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Nonlinear Model Predictive Control of an Organic Rankine Cycle for Exhaust Waste Heat Recovery in Automotive Engines

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Abstract: Energy recovery from exhaust gas waste heat can be regarded as an effective way to improve the energy efficiency of automotive powertrains, thus reducing CO_2 emissions. The application of Organic Rankine Cycles (ORCs) to waste heat recovery is a solution that couples effectiveness and reasonably low technological risks. On the other hand, ORC plants are rather complex to design, integrate and control, due to the presence of heat exchangers operating with phase changing fluid, and several control devices to regulate the thermodynamic states of the systems. Furthermore, the power output and efficiency of ORC systems are extremely sensitive to the operating conditions, requiring precise control of the evaporator pressure and superheat temperature.

This paper presents an optimization and control design study for an Organic Rankine Cycle plant for automotive engine waste heat recovery. The analysis has been developed using a detailed Moving Boundary Model that predicts mass and energy flows through the heat exchangers, valves, pumps and expander, as well as the system performance. Starting from the model results, a nonlinear model predictive controller is designed to optimize the transient response of the ORC system. Simulation results for an acceleration-deceleration test illustrate the benefits of the proposed control strategy.

Keywords: Modeling, Optimization, Optimal Control, Waste Heat Recovery, Organic Rankine Cycles.

1. INTRODUCTION

As regulations on CO_2 emissions for passenger cars and light duty trucks are becoming increasingly stringent and the fuel prices keep rising, the development of cutting edge technologies for vehicle fuel economy improvement is a major area of interest for automotive manufacturers. Among the technologies currently under development, Organic Rankine Cycle (ORC) plants can be regarded as an effective solution for automotive waste heat recovery (Chiara and Canova, 2013; Wang et al, 2011). Several contributions have been recently made for vehicle applications, with reductions in fuel consumption ranging from 5 to 10% (depending on the system and the driving cycle) up to 15% in highway conditions have been documented, see for instance (Briggs et al, 2010; Edwards et al, 2010; Seher et al, 2012; Lang et al, 2014; Hosain and Bari, 2014).

Nevertheless, very few contributions in the field of control and optimization of ORC systems have been proposed in recent years. For instance, (Peralez et al., 2013) used a Moving Boundary Model to generate a set of feed-forward references for the control and to tune a PID tracking controller. (Feru et al., 2014) used a finite volume model for the ORC plant to linearize the system and synthesize a model predictive controller to track a set point in the expander inlet quality, to ensure safe operating conditions and high power output. It is clear that developing optimization and control algorithms for Organic Rankine Cycles operating in transient conditions poses significant challenges, due to the complexity of the plant dynamics, and the presence of multiple constraints and limitations in the inputs and outputs.

This paper proposes a nonlinear model predictive control approach for the transient optimization of an Organic Rankine Cycle for exhaust gas waste heat recovery in an automotive IC engine. A detailed model was developed for simulation of the ORC plant, and calibrated using components data from various suppliers. The model, which adopts a switching Moving Boundary Method for the characterization of the transient behaviour of the heat exchangers, is able to predict the mass and energy flows in the key system components, leading to the definition of the system operating conditions and overall performance. Then a constrained optimal control problem is formulated to maximize the system performance and ensure operations within the physical limits of the components. Particle Swarm Optimization (PSO) is applied to solve the receding horizon optimization problem in the NMPC framework (Sandou and Olaru 2009, Mercieca and Fabri 2012).

Verification was conducted on a transient test corresponding to an acceleration-deceleration manoeuvre. The solution generated by the MPC algorithm is compared against a feed-forward controller based upon a quasi-static optimization, a typical process adopted for the control of ORC plants.

2. SYSTEM DESCRIPTION

This study focuses on an Organic Rankine Cycle system for exhaust waste heat recovery in a turbocharged spark-ignition (SI) engine for passenger car applications. The system

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operates with R245fa as the working fluid, and its layout is illustrated in Fig. 1. A positive displacement pump controls flow of the refrigerant through a heat exchanger where the fluid receives heat from a flow of exhausts coming from the engine. A bypass valve is used to control the exhaust flow. The refrigerant then flows through an expander, generating mechanical work, and finally through a condenser.

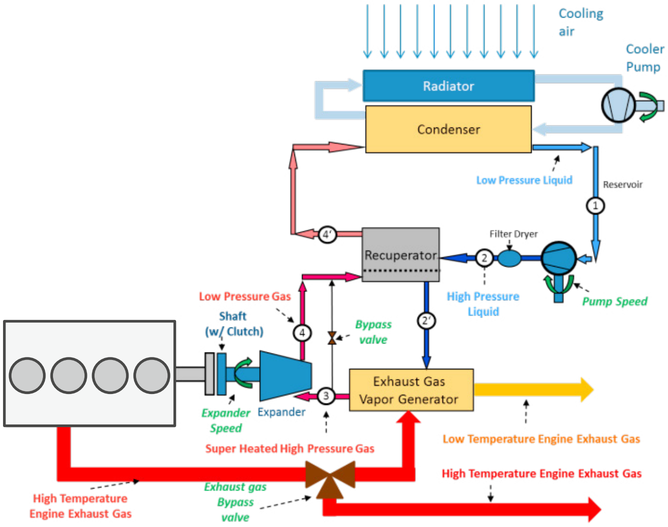

Fig. 1. Schematic of the ORC System Layout.

The ORC system is designed to operate at best efficiency at highway driving conditions, where the evaporator is intended to generate superheated vapour at the outlet. On the other hand, it may occur that during fast transients (e.g. cut-off conditions, low load...), the exhaust gas heat is insufficient to fully vaporize the refrigerant, thereby resulting into two phase vapour at the evaporator outlet. This condition, which may result in inefficient performance or unsafe behaviour of the expander, could be avoided by inserting a liquid phase separator at the evaporator outlet, bypassing the liquid directly to the condenser.

For the application considered in this study, the ORC system is directly coupled to the engine with a 1:1 gear ratio. This solution allows a more efficient use of the expander power output, without the needs of auxiliary components (such as CVTs or variable slip clutches), leading to a cost reduction.

A low-temperature cooling circuit must be used to reject the heat at the condenser. The coolant flow rate can be controlled with an electric pump. Cooling water is assumed to enter the condenser with a temperature of approximately 298K: despite the fact that this temperature could be difficult to be maintained in some conditions, the change of condensing temperature set point has no effect on the proposed methodology.

3. ORC SYSTEM MODEL

To facilitate the optimization and control design for the ORC system, a fast-running physics-based mathematical model has been developed for simulating the transient behaviour of the ORC system. The model accounts for the key components of the system, with reference to the layout sketched in Fig. 1. Thermodynamic properties of the working fluid were obtained from the NIST database, as functions of pressure and enthalpy (Lemmon et al., 2007).

3.1 Pump and Expander

The pump and expander models are based on a quasi-steady, black-box approach, (Canova et al., 2014), (Briggs et al., 2010), and calibrated using steady-state performance maps.

The expander is a positive-displacement machine whose performance parameters (volumetric efficiency η_v and isentropic efficiency η_s) are defined as:

$$\eta_v = \frac{\dot{m}_{\exp}}{\rho_{in} V_d \omega_{\exp}} \;;\; \eta_s = \frac{h_{in} - h_{out}}{h_{in} - h_{out,s}} \tag{1}$$

where $\dot{m}_{\exp}$ denotes the mass flow rate of refrigerant through the expander, V_d is the expander displacement, ρ and h are the refrigerant density and enthalpy. The isentropic and volumetric efficiency are modelled through an empirical model calibrated directly on the performance data provided by the supplier.

A similar approach is used for the pump model, for which the volumetric efficiency is given by:

$$\eta_v = \frac{\dot{m}_{pump}}{\rho_{in} V_d \omega_{pump}} \tag{2}$$

Due to the very limited enthalpy changes across the pump, the pump isentropic efficiency is assumed constant.

3.2 Recuperator

The recuperator model is based upon the ε-*NTU* method. Due to the high heat transfer coefficients, the heat exchanger is characterized by a rapid response to variations in the flow rates or inlet thermodynamic conditions. For this reason, a quasi-static approach can be used to model the heat transfer (Agarwal et al., 2012). The effectiveness is evaluated as a function of the flow rate and temperatures of the incoming fluids. A dynamic model for the outlet temperature estimation is based on energy balance equation:

$$MC\frac{dT_{out}}{dt} = \dot{m}c_p\left(T_{in} - T_{out}\right) + \dot{Q}_{in} \tag{3}$$

where M is the mass of fluid contained in the heat exchanger and $\dot{Q}_{in}$ is the heat absorbed (positive) or rejected (negative) by the fluid. Equation (3) is applied to both the hot side and cold side of the recuperator.

3.3 Expander bypass

The expander bypass is modelled as an ideal valve that automatically removes any liquid flow at the outlet of the evaporator, and routes it directly to the condenser.