- Acausal connections.
- Multi-engineering (for example mechanical, electrical).
- Reusable library.

Using the multi-engineering something the whole system can be expressed in Dymola from circuit to momentum. After creating a model, that model can be added to a library and reused in other models. For example, a turbine model can be reused in different engine types. Dymola also provides a solver that makes it possible to simulate the models. It is the language, Modelica, which provides Dymola modelling features described above.

Engine dynamics library

Engine Dynamics Library is a commercial library used to model, simulate and analyze combustion engine systems [Modelon, 2015]. The library includes for example EGR-loops, intake/exhaust flow paths, intercoolers, turbochargers. The typical applications for Engine Dynamics Library are according to Modelon control design, analysis of transient engine performance and transient emissions studies. The library has been developed in corporation with the industry.

Functional Mock-up Interface (FMI)

FMI is a standard for importing and exporting simulation models from different platforms. It was first presented in 2010 [Blochwitz, 2014]. The motivation behind FMI is the need to unravel large integrated modelling and simulation problems. The problems can be solved using two different strategies [Fritzson, 2011]:

- Export the model from one platform to another for simulation.
- Cosimulate the model on two different platforms.

The import/export of models is done using a Functional Mock-up Unit (FMU). The FMU contains an XML-file, which exposes all variables and other static information, see figure 6. There is also C-code or binary files that defines the dynamical system [Blochwitz, 2014].

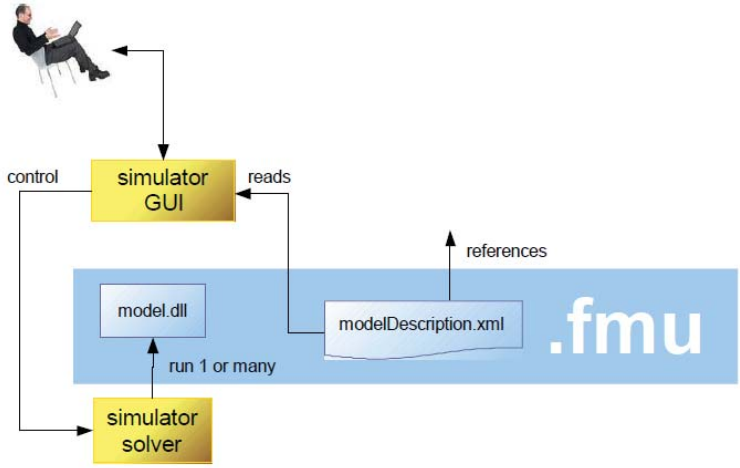


Fig. 6. The FMU contains the information of the system model. The fmu contains a dynamical system (model.dll) and static information (modelDescription.xml). The fmu needs a simulator solver to simulate and the user needs a simulator GUI to set and read values. Source: [Fritzson, 2011]

FMI toolbox

FMI toolbox is a tool to connect FMI supported platforms with MATLAB/Simulink [Modelon, 2015]. These tools including Dymola, AMESim, SimulationX [FMI standard, 2015]. The FMI Toolbox includes among many features export/import of FMUs in Simulink and DoE analysis on the FMU both dynamic and static. There are different toolboxes for different connection programs. Instead of connecting with MATLAB to solve the mathematical problem, Modelon supplies other FMI toolboxes, for example the Excel toolbox [Modelon, 2015].

MATLAB

MATLAB is a commercial numerical tool from MathWorks. It has toolboxes in for example control, optimization and simulation. This thesis uses the Control System Toolbox and Simulink. The control toolbox has functions for reducing the system and building controllers. Some of these functions are used in the thesis, for example, reducing the number of states in the engine system model. Simulink is the graphical environment where the system structure, controller and diesel engine model, is built.

2.3 Model reduction

In dynamical systems theory the model is often described by a differential equation system. In our case it is a finite dimensional linear time invariant (FDLTI) dynamical system. A FDLTI dynamical system is mathematically defined as:

$$\begin{gathered} \dot{x}(t) = Ax(t) + Bu(t), \qquad x(t_0) = x_0 \\ y(t) = Cx(t) + Du(t) \end{gathered} \tag{2.5}$$

Here, $x(t)$ is called the state of the system, the initial condition is defined as $x(t_0)$, $u(t)$ is a control signal or input to the system and $y(t)$ is the system output or measurement of the system. [Zhou, 1999]

During the design process it is often easier if the controlled system is not too large. For example, an Linear-Quadratic Regulator (LQR) uses the same amount of state variables in the controller as the system it tries to control. If the system, which is to be controlled, is too large, an LQR design might not be feasible.

In system theory when trying to reduce the model of a system, the reduction is applied in such a manner that some states are disregarded. There may be a difficulty with reducing the system, as the reduced system should keep the main properties of the main system. For instance one of the kept features is that the system is stable. Another problem is how to determine how much information is no longer described. This can be done by approximating the norm of the system error. [Antoulas, 2005]

To make the reducing of the system easier transformations can be done. A common transformation that is often used is the Hankel Singular Values.

Hankel singular values (HSV)

HSV is a means of writing both the observability (P) and the controllability (Q) Gramian. The Gramians are mathematically defined as:

$$Q = \int_0^{\infty} h_r(t) h_r^*(t) dt, \quad h_r(t) = e^{At} B \tag{2.7}$$

$$P = \int_0^{\infty} h_o(t) h_o^*(t) dt, \quad h_o(t) = C e^{At} \tag{2.8}$$

The system can be decomposed by:

$$QP = T^{-1} \Lambda T, \qquad \Lambda = diag(\lambda_1, \dots, \lambda_n) \tag{2.9}$$

here, the transformation T is the eigenvectors matching to the eigenvalues λ. The eigenvectors T *are* not unique, if the system can be realized in a minimal manner the following computation can be done:

$$\hat{P} = (T^{-1}) P T^{-1} = \Sigma \tag{2.10}$$

$$\hat{Q} = T Q T^* = \Sigma \tag{2.11}$$

here, Σ represent the diag($\sigma_1, \ldots, \sigma_n$), which are the HSV. This is often called the *balanced realization*. [Zhou, 1999]

Balanced realization

The balanced realization is not optimal in regard to norm of the HSV, but it has other good features. It preserves stability and H_∞-norm of the error system has a bound twice above the sum of removed singular values. [Antoulas, 2005]

The questions to be answered are which states are difficult to control and which states are difficult to observe? It is here the HSV is used.

$$\underset{T}{min}\, trace[TQT^* + T^{-*} P T^{-1}] \tag{2.12}$$

Using balanced realization, the error bound of the system can be estimated and the trade-off between accuracy and complexity of the model can be decided. [Zhou, 1999]

2.4 LQG control

The LQG controller is a regulator, which is suitable for Multiple Input Multiple Output (MIMO) control. To handle stationary errors an integrator is added. The extended system is stated as follows [Åström and Wittenmark, 1997]:

$$\begin{pmatrix} x_{k+1} \\ I_{k+1} \end{pmatrix} = \begin{pmatrix} A & 0 \\ -C & I \end{pmatrix} \begin{pmatrix} x_k \\ I_k \end{pmatrix} + \begin{pmatrix} B \\ -D \end{pmatrix} u_k + \begin{pmatrix} 0 \\ I \end{pmatrix} r_k + \begin{pmatrix} N \\ -I \end{pmatrix} w_k \tag{2.13}$$

The controller is calculated using the command `lqi` from MATLAB's Control System Toolbox. An observer was used for estimating the states for state feedback. Where x is the states, I is the integral of the states, r is the references and w is the disturbance.

The input needed by the function `lqi` is the state-space model, in our case the reduced system model which describes the correlation between the inputs, EGR valve position and VGT valve position, and the outputs, p_{inlet} and $flow_{air}$. The following weighting matrices are also required as inputs:

- the cost on state, error integral and output (Q)
- the cost on control signals (R)

Kalman filter

The Kalman filter was used as an observer to reconstruct the states. The observer uses the following state-space model [Kalman, 1960]:

$$\begin{aligned} \dot{x} &= Ax + Bu + Nv_1 \\ y &= Cx + Du + v_2 \end{aligned} \tag{5.1}$$

to minimize,

$$\tilde{x} = x - \hat{x} \tag{5.2}$$

here $\hat{x}$ is,

$$\dot{\hat{x}} = A\hat{x} + Bu + K(y - C\hat{x} - Du) \tag{5.3}$$

And K is defined as

$$K = (PC^T + NR_{12})R_2^{-1} \tag{5.4}$$

The v matrix (2*1) is white noise with the intensity R matrix (2*2). u, x and y are defined as in Chapter 2.4.

White noise was added to the linearized and reduced model before using the MATLAB’s `kalman` command. The intensity matrix R was chosen to identity matrix. The N matrix was chosen to be the same as the B matrix.

3. Model extensions and tuning

The model from the Engine Dynamics Library was extended and adjusted to match the requirements of the thesis. The engine model from Sec. 2.1 and the settings of the engine will be described in this chapter. Insights of limitations within the diesel engine system will be explained in this chapter. The settings of the engine model is presented in table 1.

The characteristics in table 1 require modifications of the engine model from Engine Dynamics Library to be fulfilled. Namely a VGT was added and also an intercooling system. The dynamics of the VGT was approximated from Wahlström et al. (2010) and the intercooling system was derived from Modelon’s Standard Library.

Classification criteria	Variant
Number of strokes	Four-Stroke
Emission standard	On-road
Application	On-road (trucks, buses)
Vehicle weight	Heavy duty
Crankshaft rated speed	High/medium speed $2000>N_e>600$ (rpm)
Fuel injection	Direct injection
Air charging	Turbo charged (after-cooling)
Cooling medium	Water cooled
In-cylinder NO_x emission control	Exhaust Gas Recirculation
N_{ox} aftertreatment	Selective Catalytic Reduction (SCR)
Number of cylinders	Multi-cylinder
Fuel utilized	Light-diesel fueled

Table 1, Engine configuration

3.1 VGT implementation

The VGT was implemented using two functions, one describing the pressure decrease (f_{chok}), see figure 7 and the ratio between the control signal the effective area of the VGT output (f_{vgt}), see figure. 8. The massflow could then be calculated using the following equation

$$massflow = \frac{A_{vgt} p_{out} f_{chok} f_{vgt}}{\sqrt{T_{in} rt}}$$

here, rt is the radius of the turbine blades and the two functions dynamic behaviors can be regarded in figures 7 and 8. The mass flow is controlled using the VGT which is coded in Modelica, see Figure 10. The diesel engine was extended with an extra cooler to increase the mass flow and pipe to make the model less nonlinear, see figures 10-11.

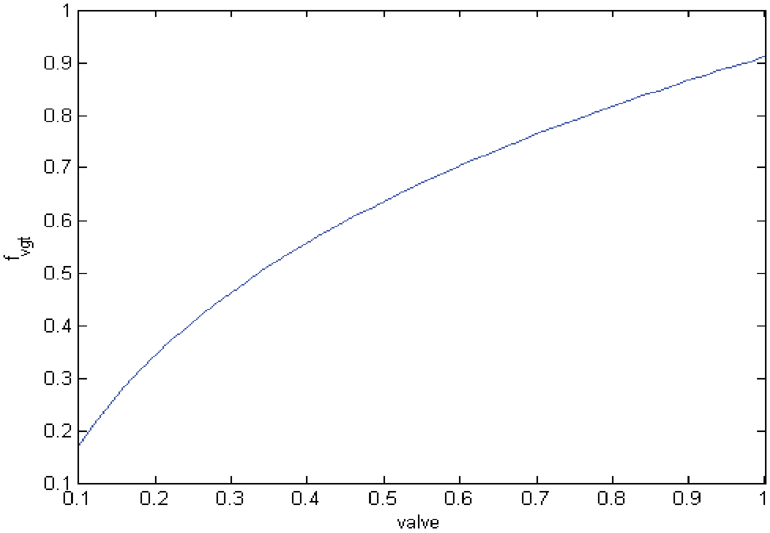


Fig. 7. Plot describing the ratio between the effective area (A_{vgt}) and the valve.

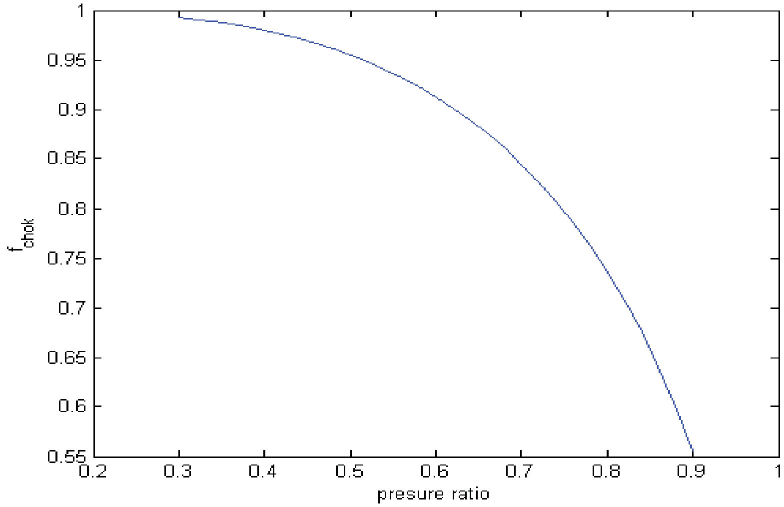
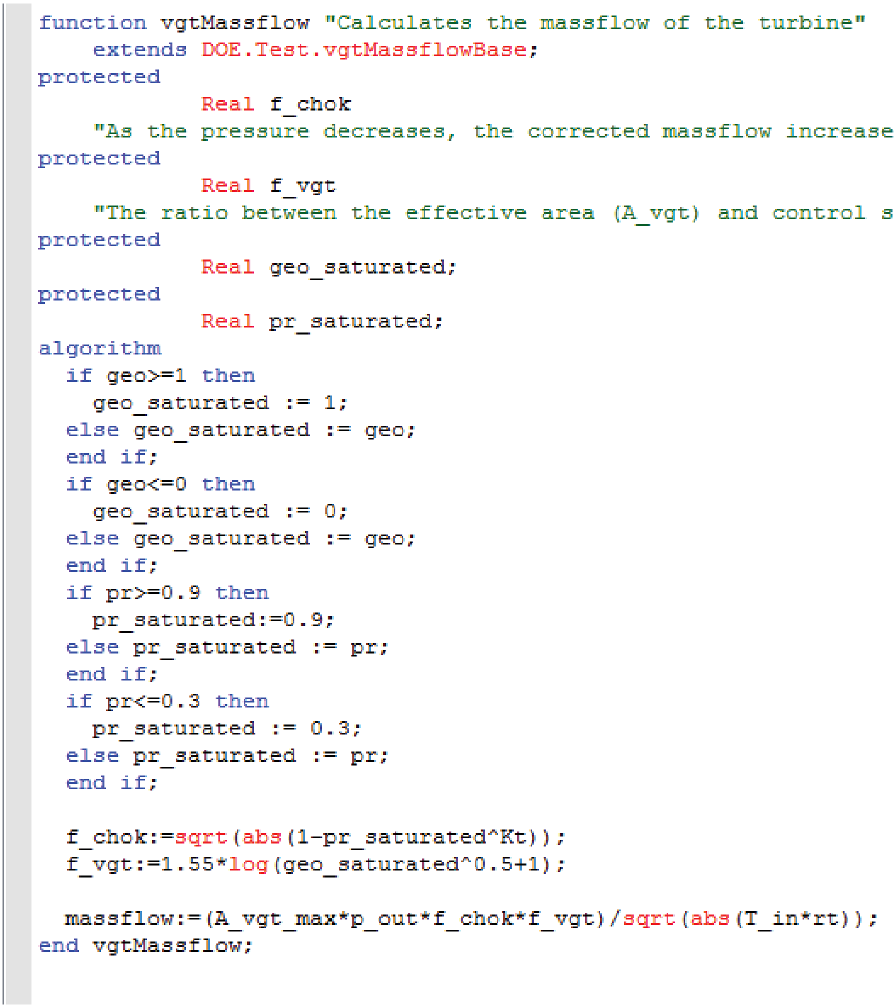


Fig. 8. As the pressure decreases, the corrected mass flow increases until it reaches a sonic level and the flow chokes.



```
function vgtMassflow "Calculates the massflow of the turbine"
    extends DOE.Test.vgtMassflowBase;
protected
            Real f_chok
    "As the pressure decreases, the corrected massflow increase
protected
            Real f_vgt
    "The ratio between the effective area (A_vgt) and control s
protected
            Real geo_saturated;
protected
            Real pr_saturated;
algorithm
  if geo>=1 then
    geo_saturated := 1;
  else geo_saturated := geo;
  end if;
  if geo<=0 then
    geo_saturated := 0;
  else geo_saturated := geo;
  end if;
  if pr>=0.9 then
    pr_saturated:=0.9;
  else pr_saturated := pr;
  end if;
  if pr<=0.3 then
    pr_saturated := 0.3;
  else pr_saturated := pr;
  end if;

  f_chok:=sqrt(abs(1-pr_saturated^Kt));
  f_vgt:=1.55*log(geo_saturated^0.5+1);

  massflow:=(A_vgt_max*p_out*f_chok*f_vgt)/sqrt(abs(T_in*rt));
end vgtMassflow;
```

Fig. 9. Modelica code of the VGT characteristics.The input *Kt* equal to 3.5 represents a parameter in the flow model, *A_vgt_max* is the maximum area of the VGT output, *geo* is the valve control signal of the VGT and *pr* is the pressure ratio.

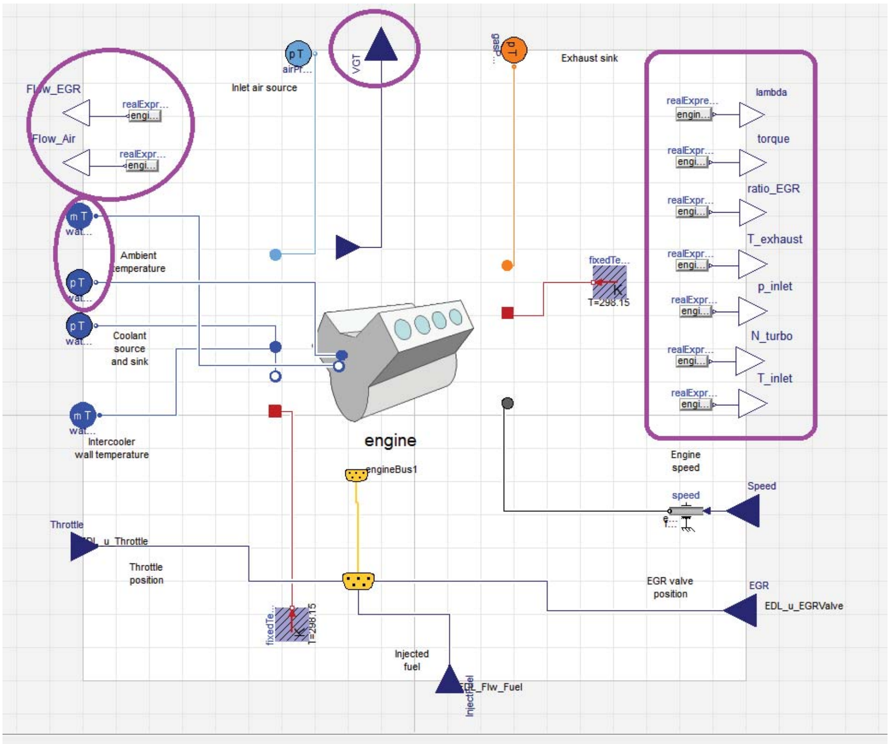


Fig. 10. The modified system with inputs (blue triangles) and outputs (white triangles). The differences with the original system can be seen in an extra control signal named VGT and the extra outputs. Enable use some of the features in FMIT for MATLAB the signals must be set as outputs in the model. Compare with figure 4.

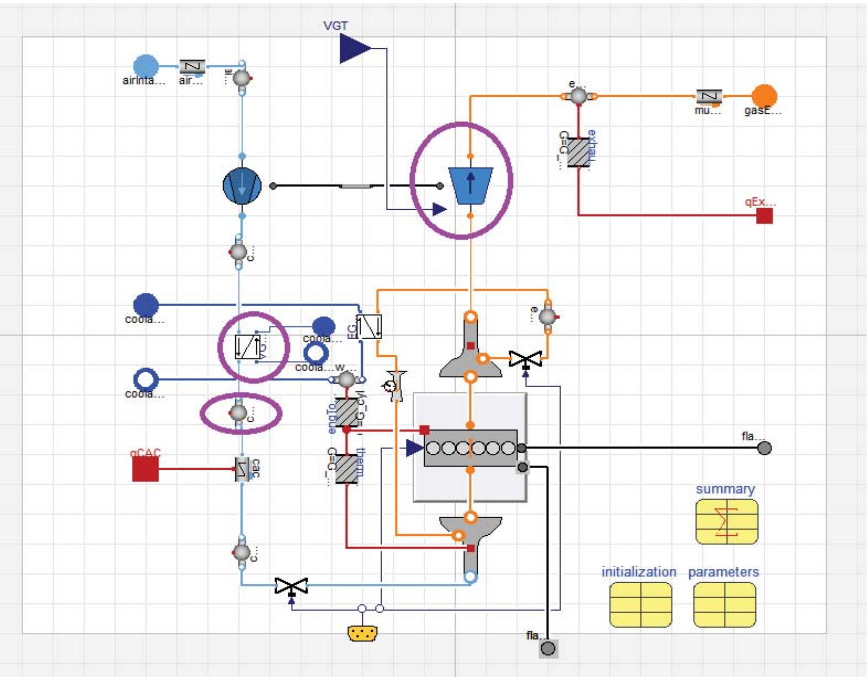


Fig. 11. The "inside" of the modified diesel engine, called Engine in figure. 10. The purple circles contains the extended parts. Compare with figure 5.

3.2 Control objectives

The output from the diesel engine system is chosen to be as similar to reality as possible. p_{inlet} for example is a variable often used in reality when controlling CI engines [Johansson, 2003] and in this thesis used as a feedback variable.

After the tuning was completed, the engine model has 27 state variables and five external inputs:

- Speed of the engine
- The position of the throttle
- The mass-flow rate of the injected fuel
- Exhaust Gas Recirculation valve position
- Variable-Geometry Turbocharger valve position

To control and analyze the diesel engine system, the following outputs were chosen:

- Pressure in the inlet (feedback to the control system)
- Flow air in the inlet (feedback to the control system)
- Speed of the turbo (to evaluate control objectives)
- Exhaust gas temperature (to evaluate control objectives)
- Exhaust geometry recirculation ratio (to evaluate control objectives)
- Torque of the engine (to evaluate the engine functionality)
- Inlet gas temperature (feedback to the control system)

In figure 11 the diesel system model does not have a Selective Catalytic Reduction (SCR) included. Instead the temperature of the exhaust is kept in an interval were it is possible for the SCR system to control the NO_x emissions in a separate loop.

The following control objectives of the diesel engine system were decided upon:

- Lambda should be above 1.3 (hard limit).
- The temperature of the exhaust should be in the interval 300-600°C (soft limit).
- The limit of the turbocharger is 11000 rad/s (hard limit).
- The system should be able to reach 480 kW, which can be translated to a mass flow of the diesel of 30 g/s (this is only tested in the Dymola design; the whole operation area was not used in the control range).
- The system should have a mass flow of 0.3 g/s in idle mode (again this is only tested in the Dymola design and was not used in the control range).

The diesel engine system has limitations. The limits also came from an understanding of the diesel engine system. For example, the EGR valve position cannot be 100% for the combustion process to work, some of the “new air” must go into the diesel engine system [Xin, 2011].

4. System analysis

The diesel engine model made in Dymola had 27 states. It was transferred to MATLAB using the Functional Mock-up Interface Toolbox (FMIT) to enable simulations and control design in MATLAB. The workflow is displayed in figure 12. This chapter concerns the steps “DoE steady-state matrix” and “Analysis of process”.

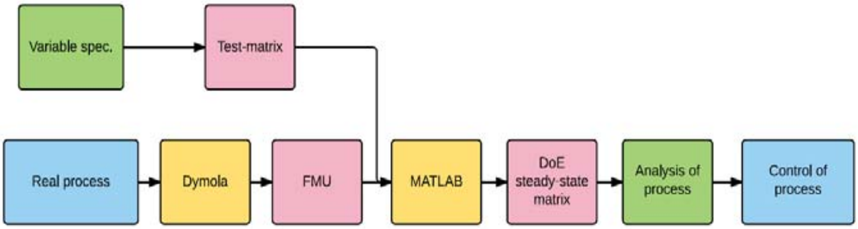


Fig. 12. The workflow of the FMI Toolbox for MATLAB. The FMI Toolbox has tools that linearizes the system and through the DoE-matrix reveals dependences of the system. The pink boxes are artefacts, the yellow boxes are platforms, the green boxes are analysis stages and the blue boxes is not part of the workflow.

Design-of-Experiment (DoE) is a method of collecting data form a model in a systematic way. The DoE process gives a model with varying variables. The settings of the DoE factors were selected according to Chapter 3, and the method `qmc` in the FMI toolbox was applied to construct a matrix with the result of 100 experiments with the ranges of the DoE factors described in the test-matrix. The method uses a Sobol sequence space-filling algorithm to put the experiment configurations in a hypercube defined by the DoE factors. In this chapter, the results of the experiments on the main effects of the diesel engine system will be reviewed, and from this conclusions will be drawn on how to best control the system.

4.1 System dynamics

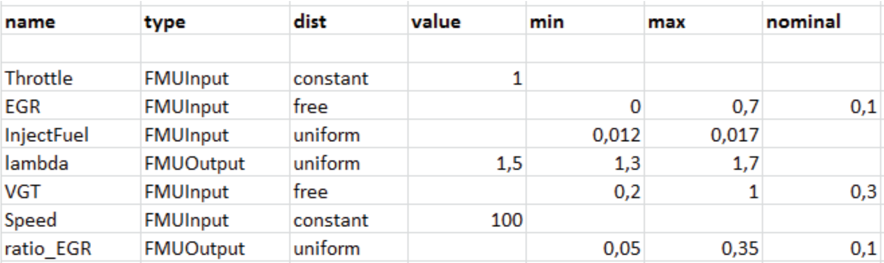
Steady-state analysis

The steady-state analysis was used to select the setting of the points where regulators would be situated. They were also used for defining the upper limit were the regulators 3 and 9 would be, see Chapter 5.

An example of steady-state analysis

A steady-state analysis of the system was performed on the FMU. A test-matrix was designed, see figure 13. Different operation points were found using a steady-state solver and the operation point was linearized. The steady-state solver tries to find a stationary point for each experiment. In this example, 100 experiments were performed and 23 was successful. The linearized diesel engine system was displayed using FMI Toolbox `main_effects` command. The `main_effects` command plots a variable against the DoE varied factors, which are variated in the setup. In figures 15, 16 and 17, the blue dots represent the different operation points.

The ranges of the variables are the FMUOutput that can be achieved of the system, see figure 14. In figures 15-17 it is clear which factors that affect the output in the highest degree. The most important conclusion that could be drawn from the plots is whether a certain setting could produce a certain value of the outputs. When analyzing the lambda plots there seems to be trouble reaching a high lambda with some settings, which seems reasonable. It is reasonable because a $ratio_{EGR}$ of 0.35 and a lambda of 1.7 is not achievable with the motor in this thesis and the settings of the experiment on injected fuel and speed of the engine.



name	type	dist	value	min	max	nominal
Throttle	FMUInput	constant	1			
EGR	FMUInput	free		0	0,7	0,1
InjectFuel	FMUInput	uniform		0,012	0,017	
lambda	FMUOutput	uniform	1,5	1,3	1,7	
VGT	FMUInput	free		0,2	1	0,3
Speed	FMUInput	constant	100			
ratio_EGR	FMUOutput	uniform		0,05	0,35	0,1

Fig. 13. The settings used to create the test-matrix in example.

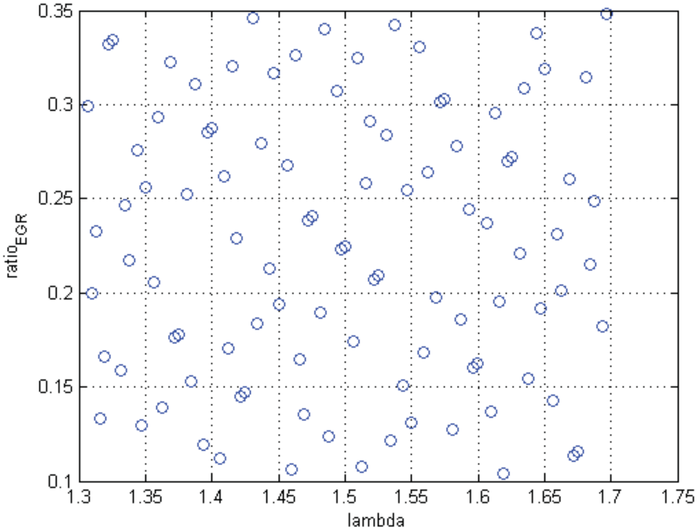


Fig. 14. The ranges of the system variables. The ranges can be explained as the output setup by the test-matrix.

Figure 14 and figure 15, subplot 3, would be the same if all the experiments were successful. But as can be seen in figure 15 subplot 2 the obtained lambda is not the same as the reference lambda. The steady-state solver could not find a stationary point in the range of the FMUinput/FMUoutput; this results in the deviation from the line in figure 15, subplot 2. First-order indices (FOI) represent the ratio of variance in between the variables. The variance is compared with a second-order polynomial approximation fitted to the operation points.

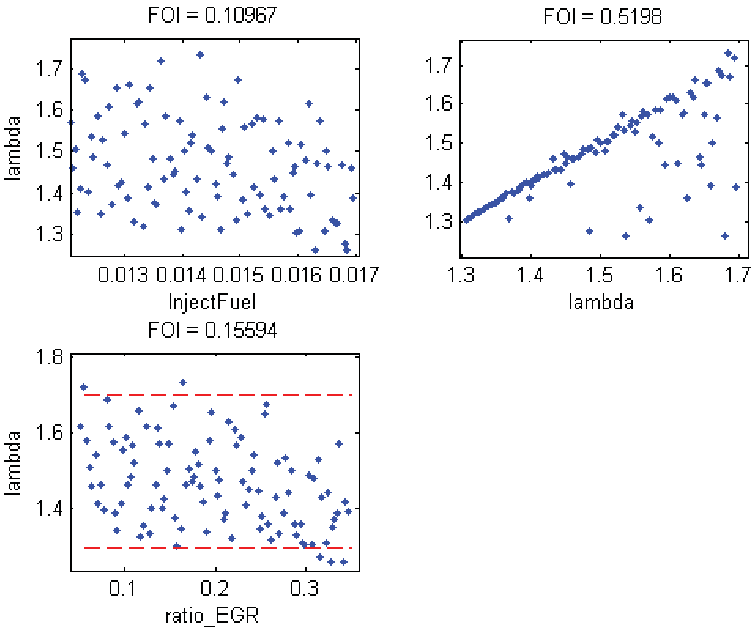


Fig. 15. The main effects on lambda of the factors using EGR value as free to adjust the linearized system.

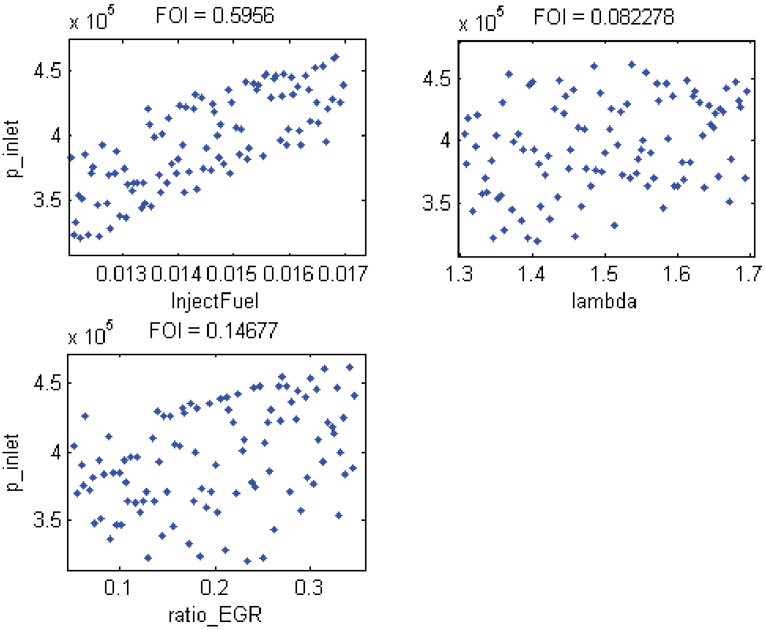


Fig. 16. Steady-state value of inlet pressure plotted against the DoE factors.

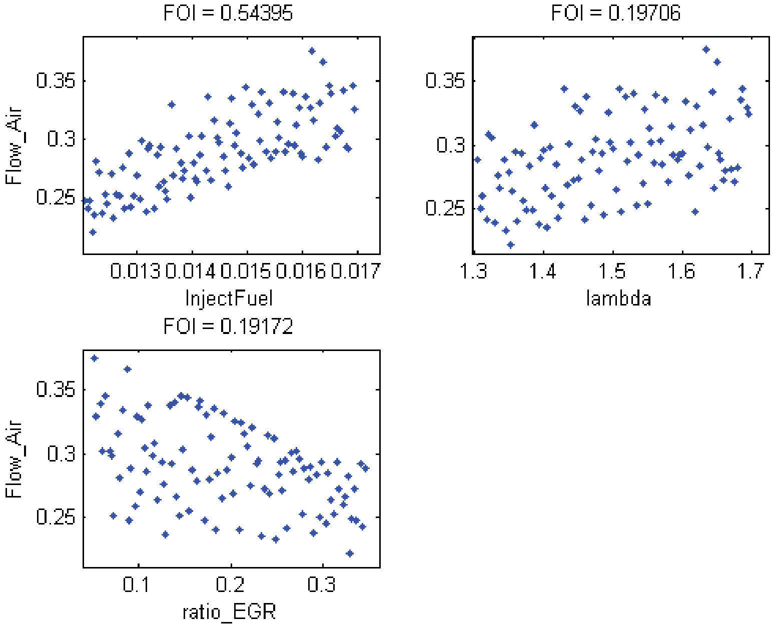


Fig. 17. Steady-state values of the flow air plotted against the DoE factors.

Analysis of dynamics

Using the analysis of dynamics it can be established that the system is nonlinear. It can also be stated that depending on, which input is used on a certain output the result is different.

An example of an analysis of dynamics

The different operation points from the successful experiments were further analyzed. Step responses for the successful experiments are displayed in figures 18-21, the plots are color coded to represent the different operation points. The plots clarify that the diesel engine system has almost no delay. The following conclusions can also be drawn:

- There is different dynamics depending on different outputs, inputs and setups of the points. The VGT signal seems to have a faster dynamic and the EGR signal has a large response.

- The system is nonlinear; this is displayed applying the same input at different operation points and getting different responses.

This was expected, but what was interesting was that:

- The initial response has similarities for the four different system.
- The settling time, the size and the sign of the response are different.

The system is a MIMO system. The step response of the linearized diesel engine system was investigated using FMI Toolbox.

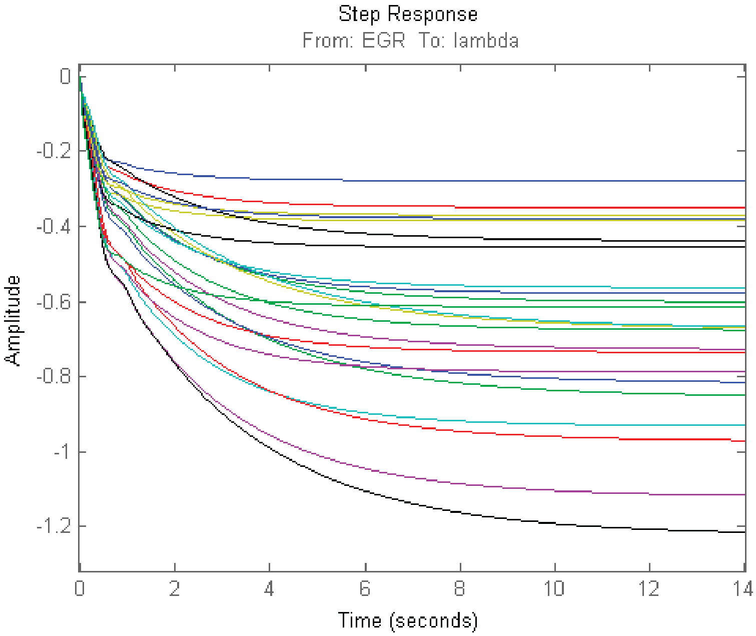


Fig. 18. Step response of the open linearized from EGR valve position to lambda. (Step amplitude 0.1 and offset 0)

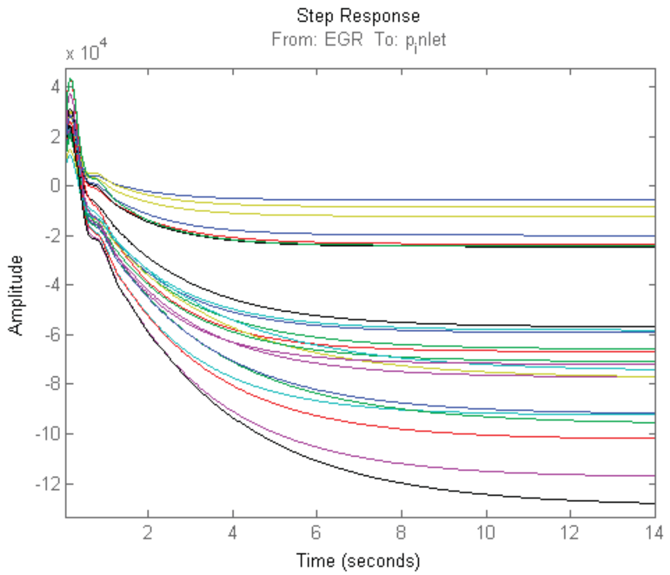


Figure 19, Step response of the open linearized from EGR valve position to p_{inlet}. (Step amplitude 0.1 and offset 0)

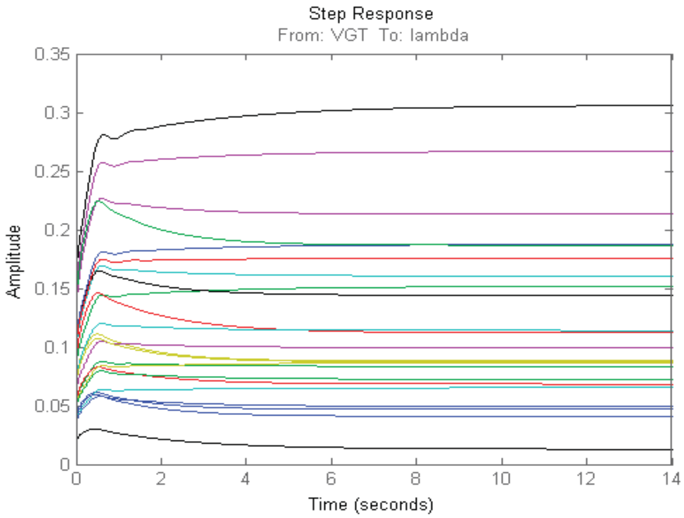


Fig. 20. Step response of the open linearized from VGT valve position to lambda. (Step amplitude 0.1 and offset 0.2)

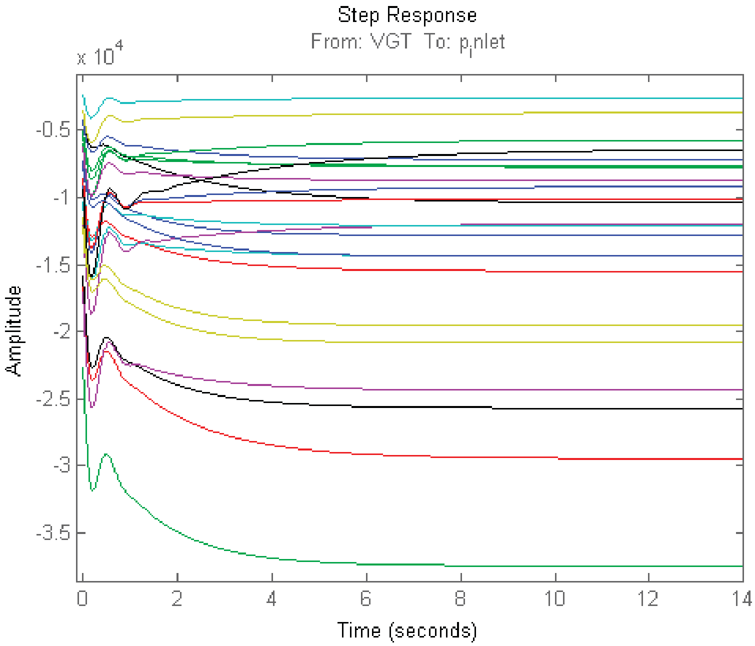


Fig. 21. Step response of the open diesel engine system, linearized with input VGT valve position and output p_{inlet}. (Step amplitude 0.1 and offset 0.2)

4.2 Reducing the system

Using the theory of the Hankel Singular Values explained in Chapter 2.4 and MATLAB's model reduction tools `minreal`, `balred` and `hsvd`, the possibility of reducing the system was investigated. The diesel engine model with two varying inputs, EGR and VGT, was used to control the outputs, lambda and p_{inlet}, was used as an illustrating example. Using the model reduction tools the 25 states with the lowest state energy was disregarding. Figure 22 shows MATLAB's analyzing-tool `hsvd` and its analysis of the system above using the state energy using Hankel Singular Values, which was used as input to `balred` enabling a reducement of the linearized 27-state model.

The reduced model created using the `balred` function is compared to the linearized 27-state model in Figs. 23-24. The plots in Figs. 22-24 are one of the operation points.

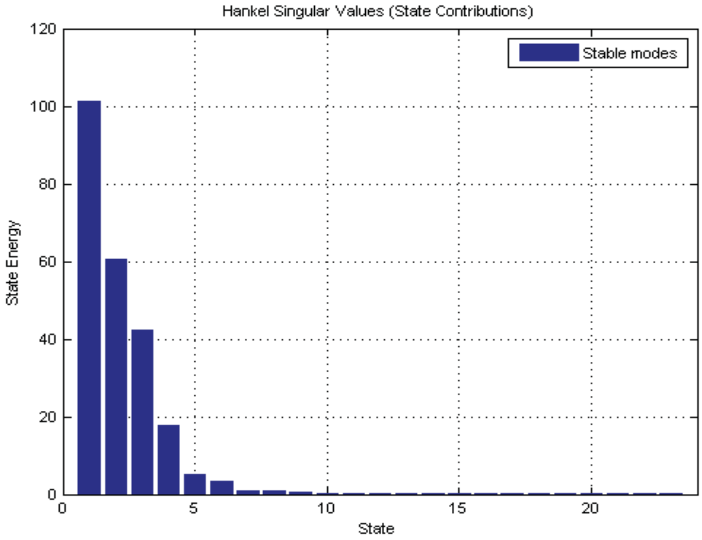


Fig. 22. The Hankel Singular Values energy investigation of the system. The plot describes how much each state energy the states has. The plot is the information of one operation point.

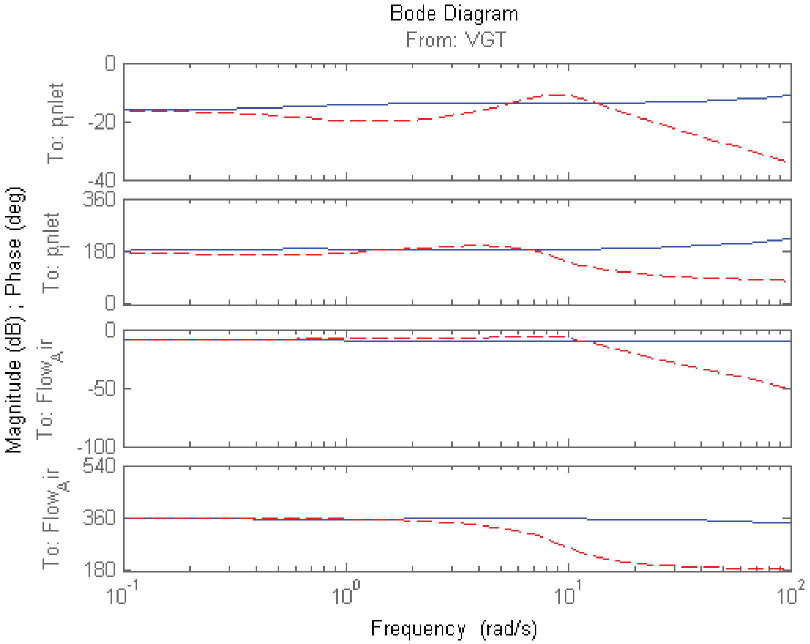


Fig. 23. The Bode diagram from input VGT to outputs lambda and inlet pressure for the original 27-state system (blue line) and the reduced 2-state system (dashed red line). The plot describes one operation point. The phase is equal to x in x + N*360, where N is an integer.

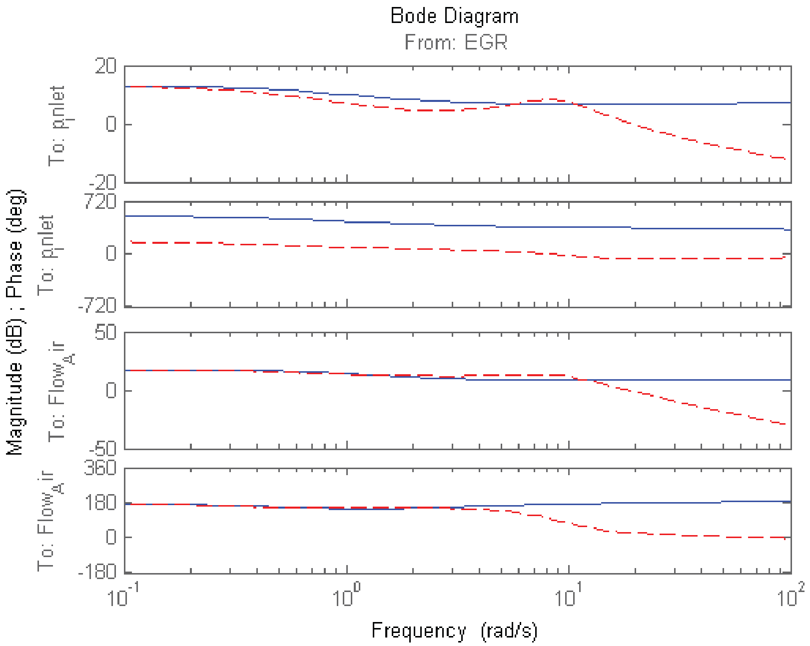


Fig. 24. The Bode diagram from input EGR to outputs lambda and inlet pressure for the original 27-state system (blue line) and the reduced 2-state system (dashed red line). The plot describes one operation point. The phase is equal to x in x + N*360, where N is an integer. In subplot 4 the phase could equivalently start in 0 degrees.

The plots in figures 23-24 show that it is possible to reduce the number of states of the diesel engine system without any major loss of accuracy. To test this hypothesis, first a simulation of the reduced process model was tried. The next step was to build a controller using the information contained in the reduced process model. The noise variable in our case is the linearization of the system and the reduction of the system. This creates an uncertainty, which was regarded as noise. If the nonlinear diesel engine system can be controlled in the neighborhood of the linearized point, it is a good result, and the conclusion can be drawn that the reduced system describes the real system adequately enough. The bandwidth frequency is around 1-5 s, which seems to be reasonable. The controller should handle a reference change within 1-5 s approximately to have the same features as other engines.

5. Control design

In this chapter the overall control design problem and the control algorithm are described. The setup of the evaluation test of the control design and the result of two different tests will be displayed. The hypothesis from the last chapter is confirmed: The reduced diesel engine system describes the engine system good enough to build a good controller.

5.1 Overall control design

The overall control structure for the diesel engine system is made up of a process block, with an option of using the Dymola nonlinear model, the linearized model or the reduced linearized model in the block. There also exists a reference generator block and a controller. The throttle was under the simulations detected to have little influence on the system. The behavior of the throttle examined using steps on the throttle valve. Different operation areas were tested, and the steps had a small influence on the p_{inlet} and $flow_{air}$. It was therefore chosen that the throttle would have a constant value of one which is equivalent with a fully open valve. The input reference to the system set by the user is the speed of the engine, the fuel injection and how much lambda the process would have at each regulator (used in the reference generator block calculating $\mathrm{flow}_{\mathrm{air}}$ and $\mathrm{p}_{\mathrm{inlet}}$), see figure 25.

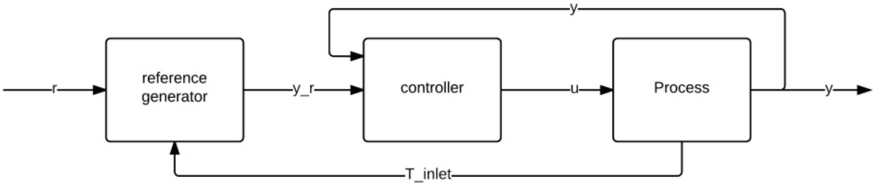


Fig. 25. Describes the input/outputs between the different blocks.

The r vector contains:

- Reference lambda vector for the different regulators
- Reference speed of the engine
- Reference flow of fuel

The y_r vector contains:

- Reference inlet pressure
- Reference flow of air
- Reference speed of the engine (used for weight purposes)
- Reference flow of fuel (used for weight purposes)

The y vector contains:

- Measured inlet pressure
- Measured flow of air

The u vector contains:

- VGT control signal
- EGR control signal

Reference generator block

The reference generator block is used to transform the flow of fuel, lambda, ratio of EGR and speed of the engine shaft into the reference inlet pressure and flow of inlet air. There is a feedback of temperature of the inlet, from the process to the reference generator block. The equations for the transformation performed by the block is found in Sec. 2.1 equation 2.4. There is an option available to use the linearized point’s inlet pressure and flow of air in the inlet as a reference point. There is a linear interpolation done on the variable lambda and ratio of EGR in the same way as the interpolation of the weights on the controller in Sec. 5.3. The reason for this interpolation is difference in the reference values of lambda in the different setups. The regulators’ different operation points are displayed in figure 26.

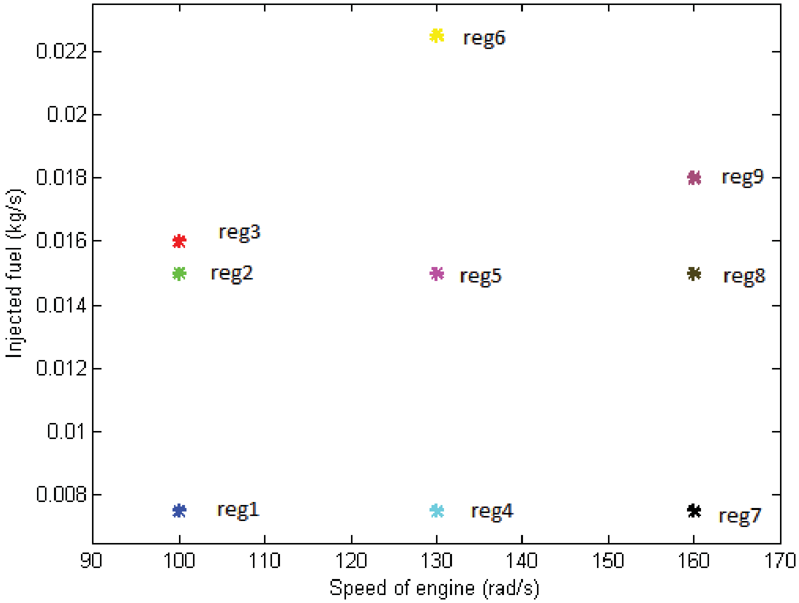


Fig. 26. Figure of the nine linear regulators and their different operation points. The different regulators are color-coded, compare with figure 36.

5.2 Linear-Quadratic-Gaussian controller

The LQG controller was created as Sec. 2.4 describes and the weight matrix was chosen as follows. The other term in Q_y comes from the Ricatti equation. Q_{yi} was chosen to have an equal cost on the p_{inlet} and $flow_{air}$ if the regulator is in an area where it is easy to follow the reference value. In an area where the control signals easily can be saturated the $flow_{air}$ value was considered to the most important signals of the two. The $flow_{air}$ can be directly connected to lambda, which is a measurement value with a hard limit. A value of lambda below 1.3 would result in soot and other emissions. C in the equations below is the C matrix in the reduced linearized system.

$$Q_y = C^T * \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} * C$$

$$Q_{yi} = \begin{pmatrix} 1 & 0 \\ 0 & 10 \end{pmatrix} \vee Q_{yi} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

The reason for using two different matrix on Q_{yi}, is because in some working ranges it was hard to achieve the reference value on both the references. The controller was therefore set to trying to achieve the correct value of flow of air, reg 3 and 9 uses this setting, a diagonal matrix with values 1 and 10. The weight matrix for the cost on the control signals was chosen as an identity matrix. This is because from a control regard the signals are equal in significance for the system. The connections done by the `lqi` command is displayed in figure 27.

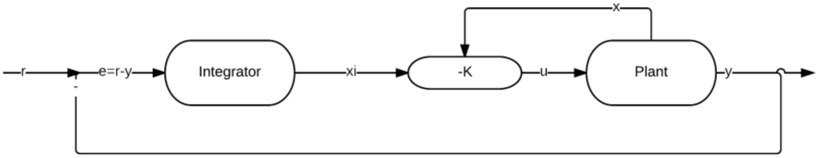


Fig. 27. The connections done by the command lqi. K is the state-feedback control.

The Kalman estimator and the LQ controller with integrator was connected, see figure 28.

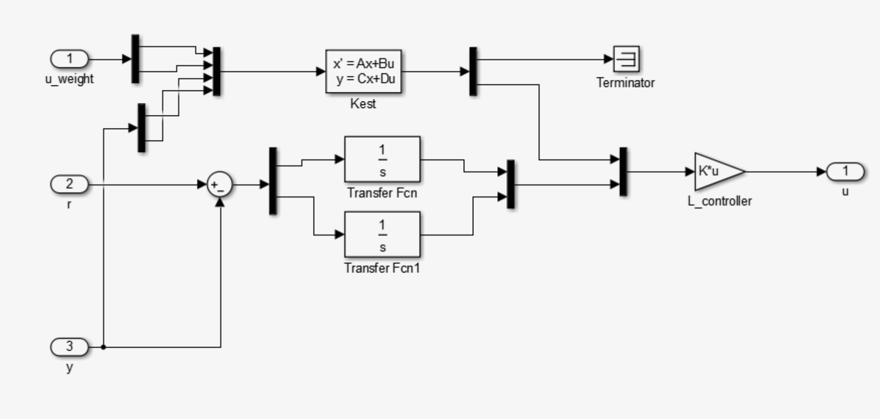


Fig. 28. The connections of the Kalman estimator and the LQ-controller. Kest is the Kalman estimator, L_controller is the state-feedback gain and u_weight is the weighted controller signal calculated in the gain scheduling.

5.3 Gain scheduling

The reason behind choosing the gain scheduling approach was because the diesel engine is a nonlinear system, and the injection of fuel, the ratio EGR and speed of the engine is changed during normal usage of the engine. The gain scheduling approach provides the possibility of having a controller with settings for a specific range. Some settings can of course use the same controller. The differentiating process for the controllers was done based on phase margin of the open system, controller and diesel engine model. During this process some setting of the controller could not reach the reference value of the flow of air and pressure of the inlet, and were therefore disregarded.

In this thesis the number of controllers were nine. The operation area was fuel flow rate 7.5-22.5 g/s, which correspond to 25% - 75% load. The operation speed of the engine was 100-160 rad/s, which corresponds to 955-1530 rpm. The operation area was plotted with the regulators, the settings and their changes, see figure 26. Weight maps were used to decide the controller's operation area. In figure 29 one of the weight maps is used to determine which controller to use each experiment case. The weighted maps were made as a reference for each controller. The nine weighted maps had their highest value in the point of each regulators linearization. The maps were made continuous and linear interpolation was then done between them to get and the weighted sum of the controllers, which was used as reference to the plant model. The reason behind using weighted maps is to get a smooth transition between the different controllers. The area of operation was evenly spread out within the possible range of operation and the distance, speed of the engine and injected fuel, to the closest controllers was used as reference to the weight maps. The implementation in Simulink can be seen in figure 30. The mathematical problem with creating the weight maps were solved using `griddata` and `meshgrid` in MATLAB. `meshgrid` creates a partial input to `griddata`, which uses Delaunay triangulation to solve the interpolation problem.

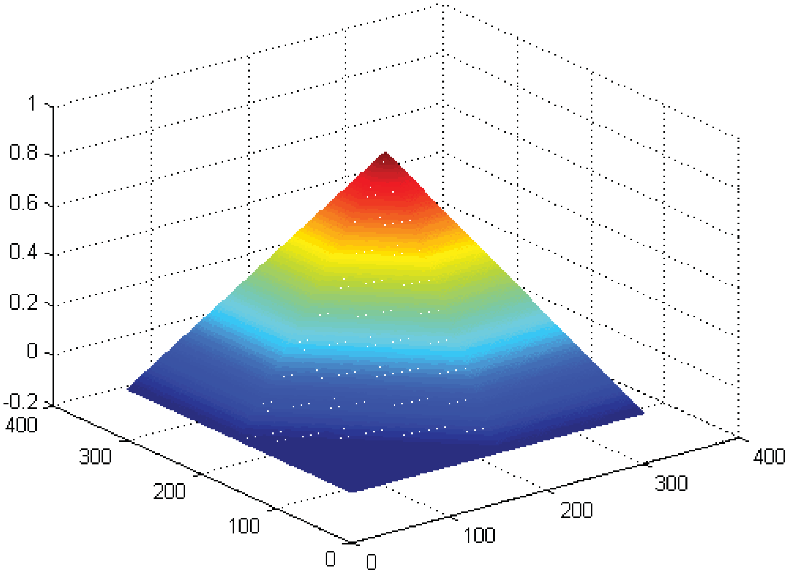


Fig. 29. One of the nine weight matrix used to decide which controllers is used to control the diesel engine system. The weight matrix is mapped against injected fuel and speed of the engine.

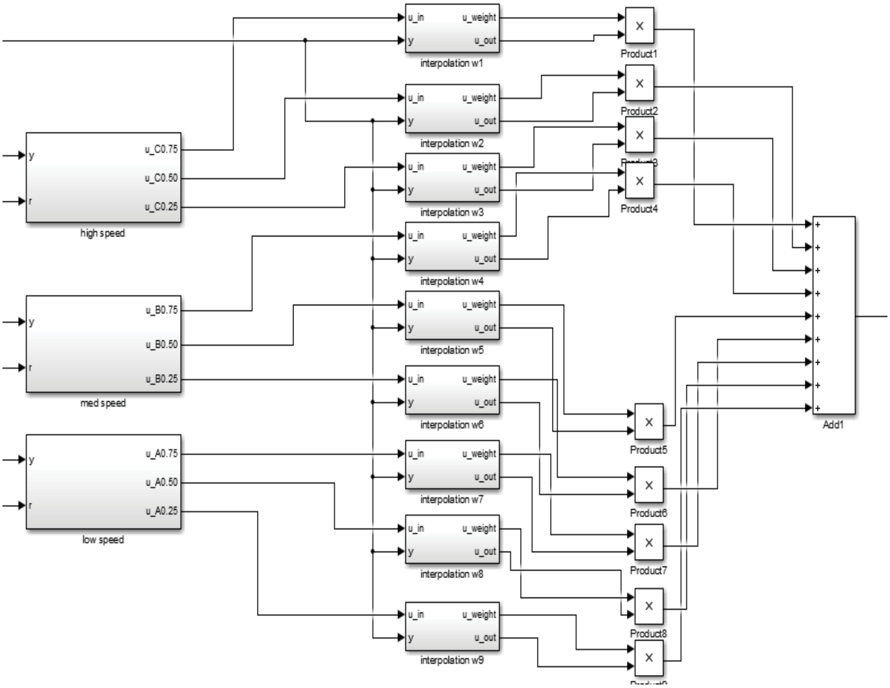


Fig. 30. Figure of the calculations in Simulink in regard to weighted sum of the control signal. The controllers live in the high speed, med speed and low speed block.

To enable the usage of the weight matrix in the Simulink, a 2-D Lookup Table block was used in Simulink. The block was used to interpolate measurement values against the weight matrix to determine what weight of the control signals to use.

As mentioned in Sec. 5.1, the reference generator block used maps of lambda and ratio of EGR and the same weight maps discussed in this chapter. The maps used by the reference generator block are displayed in figures 31-32.

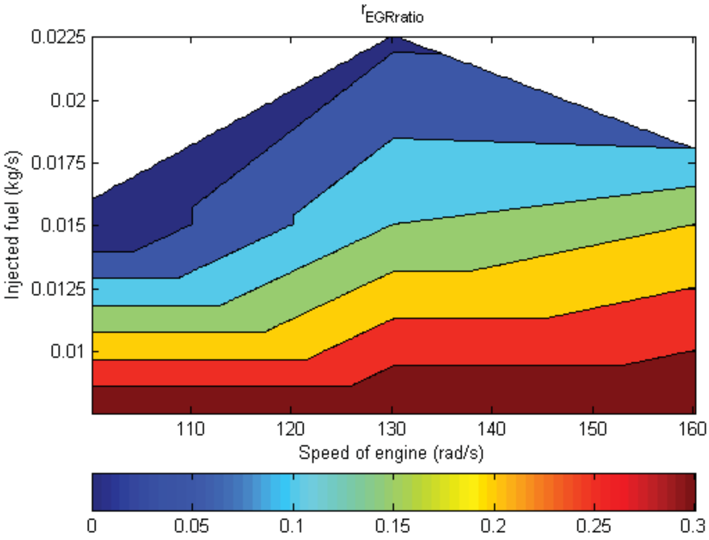


Fig. 31. Map of EGR ratio used by the reference generator block.

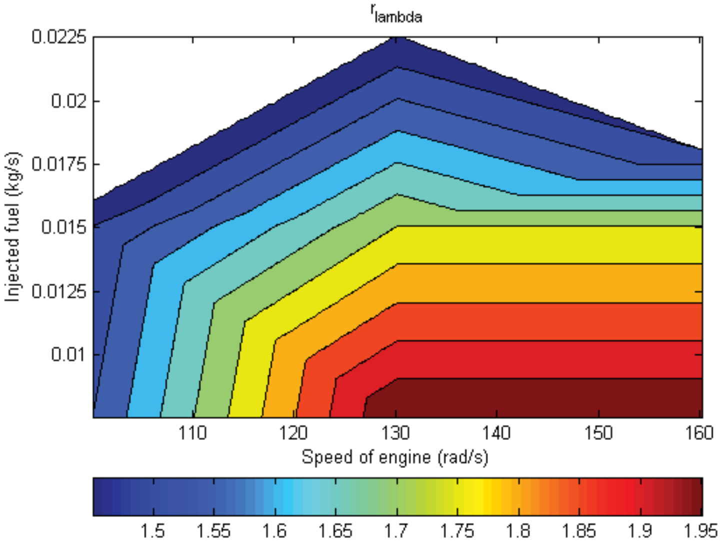


Fig. 32. Map of lambda used by the reference generator block.

5.4 Evaluation of the control design

Setup of the evaluation

The evaluation of the control system of the engine is hard to perform, because the engine is unique and there is no published control system to compare with. If there would have existed a control system, it would have been hard to compare the system. This is due to a tuning problem. Volvo trucks has a department of engineers, who can spend weeks tuning their engine. In this thesis it is not within the scope to compete with their control system. Instead an emphasis was put on achieving a control system that can handle ordinary driving with in a range. The evaluation of the controllers is done using steps on the injected fuel and the speed of the engine. The idea of the test was by using steps on speed and injected fuel move around in the operation range of the diesel engine, for example see Figs. 33 and 37.

Test 1: Load and speed transient example

The focus of analyzing the plots (Figs. 33-36) was to make sure that the objectives in Chapter 3 were met:

- Lambda is higher than 1.3, this was done by using a reference higher than 1.3 as an input to the reference generator
- The measured values of p_{inlet} and $flow_{air}$ follows their reference values.
- Make sure that the speed of the turbocharger is not higher than 11000 rad/s. This was done by using a low value, but higher than 1.3, on lambda to reduce the pressure of the inlet and thereby the speed of the turbocharger

The temperature of the exhaust was also plotted, but after a number of simulations, the conclusion could be draw that it was in its range of operation during all of our simulations. The references of the different subplots are black and the measurement values are blue. The red line is limit of soot for lambda.

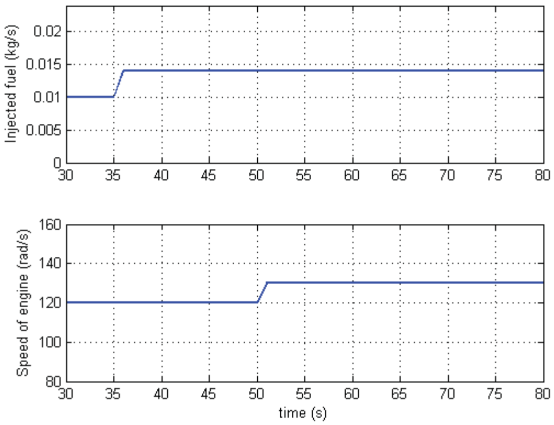


Fig. 33. A simulation of test 1. Plot of the reference injected fuel and speed of the engine. Same simulation as Figs. 33-36. Compare with figure 34, which is a plot of the two reference variables plotted against each other.

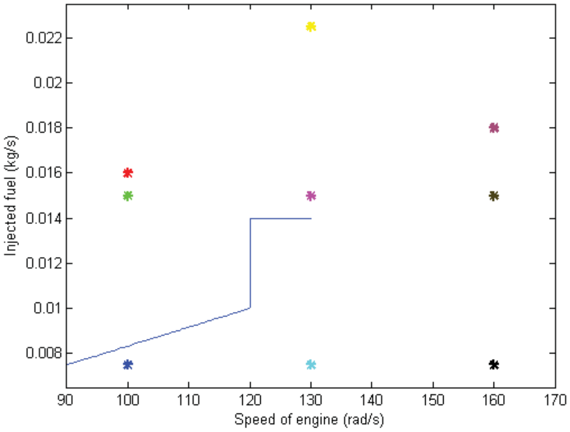


Fig. 34. A simulation of test 1. The figure displays the nine controllers (dots) and the operating load and speed (line) for trajectories in figure 33. The current position of the operating load and speed is the reference used by the gain scheduler to determine the weighted control signal.

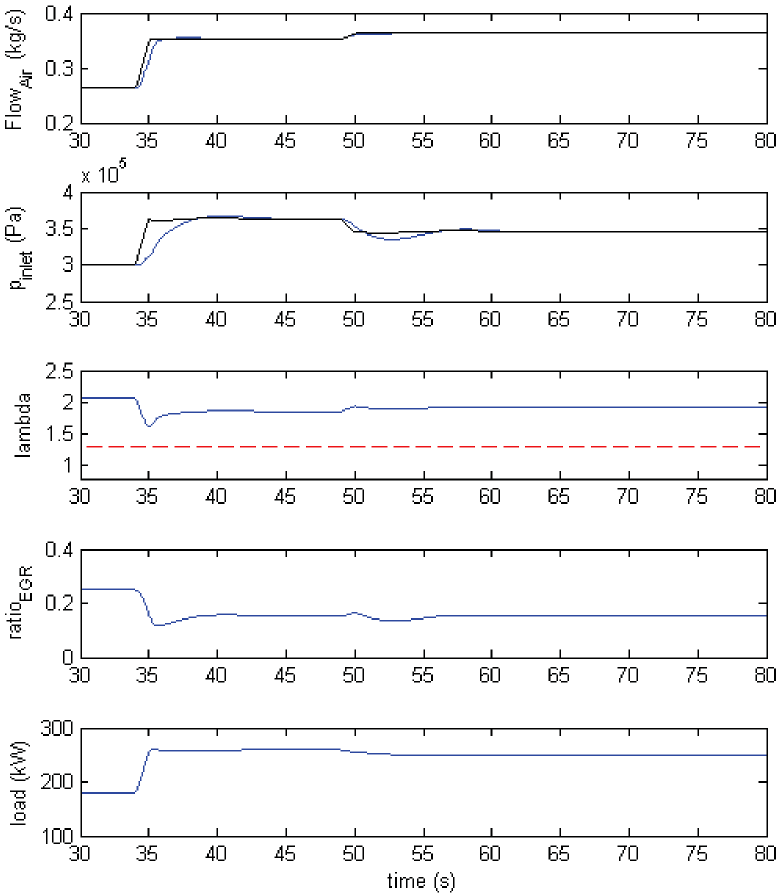


Fig. 35, A simulation of test 1. The system, gain scheduling and the diesel engine, with the signals plotted. The steps in reference are plotted in figure 33. The black lines are the reference of the subplots. The measurement value follows the reference in $flow_{air}$ better than p_{inlet}. This is the effect of prioritizing in the weight matrix. The red striped line is the hard limit of lambda. If this value is exceeded soot in the exhaust may occur.

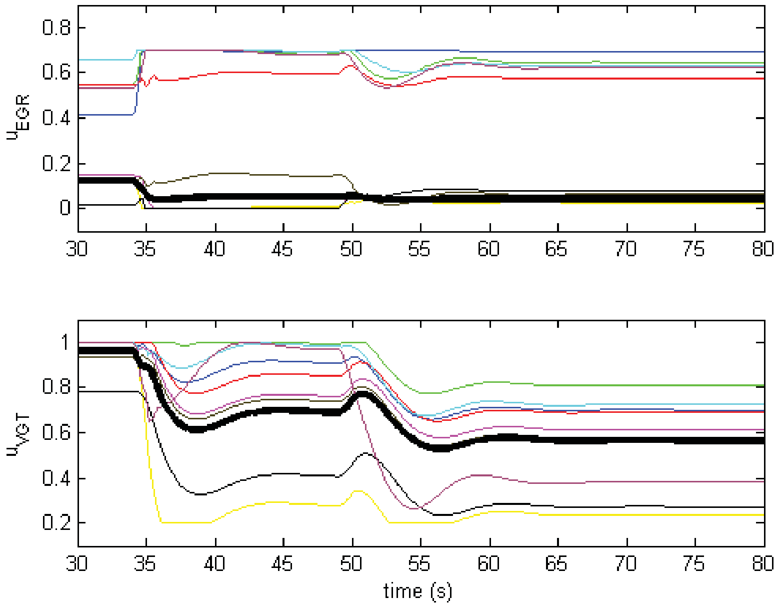


Fig. 36. A simulation of test 1. The control signals of the system. The thick line is the weighted sum for the control signals applied to the process. The thin lines correspond to the linear regulators in figure 34, the signals are color-coded.

Test 2: World harmonized transient cycle

Test 1 is not a usual driving cycle, but a test of how the controller handles steps in the reference signal. The World harmonized transient cycle is a test that has reference changes correlate to a normal driving cycle. It is one of the most common emission test for heavy-duty vehicle. The test is defined by the global technical regulation. The test is the base for EURO VI among many emission standards. The test include many parts including closed rack motoring. The controller used in this thesis cannot handle closed rack motoring (torque equal to zero and speed above zero) position. These operation point were set to the lowest value in speed and injected fuel allowed by the scope of the thesis. Due to the scope of the thesis, the operation range of the test was limited to the area injected fuel 7.5-15.5 g/s and speed of the engine 100-160 rad/s. In figure 37 the plot of the inputs of test are displayed, Figs. 37-42 contain the same simulation. The base data used and the information about the test was retrieved from United Nations (2006).

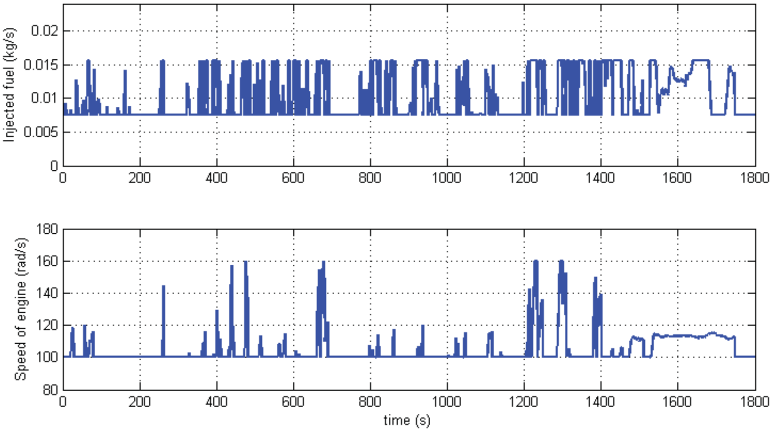


Fig. 37. A simulation of test 2. Plot of the reference injected fuel and speed of the engine. The values were retrieved for United Nations (2006) and limited. Compare with figure 38, which is a plot of the two reference variables plotted against each other.

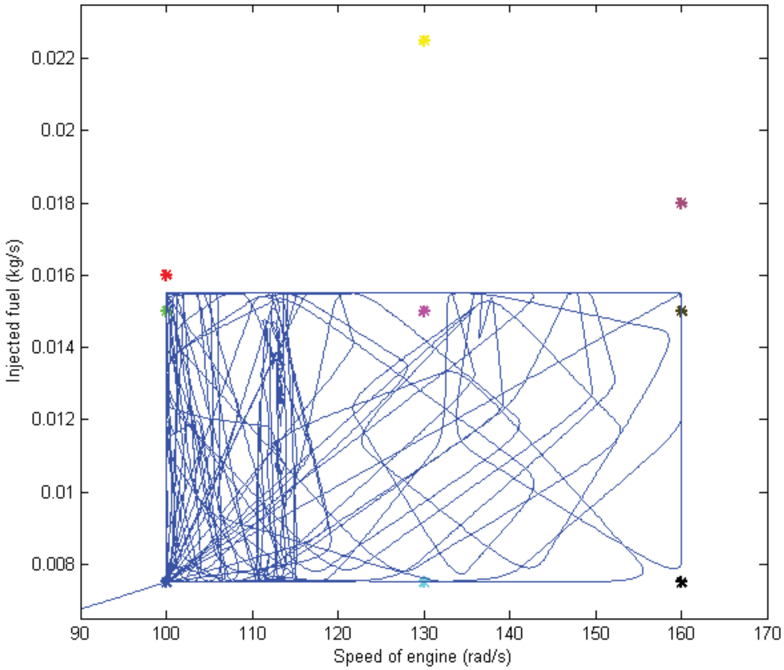


Fig. 38. A simulation of test 2. The figure displays the nine controllers (dots) and the operating load and speed (line). The current position of the operating load and speed is the reference used by the gain scheduler. The blue line is the reference of injected fuel and speed of the engine plotted against each other without the time variable.

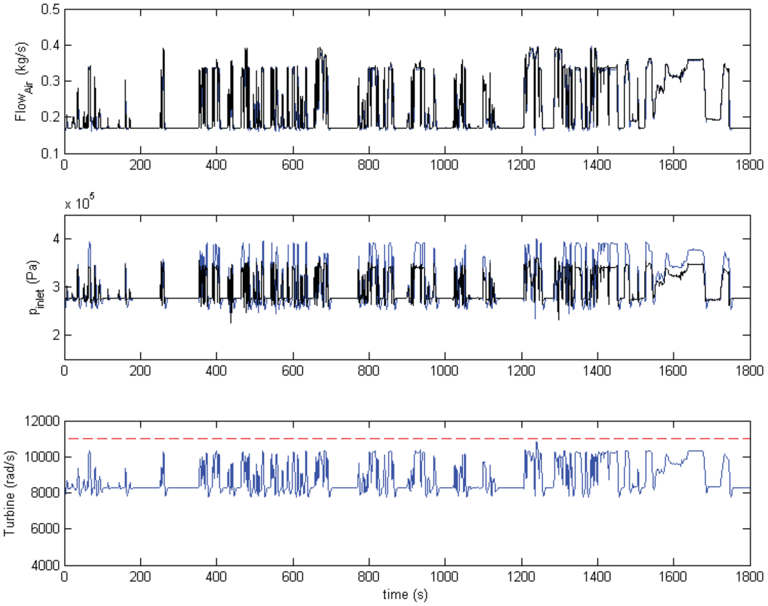


Fig. 39. A simulation of test 2. A test of the system, gain scheduling and the diesel engine, with the signals plotted. The steps in reference are plotted in figure 37. The turbine speed is not exceeded, the reference $flow_{air}$ is followed well and the reference of p_{inlet} is not followed over the whole trajectory. This is related to saturation in the control signals, see figure 41 and 42.

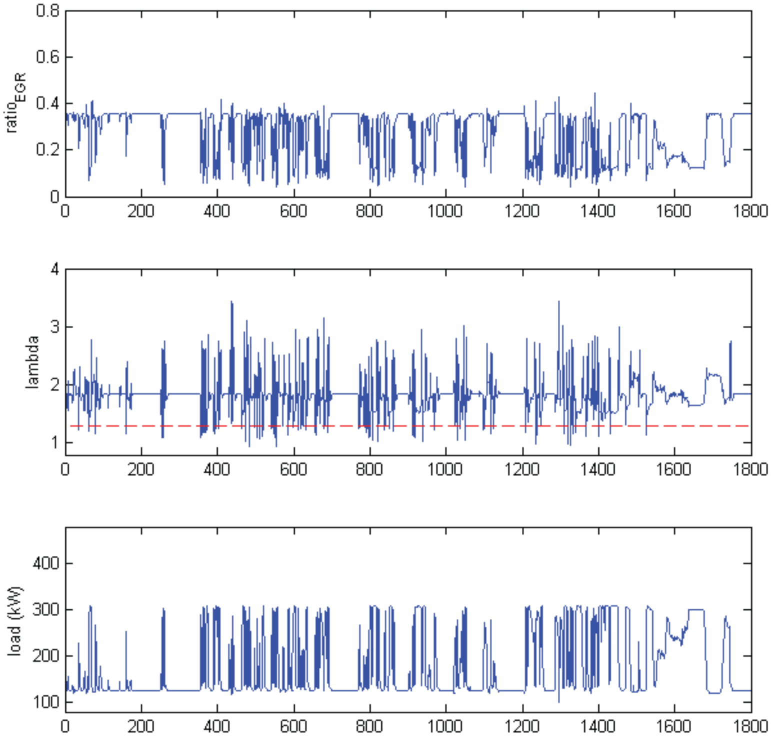


Fig. 40. A simulation of test 2. A test of the system, gain scheduling and the diesel engine, with the signals plotted. The steps in reference are plotted in figure 37. Lambda exceeds the limit (red striped line), which may cause soot. In figure 42 a zoomed part of the test cycle is plotted.

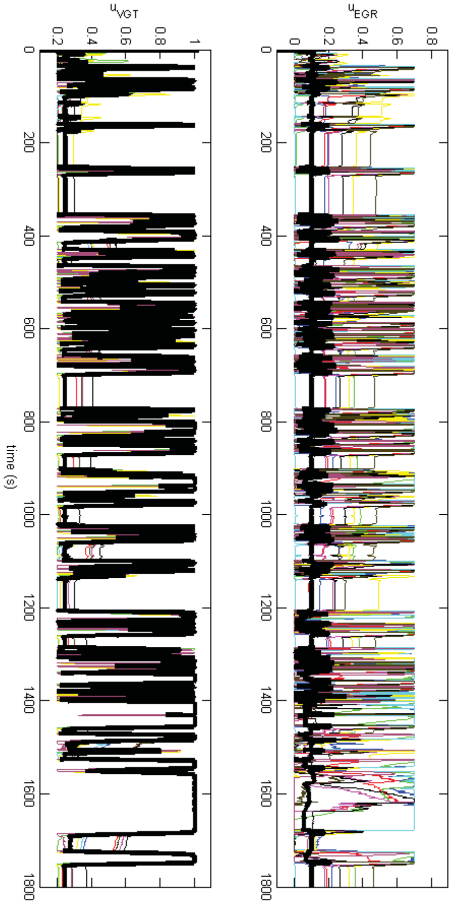


Figure 41, A simulation of test 2. The control signals of the system. The thick line is the sum for the weighted control signals. The thin signals correspond to the regulators in figure 37.

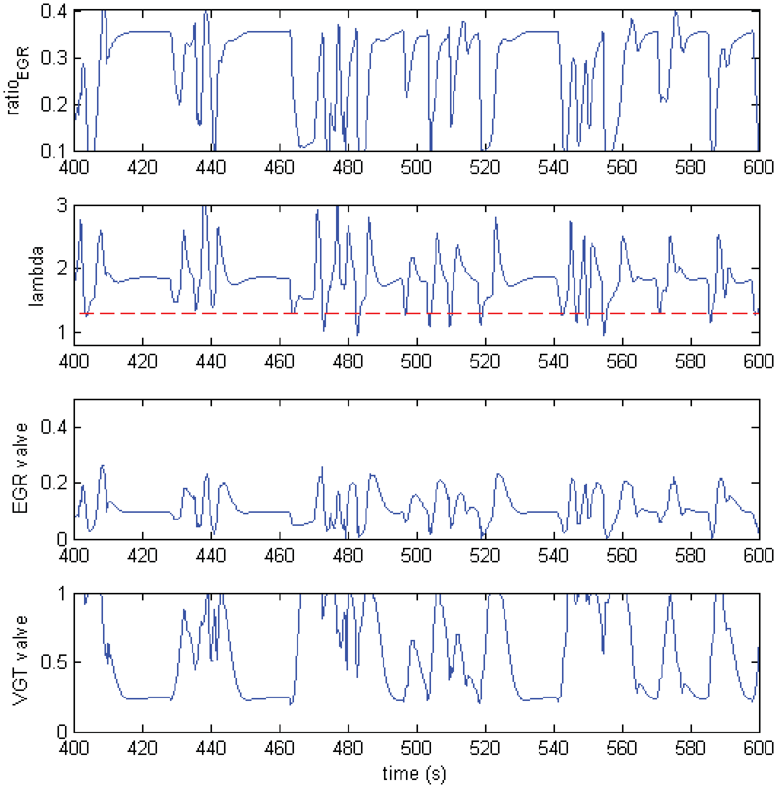


Fig. 42. A simulation of test 2. A zoom plot of simulation in Figs. 37-41. As seen in figure 40 the lambda variable exceeds its limit during the trajectory. This is connected to the saturation of the VGT control signal.

The measured values of p_{inlet} and $flow_{air}$ follow their reference well, the controllers prioritize $flow_{air}$ before p_{inlet}. Some tuning of the weight matrix might improve the result of the p_{inlet}. There are also some transient drops in lambda. This might occur because the controllers has no limit in how long or fast the reference changes of the injected fuel can occur. In a normal engine there are limits how fast changes of the reference can be made. If the changes are too fast for the controller to handle a low pass filter on the set point values with a time delay of maximum around 0.5 s. can be implemented. This was done, but the result was not an improvement.

6. Discussion

Control of a diesel engine equipped with Exhaust Gas Recirculation and Variable-Geometry Turbocharger is a knowledge area, where there has produced a lot of research papers for example Wahlström et. al. (2010), Kolmanovsky et al. (2000) and Jung and Glover (2006). This thesis is simulation based, which the others research papers are not. But a lot of the dynamics are the similar due to the modelling of the VGT is in this thesis is based on Wahlström et al. (2010). This is due to the complexity of the multivariable control problem. In this paper a workflow has been tested exploring how dynamic Design-of-Experiment can be used to in a robust approach analyze and reveal the nonlinear dynamics of the engine model.

6.1 Result of the thesis

Of course it is hard to compare the different control approaches, due to time-limits in tuning. What this thesis has revealed is the workflow treated in this paper makes it possible to control the diesel engine in a satisfying manner. It is a systematic workflow that can be applied on other processes.

It would had been interesting to test the model against an engine to be able to see how large of an approximation the engine model is. Testing the controller in hardware would of course also be interesting.

The aspect of reducing the states of the engine model seem to provide the controller with a good enough engine model, even though the engine model is complex process. The idea of locally linearizing the engine model and using gain scheduling to group together points of operations seem to be adequate for controlling the engine in a large operation area. When connecting the controllers into a gain scheduling there were difficulties with keeping a lambda above 1.3 and not exceeding the limit of the turbocharger, when running the modified World harmonized transient cycle. Maybe this problem could have been avoided using a bigger turbocharger, but the fast dynamics could have prevented that from being efficient. A better solution would have been to two turbocharger, which is often used by the industry. Using two turbochargers makes it possible for the turbochargers to be loaded with air, to have a fast response and endurance in the system. It might also be possible to not set a lambda value corresponding to each regulator as well if the range of the turbocharger was extended with the stated solution. Another reason for the World harmonized transient cycle having trouble keeping lambda above 1.3 during some parts of the World harmonized transient cycle might be that the tuning of the weight matrices is not good enough.

In a workflow interest the procedure used in this thesis does not only makes it possible to reuse models and also used the same models in different subsystems of the project group. For example, the control department and the system design department could be using the same models. This peer-to-peer model level exchange does not only strengthen the communication between different divisions in the company. FMI makes the product development cycle shorter and reduces the room of error.

6.2 The future of system design

The diesel engine system becomes complex and the variables often become more dependent of each other in the ongoing development of the diesel engine. The number of control circuits is one correlating factors with how large the model is. The drive of development of the diesel engine is to meet the demands of reducing fuel consumption and emissions of the combustion process. During the development of the diesel engine, the control problem becomes even larger and more nonlinear. It sets high demands on the control system to have a good structure before using it in real life, due to the many alternatives of control design in the engines control loops. The future of simulation may lie in solving this problem, and being able to disregard bad concepts before any hardware is available.

7. Conclusion

Simulations are often cheaper and faster to perform than building test-prototypes of the system. But there are also cons of simulations, one is the many stages of approximation. The model in Dymola is an approximation of the real diesel engine system. The linearization and the model reduction process are also approximations. It is therefore good to use Design-of-Experiment to be able to take in to account the variability of model design in simulations. Related to this, it is interesting to observe that in this paper a 27-state system was approximated to a 2-state problem and a good control system was still achieved. Considering the uncertainty of the linearized system and the reduction of the system it is a good approximation in a control aspect.

The controller successfully runs over a large part of the World harmonized transient cycle. It shows potential, but of course it would require a lot of tuning and maybe more controllers and sometimes delays of reference changes would improve the result. Another approach would also be to use model predictive control to anticipate the changes in reference. It would be interesting to see how that would affect the control system. During this thesis there were some testing using Hankel Singular Values instead of balance reduction, when reducing the system. The difference between this method and balance reduction was little, but it would be interesting to see if there is a difference when it is implemented in gain scheduling process.

One of the greatest benefits of the FMI standard is the ability for each person/department to work in the platform environment that he/she is used to. To be able to work on the same model in different environments will make it possible to simulate big complex system at a low development cost. The control team may work on a complex control design and an easier mock-up of the rest of the system. While the system design team might work on a complex engine model and an easy PI-control for the control structure. At the meantime the project manager will be able to simulate the whole complex control and engine system to see that all the requirements are met.

7.1 Open questions

Questions still remaining, for example how the limitations of the thesis are solved. Some sub-questions in the limitation area is:

- How to handle the Selective Catalytic Reduction?
- Could this have been better handled in the workflow of this thesis or should it still be a limit?
- If the extended diesel engine model is a good enough approximation of the real engine process.
- Can the control structure created in this thesis control the real diesel engine?

In the scope of the thesis it was not included to try the control model on real engine. Of course it would be interesting to do so. To enable this a low-pass filters would have been implemented on the signal coming out of the FMU and going in to the controller. This would be done to simulate the slow dynamics, which exist in the sensors. The robustness in the system could of course been checked using noise on the states and the output. The problem with implementing this would be that the states exist in the FMU (using the same state-space as in the Kalman filter section under Sec. 5.2 describe the A and B matrix exist in the FMU and one would like to add the M matrix). Applying noise on the outputs would not give a unique analysis. The robustness of the outputs is tested with the linearization and reduction of nonlinear system and using the controller in its neighborhood. This workflow applies noise to the controller, which the controller handles well. Hardware iteration might be able to remove the problems with the transients of lambda.

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Title and subtitle
Control design for diesel engines using a Modelica model

Abstract

The Modelica language supports reusable components throughout the design process. Using the Functional Mock-up Interface, system model built by reusable components can be transferred to different platforms. This can be done in a straightforward manner and makes it possible for different engineering divisions to use the same Modelica models.

In this thesis, it is displayed how a Modelica model of a diesel engine can be used for control design. The diesel engine model is a multiple input and multiple output system. It is also nonlinear and has a higher order than most control design algorithms are able to handle in a numerically robust manner.

In this thesis the following approach was used to be able to control the system. Design-of-Experiment is used to analyze the variation of the dynamics of the system in the operating range of the engine. The Functional Mock-up Unit is linearized and the number of states are reduced.

The controller used consists of nine multivariable Linear-Quadratic-Gaussian (LQG) controllers spread out over the operating range of the engine. Using a gain scheduler the different LQG controllers are connected.

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