Model Predictive Control of an Automotive Organic Rankine Cycle System

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Presentation Outline

- System Description, Layout, and Test Rig Setup
- Control Development Challenges
- PID Based ORC Control
- Model Predictive Control (MPC)
- Summary
Introduction

- Organic Rankine Cycle (ORC) is a promising waste heat recovery technology providing 3-5% fuel economy improvement for Heavy-Duty On-Highway trucks

- A typical ORC cycle
ORC Test System

- An ORC test rig was built
- Motivation
  - System integration and control development
  - ORC component performance and durability testing
  - Fuel economy benefit measurement
- Features
  - Coupled with a 13L HD diesel engine w/ HP EGR & VTG
  - Tailpipe and EGR evaporators in parallel
  - Turbine expander with 48V integrated generator
  - Ethanol as working fluid
ORC System Layout

Exhaust gas mass flow → Exhaust Gas Bypass Valve → TP Evaporator → EGR Evaporator → EGR mass flow

TP Distributor Valve → EGR Distributor Valve → HP Pump

Expansion Tank → Condenser

LP Pump

Turbine Bypass Valve → Turbine Valve → Turbine Expander

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High Pressure: 20-40 Bar
Low Pressure: 1 – 5 Bar
System Development – Hardware

PRODUCT RANGE

- EGR evaporator
- Exhaust tailpipe evaporator
- eTurbine expander
- eTurbine Controller
- Exhaust bypass valve
- Condenser

BorgWarner offers a wide range of components for the ORC system
ORC Test Rig / Dyno Controls Setup
ORC Control Challenges

- Complex MIMO nonlinear system

- Wide operation range (T, P, 2-phase, expander speed)

- Very challenging ORC control in transient cycles
  - Fast disturbances (engine exhaust flow/T) while slow WF temperature response
  - Different time constants for EGR and TP evaporators
    - After-treatment system on TP path as a thermal buffer
    - Limited information in literature on ORC transient control

- An optimal control problem with safety limitations
  - Temperature limit due to dissociation/flammability of working fluid
  - Pressure limit due to structural integrity of key components
  - Vapor phase limit on turbine expander operation
A PID based ORC controller was developed and enabled steady state and slow transient operation of the test rig. The PID controller worked well in steady-state and slow transient operations, but had difficulties in fast transient conditions due to poor disturbance rejection and undesired coupling between PID control loops. Therefore Model Predictive control (MPC) approach was adopted in the second phase of the project.
MPC Control Structure

Objective is to minimize the temperature tracking error

Constraints represent physical actuator limits and safety bounds

MPC optimizer finds the optimal control inputs to minimize the objective function. It has a reduced order, control oriented plant model built in.

Some system states cannot be directly measured, a state estimator is required

r: reference point
w: engine input
y: output
u: control input
x: state
Evaporator Control Oriented Model

- Moving boundary model (MBM): 3 regions

6 states: \( x = [L_1, L_2, h_{f,\text{out}}, T_{w1}, T_{w2}, T_{w3}] \)

Inputs: \( \dot{m}_{f,\text{in}} \); Outputs: \( h_{f,\text{out}} \); Disturbances: \( \dot{m}_{g,\text{in}}, T_{g,\text{in}}, h_{f,\text{in}} \)

The MBM model was correlated with test rig data

MPC Implementation on an Embedded Platform

- Embedded Control Hardware Specification
  - dSpace Micro Autobox Gen II
    - IBM PowerPC 900MHz, 16MB RAM

- MPC Real-time Implementation
  - Execution time reduction to meet real-time constraint
  - Memory consumption reduction to fit into embedded platform

- Two variants of MPC
  - Adaptive Linear MPC (LMPC)
    - Mathworks MPC Toolbox
  - Nonlinear MPC (NPMC)
    - ACADO Toolkit from Univ. of Leuven
Comparison of PID and MPC – Simulation

- Engine conditions:
  - B (1575RPM, 1540Nm) to A (1200 RPM, 1000Nm) to B
  - Step working fluid T setpoint

MPC has better temperature regulation and disturbance rejection, with fast response and minimal overshoot
MPC Simulation over a Transient Cycle

LMPC and NMPC produce comparable results
The working fluid temperature is well regulated within ±10°C
MPC Controller Test Result – T Step

Fast T step response with no overshoot
Small steady state error
MPC Controller Test Result – Engine Speed/Load Ramp

WF Temperature is well regulated
Summary

- An ORC test system, which recovers waste heat from engine tailpipe exhaust and EGR, was implemented.

- A PID based controller was developed enabling steady state and slow transient operation of the ORC system.

- Two MPC controllers (LMPC & NMPC) were developed which provided better temperature control and improved disturbance rejection in simulation.

- MPC controllers were implemented on a real-time embedded platform and initial test results were satisfactory.
Thank you!
ORC Publications

Publications

MPC vs PID Controller

- MPC has better performance over PID in transient conditions
  - Built-in plant model for response prediction
  - Optimizer to find optimal control inputs
  - Potential synergy with future GPS-based road load prediction system

but requires more CPU computation time, memory consumption, and modeling effort.

- Looking into ORC control options on vehicle
  - Advanced PID with better feed forward model
    or
  - Linear MPC