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Development and assessment of model-based and sensor-based algorithms for combustion and emission control in diesel engines

Summary

To the Reviewers Attention:

The tightening of the engine pollutant emission regulations due to the increased environmental concern has made the performances obtainable from steady-state map controls, commonly employed in internal combustion engine management, unsatisfactory. To overcome these performance limitations, control systems have to cope with the engines transient operation conditions, coupling between its subsystem dynamics, and the trade-off between different requirements to efficiently manage the engine.
This thesis work reports innovative control methodologies, structures and controller design for a heavy-duty F1C FPT diesel engine.

The work demonstrates the deployment of nonlinear data-driven models such as neural networks in a model-based control approach. It explores ways to reduce the control system coefficient maps lengthy calibration time and associated high costs. The test engine main air path control inputs are the EGR valve and VGT positions. The fuel injection system is managed by setting injected fuel quantity and start of injection of the main pulse.

The current techniques used to manage control inputs in both air-path and fuel path are open-loop, based on look-up tables obtained during the calibration process. All the calibration efforts aim to optimize the combustion process under different engine operating conditions regarding combustion noise, combustion efficiency, fuel economy, and regulated emissions. However, by applying proper closed-loop control systems, these inputs can be adaptively controlled and automatically adjusted to meet the requirements placed on engine performance more accurately and robustly.

Due to the intrinsic nonlinearity of the diesel engine, real-time control of exhaust gas recirculation valve and variable geometry turbocharger is a challenging task. A modern model-based multi-variable control strategy has been demonstrated in the closed-loop control of the air path, while a closed-loop cycle-to-cycle control regulates the fuel path.

Variable correlation analysis showed the link of intake O_2 concentration with NOx pollutant. As a result of this analysis, intake O_2 concentration and IMAP were chosen as the air path control system targeted variables. Actuators step-tests were used to understand the system behavior and the effects of choosing the intake O_2 concentration as a controlled variable instead of the commonly targeted air mass flow rate. Then, air path models were retrieved through system identification technique. These models have been embedded in a nonlinear quadratic regulator system for the high pressure exhaust gas recirculation loop of the turbocharged FPT F1C diesel engine. This model-based control approach exploits the prediction of two dynamic recurrent neural networks to evaluate the actuation for the HP-EGR valve and VGT rack positions. A closed-loop control system was developed for the cycle-to-cycle correction of injected fuel mass and injection timing of the main pulse, exploiting virtual sensor feedback information. The virtual sensor providing the feedback to close the loop is a predictive combustion model calibrated on real test bench measurements. Thanks to the virtual sensor, no direct in-cylinder pressure measurement is required. The developed control system through the two actuators, q_{main} and SOI_{main}, regulates the engine load through the BMEP and

engine-out NOx emissions. The control system comprises two separate loops for each cylinder implementing PI and lag regulators, one to control the engine load and the other the NOx.

A control system coordinator based on neural networks is also introduced to exploit the best performance of the two developed control systems. This allowed a strict control of emitted NOx pollutants to be achieved. Simulation results show that engine deviation with respect to the target BMEP and NOx are maintained below 0.1 bar and $\pm$ 150 ppm. Over a WHTC, the NOx deviations are around 5%. A BMEP error as low as possible means always having the required torque. Thus, torque gaps are greatly reduced. Regarding the NOx, the result of 150 ppm is remarkable, compared with the accuracy of measurement instruments of roughly 100 ppm. The key idea is to generate air path targets coherent with the ones of the combustion control systems. In this way, the air path control system provides the global condition for the correct functioning of the engine. In contrast, the combustion control will react to fast changes in the engine operating state and compensate for the remaining deviations with respect to load and NOx targets.

Conclusions include the feasibility of the model-based approach. Simulations showed encouraging results, motivating the use of this approach. Proposals for further work include the development of innovative models and optimization solvers to be able to exploit these models in real-time. Furthermore, as data collection is the fundamental and costly part of data-driven approaches like neural networks, a procedure to determine a suitable number of experiments is needed.

Outline

Chapter 1 - Introduction lays out the background and motivation of this research, placing it in the current scenario.

Chapter 2 - State of the art reviews the diesel engine models used to control its subsystems. Then it passes through the control systems used for the air path and combustion regulation. Much of the focus of this section is given to model predictive control.

Chapter 3 - Target platform presents the engine together with its GT-Power model used in this work. It describes the model development and performance and the experimental dataset exploited.

Chapter 4 - Air path controller introduces the EGR - VGT control system with the used methodology. Control variable selection, system dynamics, and model description complete the discussion. The last section of this chapter presents the result of its implementation in coupled simulations between Simulink and GT-Power.

Chapter 5 - Combustion controller describes a closed-loop combustion controller to adjust injected fuel mass and injection timing of the main pulse. A key part of this chapter is the description of the semi-physical model used to retrieve the feedback for the control system. The chapter shows at the end the MiL simulation results.

Chapter 6 - Coordinator investigates a neural network based coordinator for the two developed control systems. It unfolds the structure of the networks with their training and validation performance. Then it discusses the results of the MiL tests for the coordinated control systems.

Chapter 7 - Conclusion and Outlook extracts the conclusions and briefly discusses future work.

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Declaration

I hereby declare that the contents and organization of this dissertation constitute my own original work and does not compromise in any way the rights of third parties, including those relating to the security of personal data.

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