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Model predictive control of an automotive waste heat recovery system

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ABSTRACT

This paper proposes a model predictive control strategy for an Organic Rankine Cycle based waste heat recovery system. The control strategy uses a prediction model based on gain scheduling of local models, which results in a quadratic program to efficiently calculate the optimal control inputs. To ensure an optimal system operation, the reference values are obtained from a steady-state optimization. To capture a model-plant mismatch, the control concept features an EKF-based estimator of the model uncertainties. Simulations on a validated simulation model show that this control strategy can track the optimal reference very well, even for a large model-plant mismatch.

1. Introduction

Research on fuel efficient technologies for internal combustion engines has become very important in the last years to reduce the fuel costs and to meet the strict regulations on CO_2 emissions. Concerning this matter, heavy-duty trucks offer a high fuel saving potential because they have a high fuel consumption combined with a high yearly mileage.

A state-of-the-art heavy-duty diesel engine can reach fuel efficiencies of 45% in best operating points, while approximately one third of the fuel energy is lost through the exhaust gas. Thus, current research focuses on systems that recover waste heat from the exhaust gas, to improve the overall system efficiency, see, e.g., Arnaud, Ludovic, Mouad, Hamid, and Vincent (2014). Among the investigated concepts, waste heat recovery (WHR) systems based on the Organic Rankine Cycle (ORC) are a promising technology for heavy-duty applications, cf. Luong and Tsao (2014), Seitz, Gehring, Bunz, Brunschier, and Sawodny (2016a) and Tona and Peralez (2015). The expected fuel savings range from 5% to 10%, see, e.g., Peralez, Tona, Sciarretta, Dufour, and Nadri (2012).

Fig. 1 depicts an ORC WHR system with one evaporator, where the hot exhaust gas evaporates an organic working fluid at a high pressure level. The vaporized working fluid expands over an expansion machine to a lower pressure level and its internal energy converts into mechanical energy, which can be directly used for traction (Horst, Rottengruber, Seifert, & Ringler, 2013) or stored in an energy storage system (Peralez et al., 2012). The hot working fluid then condenses in the condenser and the residual heat is transferred to the cooling water, see, e.g., Horst et al. (2013) and Peralez et al. (2012).

In the past, research on ORC WHR systems was primarily concerned with the cycle topology (number and arrangement of the evaporators) and the suitability of certain working fluids, see, e.g., Drescher and Brüggemann (2007), Glover, Douglas, Rosa, Zhang, and Glover (2015), Grelet, Reiche, Lemort, Nadri, and Dufour (2016) and Song and Gu (2015). In this context, a former work of the authors focused on calculating optimal steady-state operating points with the corresponding control inputs for given exhaust gas mass flows and inlet temperatures, cf. Koppauer, Kemmetmüller, and Kugi (2017). The dynamic operation of automotive ORC systems brings along additional demands on the control design because the exhaust gas heat flow rates are changing in a highly dynamic way and several state constraints have to be met to ensure a safe system operation, see, e.g., Esposito et al. (2015) and Feru, Willems, de Jager, and Steinbuch (2014). A suitable control strategy must avoid dryout and temperature shocks of the evaporators, cf. Luong and Tsao (2014), as well as the decomposition of the working fluid. Moreover, the control algorithm has to account for the considerable nonlinearities of the ORC system, mainly of the heat exchangers, to yield a high control and system performance. These challenges make the control of the high-pressure part of the ORC WHR system an interesting field of research.

The ORC systems examined in the literature differ in their system topologies (e.g., the number of evaporators Grelet et al., 2016), the type of expansion machine (e.g., turbine Horst et al., 2013, screw Song & Gu, 2015 or scroll expander Seitz, Gehring, Bunz, Brunschier, & Sawodny, 2016b), and the number and the type of the actuators. The common control goal is to control the system states at the evaporator outlet or at the inlet of the expansion machine. In recent years, a number of different control concepts have been presented in the literature. In Seitz et al. (2016a), the authors propose a combination of a model-based nonlinear feedforward controller including a parameter adaption with

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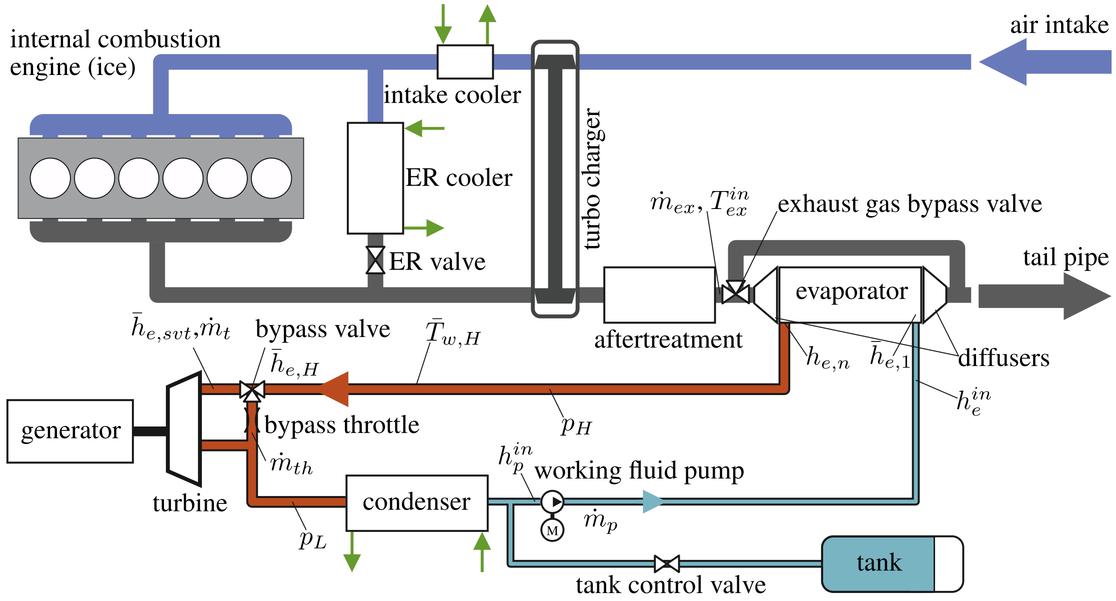

Fig. 1. Sketch of the considered WHR system with one evaporator.

a PID feedback controller. A similar concept is presented in Peralez et al. (2013), but instead of a single PID controller a gain scheduled PID controller is used to account for the system nonlinearities. Moreover, in Seitz, Gehring, Bunz, Brunschier, and Sawodny (2018) a nonlinear feedforward controller is combined with a gain scheduling of LQR controllers and corresponding Luenberger observers. To consider a model-plant mismatch, the heat transfer parameters of the feedforward model are adapted online and the linear models for the Luenberger observers are extended with an unknown output disturbance. The authors of Luong and Tsao (2014) use a Linear Quadratic Integral (LQI) controller to control an ORC system with multiple control inputs. Compared to a pair of single PID controllers, the LQI controller shows a superior control performance.

The control schemes presented so far do not allow to consider state constraints in a systematic way. Several other works, e.g., Feru, Willems et al. (2014), Hernandez et al. (2017) and Petr, Schröder, Köhler, and Gräber (2015), examined the application of model predictive control (MPC) to automotive ORC systems. MPC takes into account the state and the actuator constraints as well as the measured disturbances and can handle multi-input multi-output control problems, cf. Rawlings and Mayne (2009) and Wang (2009). To allow for a real-time implementation on an automotive electronic control unit (ECU), a linear MPC based on three reduced order system models is presented in Feru, Willems et al. (2014), which considers the system nonlinearities by switching the prediction models depending on the actual exhaust gas heat flow rate. This switching may cause bumps of the estimated states and consequently larger control deviations after changing the prediction model. To avoid this, the rate of change of the control inputs has to be restricted for this control concept. Further investigations show that using a nonlinear MPC could improve the control performance (time with superheated vapor at the evaporator outlet) by $\approx 10\%$, but it is not feasible for a real-time implementation, cf. Feru, Willems et al. (2014). Nonlinear MPC using a simplified model is also investigated in simulations in Petr et al. (2015). To account for the system nonlinearities, the authors of Hernandez et al. (2017) propose an adaptive linear MPC for the evaporating temperature, which uses a system model of two first order transfer functions plus time delay with gain and time constants depending on the actual superheating of the working fluid and the exhaust gas mass flow. Both quantities were identified for several operating points and fitted with two-dimensional polynomials. This method considers only one actuating variable and no coupling between the output variables.

Analyzing the results of these articles concerning MPC indicates that the system control performance can be improved by systematically taking into account the system nonlinearities. However, a nonlinear MPC is not real-time capable for an automotive ECU. Thus, this article presents an MPC concept that approximately considers the system nonlinearities, but only requires a similar computational effort as linear MPC. As mentioned in Seitz et al. (2018), an appropriate control strategy for an ORC WHR system must be able to cope with an unavoidable model-plant mismatch. Therefore, a suitable method is investigated to identify the model-plant mismatch and consider it in the MPC model.

In general, an ORC system with two evaporators in parallel offers a high recovering potential, but brings along higher requirements on the control strategies, see, e.g., Grelet et al. (2016) and Koppauer et al. (2017). Hence, as a first step for designing an appropriate MPC strategy for dual evaporator WHR systems, this article focuses on controlling the working fluid state at the turbine inlet of an ORC WHR system with one evaporator, as it is presented in Fig. 1.

This article is organized as follows: First, Section 2 describes the system under investigation and its specific properties. Next, the mathematical system model and its gain scheduling approximation is given in Section 3. Section 4 explains the developed control scheme in detail. Finally, Section 5 discusses the simulation results for the presented control scheme.

2. System description

Fig. 1 shows the considered test-bench setup of the WHR system. An Euro VI six cylinder diesel engine, coupled to an electrical brake, discharges hot exhaust gas with highly varying mass flows and temperatures. The pump delivers the working fluid (ethanol) to a counterflow evaporator, which is placed in the exhaust gas path after the exhaust aftertreatment. There, the exhaust heat is used to heat up and evaporate the working fluid. If the system restrictions do not allow any further heat transfer to the working fluid, the proportional exhaust gas bypass valve can reduce the exhaust gas mass flow through the evaporator. Possible system restrictions are, e.g., the maximum temperature of the working fluid or the maximum pressure due to the system construction.

A radial turbine is utilized to convert the internal energy of the vaporized working fluid into mechanical power. It also drives the generator, which is operated to yield an optimal rotational speed of the turbine, cf. Feru, Willems et al. (2014) and Peralez et al. (2012). To prevent droplet erosion, a minimum vapor quality has to be ensured at