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Control Design Based on FMI: a Diesel Engine Control Case Study

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Abstract: Successful implementation of model-based design processes is a key factor for remaining competitive in the automotive industry. This implies that synergies must be exploited by reusing plant models for different contexts. To this purpose, the FMI standard has been created to exchange dynamical simulation models between different tools. The FMI standard is highly relevant for automotive control research by providing a standardized way to give control engineers access to plant models from a large range of tools.
This paper presents a use case for an FMI-based workflow for engine control design: an off-the-shelf diesel engine plant model from Dymola is used for designing a nonlinear airpath controller in MATLAB/Simulink.

Keywords: Design-of-Experiments, Controllers, Modelica, FMI, Engine Control

1. INTRODUCTION

Model-based engineering practices are becoming increasingly important for product development companies. Simulation models and technology are key enablers in this context; a faster development cycle requires that most analysis, development, verification, and validation be done before physical prototypes are available. To get maximum return on investment in a simulation model portfolio, a coordinated strategy is required for how to reuse the models throughout the development process.

Consequently, it becomes more common for plant models created by domain experts to be reused for various different purposes such as component sizing, subsystem integration, control design, and software verification. A standard format for exchange of dynamical systems models is then required, and to this purpose the FMI standard (FMI standard (2015)) was developed and released in 2010. The standard has rapidly been adopted by industry, and is today supported by more than 60 tools for computer-aided engineering.

This trend opens new research directions in automotive control, in terms of how to systematically reuse existing dynamical plant models for control design. Most control design methods are geared towards simple, low-order, and preferably linear models, whereas plant models developed for a wider scope are generally significantly more complex. New methodologies and approaches are needed that scale to higher-order nonlinear models, and that provide systematic ways for control engineers to work with plant models from a wide range of modeling tools.

The FMI standard provides a suitable platform for developing tools and methodologies for such workflows, due to its widespread adoption in a variety of tools and the flexibility in representing dynamical systems. Engineers can get access to state-of-the-art physical models without having to learn each state-of-the-art tool, and can do the model analysis in tools they are familiar with.

In this paper, a case study is shown for how to design a nonlinear airpath controller for a diesel engine in MATLAB based on an off-the-shelf model of a diesel engine from Dymola. The workflow starts with exporting the model as a Functional Mockup Unit (FMU) from Dymola. The model is then imported into MATLAB using the FMI Toolbox for MATLAB/Simulink. In MATLAB, the steady-state behavior of the model is analyzed and the model is linearized at multiple points in the operating range to design a gain-scheduled controller.

Control of the gas path in diesel engines equipped with Exhaust Gas Recirculation and Variable-Geometry Turbine is a challenging multivariable control problem that has been addressed in many research papers; Wahlström and Nielsen (2010); Stefanopoulou and Freudenberg (2000); Jung and Glover (2006); Guzzella and Onder (2010). This makes it a good test case for demonstrating workflows and methodologies for model-based control design.

The workflow starts with identifying a set of characteristic operating points of the engine using a quasi-random experiment design. The conditions of the engine are then calculated for each operating point, and a linearized model is defined. The resulting linearized models are of high-order and not directly applicable to standard control design

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algorithms. A model reduction step is then performed to obtain reduced-order models that are used for LQG control design. A global nonlinear controller is implemented by interpolating the output of the local linear controllers. Simulation results verify that the reduced-order controller gives successful performance when applied to the full-order nonlinear engine model.

2. BACKGROUND

2.1 Modelica

Modelica is an object-oriented language for component-based modeling of physical systems from different domains such as thermal, electrical and mechanical. Modelica is an open, tool-independent standard. In this paper, Dymola is used for creating the engine model. Dymola is a tool for authoring, compiling, and simulating Modelica models.

2.2 FMI

FMI is an open standard for exchanging dynamical simulation models between different tools. The first version of the standard was released in 2010 and it has rapidly been adopted by industry as a standard format for plant models for virtual development and testing processes. *FMU* is a simulation model implementing the standard. It corresponds to a file (with extension .fmu) that specifies the interface (inputs/outputs/parameters) and binaries or source codes that execute the model. *Model Exchange (ME)* is the FMI flavor used in this paper, ME FMUs provides a representation of the dynamical system as a system of ordinary differential equations that the importing tool can solve using a numerical solver.

3. DIESEL ENGINE MODEL

For this case study, a mean-value diesel engine model, Dahl and Andersson (2012), from the Modelon's Engine Dynamics Library is used. The model represents a four-stroke motor with six cylinders, a total displaced volume of 13 dm^3, and a compression ratio of 16. The system setup is displayed in figures 1 and 2.

The engine has a high-pressure Exhaust Gas Recirculation (EGR) loop, a throttle for the intake air flow, a charged air cooler and an EGR cooler. Table-based maps are used for volumetric efficiency, combustion energy conversion efficiency, exhaust gas temperature, and emissions. The main dynamic effects in the engine are caused by pressure dynamics in pipes and volumes, thermal masses of cylinder block and pipe walls, and moment of inertia of cylinder flywheel and turbo.

For this paper, the engine model from the library was extended with a Variable-Geometry Turbine (VGT). The behavior of the VGT has been modeled according to Wahlström and Nielsen (2010).

The engine model setup used in the paper has 27 states and five external inputs:

(1) Mass flow rate of injected fuel.
(2) Position of the throttle.
(3) Engine speed.
(4) Exhaust gas recirculation (EGR) valve position.
(5) Variable-geometry turbine (VGT) vane position.

The throttle under the simulation detected to have a small influence on p_{inlet} and $flow_{air}$, in the operation area. It was therefore set to fully open.

For simulation and analysis of the system, any combination of the more than 600 time-varying variables of the system could be selected as output. In this paper, the focus is on:

(1) Air mass flow.
(2) Inlet manifold pressure.
(3) Exhaust temperature.
(4) Turbocharger rotational speed.
(5) EGR ratio.
(6) Air-fuel ratio.
(7) Engine torque.

The two first outputs are used as feedback signals for the controller in Section 6. The other outputs are chosen because they represent important engine characteristics, and represent different dynamic time-scales.

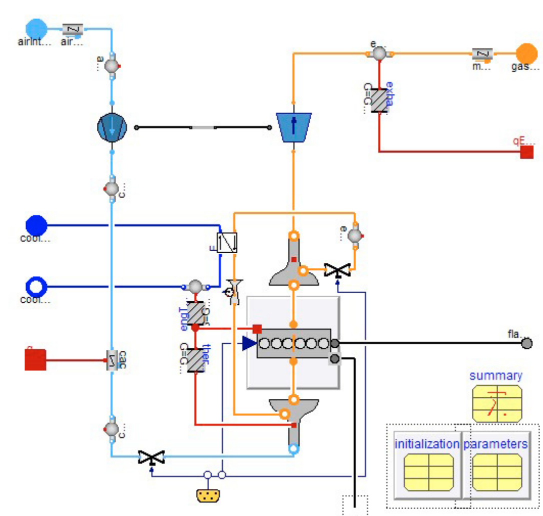

Fig. 1. Modelica diagram of internal structure of engine model from Engine Dynamics Library. The model contians components for engine cylinders, intake- exhaust manifolds, compressor and turbine and control valves. See Fig. 2 for connecting the engien to a test bench.

4. DYNAMIC DOE ANALYSIS OF ENGINE MODEL

In the DoE terminology, a *factor* denotes a quantity that is to be varied in the data set. An *experiment* is the procedure of testing the system with a particular choice of factor settings. A *response* is an outcome that is measured in the experiment. A *test matrix* is a list of factor setting combinations to be tested. In this section an analysis of the system is done both of the dynamics and the constraints of the system.