Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 129 (2017) 184–191

Energy Procedia

www.elsevier.com/locate/procedia

IV International Seminar on ORC Power Systems, ORC2017
13-15 September 2017, Milano, Italy

Model Predictive Control of an Organic Rankine Cycle System

Xiaobing Liu[a,]*,Adamu Yebi[b], Paul Anschel[a], John Shutty[a], Bin Xu[b], Mark Hoffman[b], Simona Onori[b]

[a]BorgWarner Inc.,3800 Automation Ave., Auburn Hills, MI 48326, USA
[b]Clemson University, 4 Research Dr, Greenville, SC 29607, USA

Abstract

Organic Rankine Cycle (ORC) waste heat recovery systems offer promising engine fuel economy improvements for heavy-duty on-highway trucks. An ORC test rig with parallel evaporators to recover both tailpipe and EGR waste heat from a 13L heavy duty diesel engine was developed and used in this work to demonstrate a novel control strategy based on Model-Predictive Control (MPC). The main control objectives for the ORC system are: (i) regulation of working fluid temperature, (ii) safe turbine operation - away from 2-phase region, and (iii) maximization of waste heat recovery. The MPC uses a built-in moving boundary evaporator model to predict future system response and generate optimal actuator reference commands. Two variants of MPC were considered in this work: an adaptive linear MPC (LMPC) and a nonlinear MPC (NPMC). Compared with the traditionally used PID controller, MPC demonstrates more accurate temperature control and improved disturbance rejection in simulation. Finally, the LMPC and NMPC controllers were implemented on the ORC test rig and showing promising initial test results.

Peer-review under responsibility of the scientific committee of the IV International Seminar on ORC Power Systems.

Keywords: Model Predictive Control; Waste Heat Recovery; Organic Rankine Cycle

1. Introduction

With tightening emission regulation on heavy-duty on-road vehicles, engine waste heat recovery technologies have been under extensive study in recent years. Organic Rankine Cycle (ORC) is a promising waste heat recovery technology providing about 3-5% fuel economy benefit in addition to base engine efficiency improvement [1]. In the SuperTruck program, Cummins reported a 3.6% absolute improvement in brake thermal efficiency of a heavy duty truck engine due to ORC with EGR and exhaust tailpipe evaporators [2]. ORC is similar to the conventional

---

* Corresponding author. Tel.: +1-248 754 0514
E-mail address: xliu@borgwarner.com

Peer-review under responsibility of the scientific committee of the IV International Seminar on ORC Power Systems.
10.1016/j.egypro.2017.09.109

steam cycle used in power plants, except an organic fluid, such as ethanol, replaces water as working fluid due to the low-temperature heat source. The main challenge of operating an ORC in automotive applications is handling the highly transient and wide ranging engine operating conditions. This poses challenges on the ORC control system design. Tona and Peralez [3] presented a literature review on different ORC system architectures and control strategies used for heavy-duty vehicles. The ORC control approaches can be classified into two categories:

- traditional PID-based, e.g., PI feedback plus feedforward [4], PI-based decentralized control [5]
- advanced Model Predictive Control (MPC) [6,7,8]

Advanced MPC demonstrates better performance in simulation, but real-time implementation and validation on test rigs are scarce in literature if not absent at all. In this paper, the implementation of an adaptive linear MPC (LMPC) and a nonlinear MPC (NMPC) are described. Both simulation and preliminary experimental results are presented.

The paper is organized as follows. Section 2 describes the layout and main components of the ORC system. Section 3 presents the ORC control goals and challenges. Section 4 describes a PID controller implementation. Section 5 presents the MPC control structure, formulation, and evaporator modeling. Section 6 provides a comparison of MPC vs PID simulation results, and initial MPC test results. Finally, conclusions and future work are presented in Section 7.

2. System Description

2.1. ORC system layout

In order to provide OEMs with ORC components optimized for the engine application environment, BorgWarner has taken a “Systems Approach” to refine the ORC components via on-engine transient testing. An ORC test rig with parallel evaporators to recover both tailpipe (TP) and Exhaust Gas Recirculation (EGR) waste heat was developed to evaluate the dynamic requirements of ORC systems and refine the products accordingly. Fig. 1a shows a simplified schematic of the ORC system [6]. Major components in the system include: 2-stage pumps, two flow distribution valves, two evaporators in parallel, a turbine expander, a motor/generator, a condenser, and an exhaust gas bypass valve. The pumps increase the working fluid pressure up to 40bar and circulates working fluid through the evaporators. The low pressure feed pump is upsteam of the positive displacement type high pressure pump to prevent cavitation. The distribution valves determine the flow split into the two evaporators. Inside the evaporators, working fluid absorbs heat from engine exhaust and EGR, and undergoes phase changes from liquid to two-phase and then to vapor. The high-pressure and high-temperature vapor then expands through the expansion device, extracting useful work and driving either an electric generator or the engine crankshaft via gear reduction. Turbine inlet and bypass valves protect the turbine from two-phase working fluid and ensure smooth startup and shutdown of turbine expander. Finally, the working fluid vapor exiting from the expansion device flows through the condenser and transitions back to liquid phase. In the test rig, ethanol was selected as working fluid due to its favorable thermophysical properties and low global-warming potential [9]. A turbine expander with an electric generator was chosen as the expanding device due to its high thermal efficiency, wide operating range, small package volume, and low mass [10].

The ORC system is coupled to a 13L heavy duty diesel engine which is equipped with a high-pressure EGR system and a turbocharger with variable geometry turbine. The stock EGR cooler is replaced by the ORC EGR evaporator. The ORC tailpipe evaporator is placed downstream of the after-treatment system. A tailpipe evaporator bypass valve is installed in the exhaust gas path to divert a portion of the exhaust gas away from the tailpipe evaporator at high engine load conditions. The bypass valve protects the working fluid from overheat and potential degradation while also limiting heat rejection to the vehicle cooling package that would require use of the electric cooling fan. By design, the valve moves to the full bypass position at failure modes.

The 13L heavy duty diesel engine is controlled by an open ECU with an ETK interface. ECU calibration is through ETAS INCA software. The dyno control software is AVL PUMA. The ORC system is controlled by a dSPACE MicroAutoBox prototype controller. It interfaces sensors and actuators through CANSAS data acquisition system. The communication between controllers is through CAN bus.