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"Optimization of SI and CI engine control strategies via integrated simulation of combustion and turbocharging"

ABSTRACT

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Combustion engines have been for a long time the most important prime mover for transportation globally. A combustion engine is simple in its nature; a mix of fuel and air is combusted, and work is produced in the operating cycle. The amount of combusted air and fuel controls the amount of work the engine produces.

The engine work has to overcome friction and pumping losses, and a smaller engine has smaller losses and is therefore more efficient. Increasing engine efficiency in this way is commonly referred to as downsizing. Downsizing has an important disadvantage; a smaller engine cannot take in as much air and fuel as a larger one, and is therefore less powerful, which can lead to less customer acceptance.

By increasing the charge density the smaller engine can be given the power of a larger engine, and regain customer acceptance. A number of charging systems can be used for automotive application, e.g. supercharging, pressure wave charging or turbocharging. Turbocharging has become the most commonly used charging system, since it is a reliable and robust system, that utilizes some of the energy in exhaust gas, otherwise lost to the surroundings.

There are however some drawbacks and limits of a turbocharger. The compressor of a single stage turbo system is sized after the maximum engine power, which is tightly coupled to the maximum mass flow. The mass flow range of a compressor is limited, which imposes limits on the pressure build up for small mass flows and thereby engine torque at low engine speed. Further, a turbo needs to spin with high rotational speed to increase air density, and due to the turbo inertia it takes time to spin up the turbo. This means that the torque response of a turbocharged engine is slower than an equally powerful naturally aspirated engine, which also lead to less customer acceptance

A two stage turbo system combines two different sized turbo units, where the low mass flow range of the smaller unit, means that pressure can be increased for smaller mass flows. Further, due to the smaller inertia of the smaller unit, it can be spun up faster and thereby speed up the torque response of the engine. The smaller unit can then be bypassed for larger mass flows, where instead the larger turbo unit is used to supply the charge density needed.

In the dissertation, the value of engine system modeling has been discussed. It was shown how modeling in-cylinder processes and turbocharger can aid the development of the control strategies saving time and money efforts. All the developed models were experimentally validated and applied for optimization analysis or real-time control.

Particularly the model based optimization of the engine control variables of an automotive turbocharged Diesel engine has been presented. The model structure is based on a hybrid approach, with a predictive multi-zone model for the simulation of in-cylinder processes (i.e. combustion and emissions formation) integrated with a control-oriented turbocharger model to predict intake/exhaust processes. Model accuracy was tested via comparison between measured and simulated in-cylinder pressure and engine exhaust temperature on a wide set of experimental data, measured at the test bench. Validation results exhibit a correlation index R^2 equal to 0.995 and 0.996 for IMEP and exhaust temperature, respectively. The optimization analysis was aimed at minimizing NO emissions in four steady state engine operating conditions, selected among those of interest for the ECE/EUDC test driving cycle. Constraints were introduced to prevent from increase of soot emissions and low exhaust temperature which would have a negative impact on the efficiency of the after-treatment devices. The optimization results evidence a significant reduction of engine NO emissions by means of increased EGR rate and earlier main fuel injection.

A model-based optimization was also applied for a CNG heavy-duty engine, equipped with turbocharger and EGR. The optimization analysis was addressed to design the set-points of engine control variables, following the implementation of an EGR system aimed at reducing the in-cylinder temperature and preventing from the thermal stress of engine components (i.e. head and valves). A

co-simulation analysis was carried out by coupling a 1-D engine commercial code with a classical constrained optimization algorithm. The 1-D model accounts for intake and exhaust gas flow arrangement, comprehensive of EGR system and turbocharger, while an empirical formulation based on the classical Wiebe function was implemented to simulate the combustion process. An intensive identification analysis was performed to correlate Wiebe model parameters to engine operation and guarantee model accuracy and generalization even in case of high EGR rate. 1-D model and identification results were successfully validated against a wide set of experimental data, measured on the test bench. The results of the optimization analysis, aimed at minimizing fuel consumption while preventing from thermal stress, showed an increase of fuel economy up to 4.5% and a reduction of the thermal load below the imposed threshold, against five engine operating conditions selected among the most critical of the reference European Transient Cycle (ETC). Particularly, the effectiveness of the co-simulation analysis is evidenced in pursuing the conflicting goal of optimizing engine control while reducing the recourse to time consuming and expensive experiments at the test bed. This latter point is becoming more and more critical as the number of control variables is increasing with engine complexity.

Both the presented optimization analyses evidenced the key-role of the turbocharger to face with energy and emissions issues. Particularly the impact of the turbocharger management via wastegate or VGT control was evidenced. Indeed, by acting on these components, the amount of exhaust gases evolving in the turbine can be managed thus regulating the supercharging degree and the boost pressure. This allows keeping the throttle valve fully open with significant decrease of pumping losses. The wastegate position is defined by a pneumatic actuator in which the pressure is regulated by a solenoid valve fed by a PWM signal. The drawback of this system is the dependence of the PWN signal, and afterwards of the performance, from the system supply voltage. During the thesis the development of a wastegate actuator model was carried out in order to compensate the actuator PWM signal to improve boost pressure control. The compressible flow equations were found to be sufficient to describe the actuator system mass flow and both discharge coefficient and static actuator chamber pressure were modeled using polynomials in PWM signal. Furthermore a simple friction model was implemented to simulate the actuator system. The boost pressure controller based on the developed compensator has shown to give limited undershoot and overshoot and is further able to reject the disturbance in supply voltage. The compensator was incorporated into a boost pressure controller and the complete control system has shown to reject system voltage variations and perform good boost pressure control in both simulations analyses and experimental tests on the engine test stand. Model simulations evidenced the need to ensure low enough vacuum pressure to enable fully closed and open actuator while a switch type controller was proved to be sufficient for vacuum tank pressure control.