Final report
CENIIT Project 06.13
Modeling and Control of Turbocharged Combustion Engines

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Executive summary

This project aimed at building up a research group, working with questions in the area of modeling and control of complex engines and turbocharging systems in modern automotive powertrains. The key results:

- 2 book chapters, 15 journal papers, and 26 conference papers have been published within the project.
- 5 PhD theses have been examined: Ylva Nilsson (2007), Markus Klein (2007), Johan Wahlström (2009), Per Öberg (2009), Erik Höckerdal (2011).
- 3 Lic Theses have been examined: Oskar Leufven (2010), Erik Höckerdal (2008), Johan Wahlström (2006).
- About 20 MSc theses have been completed in the area.
- A strong network with industry has been built up. It started with SAAB Automobile, Hoerbiger Control Systems, and Scania. During the project good contacts have been established with the following companies Siemens Gas Turbines, Volvo Powertrain, Volvo CE, Volvo PV, and BAE Systems Hägglunds.
- There project has also strengthened the undergraduate education where one new course "Vehicle Propulsion Systems" has been added and specific research results have been introduced in the course "Vehicular Systems".
- The area continues to evolve and there are now 6 active PhD students.

The funding has covered about 40% of the project leader's salary while the PhD students that have been working in the area have been funded through other grants.

1 Visions and Plans

The vision for the project was to build a strong research group, with engine control system competence, that will be an attractive partner for both industry and academia in future engine research projects. Our overall goals are to deliver relevant research but also research educated persons with central competences within modeling, simulation, and control of combustion engines. The aim in this project is to develop methods and tools that help the automotive industry in achieving emission goals and optimizing fuel consumption through model based methods. Furthermore our long term efforts are to integrate combustion engine control with the complete driveline and vehicle control, and employing methods for optimizing the entire system, making further performance improvements possible.

2 Background and industrial motivation

Combustion engines are complex, highly engineered systems, where established base techniques in the technological sciences are combined with industrial engineering practice to yield a system that fulfills performance requirements. Engine control systems is a central component and strategically important for achieving the desired performance. Legislators and customers are technology drivers through their requirement on reduced emissions and demands for improved fuel economy, driveability and comfort.

The development is in a direction where new components are added, giving the control systems more degrees of freedom for optimizing the performance, which in addition increases the complexity and makes them more difficult to handle. The message from the industry is clear that traditional design methods, based on expensive test cell calibration of look up tables, will not suffice for the new complex systems. New systematic design methods that can handle the system complexity must therefore be developed. A solution is model based methods that have the potential to handle the increased complexity and provide the engineers with the necessary tools. Modeling and analysis of how new control strategies and control variables affect the engine performance both with respect to emissions and efficiency are therefore central areas.

To successfully apply the model based approach both consolidation of available model knowledge and new model development is needed. Only then will we be able to cover a complete system with the necessary models. In addition it is important to also develop systematic methods for acquiring and adjusting the parameters of the models. Another area of high industrial importance is the automatic generation of program code from simulation and validation environments directly to the electronic control units, and we are aiming at developing models that are implemented in such environments e.g. Simulink.

A requirement for the control loops is that there are sensors or virtual sensors (observers) available which can be used to give the necessary information to the control systems. It is also clear that there will be a demand for even more information in the future so that the control system can optimize the trade-off between emissions and fuel consumption. An important problem is that many of the quantities that influence performance are not directly measurable in an real application, one example is the amount of oxygen in the combustion chamber. For control purposes it is desirable to acquire information about such important quantities with as small time delay as possible, which highlights the importance of applying observers. Furthermore, for cost reasons it is obvious that it is preferable to utilize algorithms if possible, instead of having to introduce extra sensors.

A component or module based thinking with systematic tuning of model parameters is also tractable, especially during the design phase when experiments are done by switching components without having to recalibrate all control and diagnosis function for the models in the system. The complexity of the models must be appropriate for implementation in a control system and there is a gap between the mean value engine models that can be used in the control system and the complex 1D-3D FEM models that have best predictive capabilities. There is a need for a link between these model areas. Research in this direction requires a cross-scientific approach combining control theory and engine research.

Reducing fuel consumption is a key issue and this project is focusing on concepts that fall into the category of down-sizing and supercharging. Supercharging have several advantages where some are obvious, but some are sometimes overlooked. For example they are not relying on the development of new catalysts nor new sensor technologies which is necessary for some other proposed new technologies. There is an increased industrial effort put into developing supercharging systems such as for example classical turbo, variable geometry, double turbo, compressors and turbo compound. This is an area where there is a lack of accurate models suitable for control design.

2.1 International and industrial perspective

Sweden is among the world leaders when it comes to turbocharged engines. SAAB were pioneers in turbo on production cars, and continued to lead the development through their investment in gas stand equipment. To further support the importance it is worth to note that all Swedish vehicle manufacturers (Volvo Cars, Volvo Trucks, Volvo CE, Scania) use turbocharged engines in their product lines.

3 Project description

The goal with the project was to build a strong research group centered around control of advanced combustion engines. The project built upon previous results which have solved many problems but have also spawned new ideas that provide a starting point for future projects. Five prioritized areas around engine modeling and control are listed below. The recurring theme in this project is engine system models and the topics range from development of new component models to methodologies for analysis of system properties based on models. In addition to this the project is slightly widening to also cover integrated engine and driveline but the theme of system modeling and integration is maintained.

3.1 In-cylinder modeling

These models describe the important in-cylinder processes that generate work and emissions and can be used for evaluation and design of control schemes. However they are to detailed for being implemented in an engine control system. The emphasis is on finding and compiling simple but sufficient models that assist the control design and can be used in simulation to evaluate how new control schemes affect the performance. It is therefore one of our future core directions. This area builds upon my PhD thesis and is extended by the recent research documented and reported in the papers [1, 2, 7]. One part of the thesis [53] fall into this area where a variable compression ratio engine is modeled, and where a new formulation of multi-zone models is presented in [3]. It is based on the estimation using an in-cylinder model.

A continued development of the already existing multi-zone in-cylinder model [3] is planned where methods for systematizing the parameter identification by combining cylinder pressure measurements and regularization techniques. The first steps have been taken in the study of the special case of compression ratio estimation [11, 26]. Another interesting area is that the models that are received from zero-dimensional modeling are have many parameter and the system identification has to be supported using regularization techniques. In the last part of [52] regularization methods have been proposed and investigated for this application some results also appear in [9].

This modeling approach has now been applied to a variable valve timing engine and is used to study gas exchange effects, [27, 28, 12, 54], and can be seen as a bridge to the next subproject. In addition a computationally efficient model for the cylinder pressure has also been developed and it has been tailored to describe the ion current [16].

3.2 Mean value engine modeling

Mean value engine models cover the cylinder processes on a macroscopic scale and include other gas flow components like: intake, exhaust, throttles, intercooler and turbocharger. Mean value models are used for observer, control and diagnosis design since they describe the engine dynamics with a level of detail suitable for implementation in engine control systems. This is therefore a key area in the project. In particular we are interested in modeling and control of supercharged engines. A first step has been to compile and evaluate models for components in turbo charged engines which was reported in [5, 6].

In the next step a control oriented model for the gas exchange process in an engine with variable cam timing has been developed, these results have been published in [27, 28, 12]. Furthermore we have continued to develop a new model [13, 29, 30] that is purposed for fuel optimal control of the variable compression engine. Gas turbines is also modeled with a diagnosis purpose [43].

An area has been identified, that is still open, and it is control oriented modeling of turbochargers, i.e. compressors and turbines. Our recent modeling achievements indicate that dimensionless numbers, from fluid dynamics, are well suited for building compact models for the compressor. This has been explored further for both compressors and turbines and more advanced supercharging concepts [31, 15, 41, 24, 25]. In addition compressor surge control has been investigated in [36] where a novel concept of time to surge is introduced and used for control. As a side effect the control oriented modeling for automotive turbochargers has been extended to gas turbines and used in diagnosis project with Siemens Gas Turbines results on this is presented in [43, 50].

Joint with SAAB there has been a development of control structures for boost pressure control as well as efficient tuning methods for these. The results have been published in [39].

3.3 Control and optimization of gas flows in turbo engines

Gas flows have a direct impact on the emissions and fuel consumption of an engine and are important to control. Multi-variable control schemes that handles the basic flow requirements have been developed and analyzed for turbocharged engines in [8].

The project continued to develop a controller for simulataneous control of exhaust gas recirculation (EGR) and variable turbine geometry on a diesel engine which minimizes the fuel consumption and the successful results have been reported [32, 57, 35, 37, 38, 18, 44, 20, 22, 23]. In addition to these the project submitted a solution for the Throttle benchmark problem of the ECOSM conference, [40] and this was presented as the best performing controller by the organizers and selected to be extended to a journal paper, [19]

3.4 Observer and sensor system selection

This area concerns systems analysis and method development that will guide future choices of sensors and their placement as well as the development of observers that estimate important control variables that aren't measured. An important aspect is to handle filtering of signals without introducing time lags, otherwise the control system will not be as responsive as necessary for achieving the emission levels during transients.

The aim of this subproject is to clarify the conditions and specifications of different sensor system configurations. The problem of configuring an engine system is so complicated that the industry doesn't know exactly what sensors to choose and their exact placement for best result. The interplay between system performance and sensor performance is thus central. A systematic analysis of this interplay will be based on system modeling of the complete system and a following analysis of sensitivity and optimality based on the system specifications.

Results on modeling and sensor quality have been reported in [33, 34, 14, 17, 42, 42, 21, 10].

3.5 Observers for stiff gas flow systems

Gas flow models are nonlinear and stiff in certain operating regions. An implementation of generic gas flow observers in the control systems is therefore an unsolved problem. Here we have a new idea which is to develop a tailored discretization scheme based on the structure of the gas flow models, which will allow the system of equations to be solved efficiently and enable real time implementations for engine control systems. Work in this area was started and DAE based observer is reported in the last chapter in the PhD thesis from 2011 by Erik Höckerdal.

4 Relation to other CENIIT projects

In general this project shared the methodology interests, concerning the usage and analysis of models for dynamic systems, with the projects that were associated with MOVIII and LINK-SIC. Furthermore there were two direct connections to the previous project 04.14 “Model-based diagnosis of technical systems”, that was managed by Erik Frisk, in that we shared the supervision of 2 PhD students. The first is Erik Höckerdal that is working under the project area “Observer and sensor system selection”. This is a good meeting point where we both share application and methodological interests around how to extract information from complex processes. In this sub-project we had project meetings according to a regular schedule this gives us insight into each others work and competences. The second was Emil Larsson who is working on diagnosis of turbo machinery with Siemens in Finspång. This latter project has a direct relation to the mean value engine modeling subprojects that follow a modeling framework that can be directly utilized in diagnosis.

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