MULTIVARIABLE EPSAC PREDICTIVE CONTROL FOR ORGANIC RANKINE CYCLE TECHNOLOGY

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EXTENDED ABSTRACT

INTRODUCTION

The Organic Rankine Cycle (ORC) technology has become very popular, as it is extremely suitable for waste heat recovery from low-grade heat sources. As the ORC is a strongly coupled nonlinear multiple-input multiple-output (MIMO) process, conventional control strategies (e.g. PID) may not achieve satisfactory results. In this contribution our focus is on the accurate regulation of the superheating, in order to increase the efficiency of the cycle and to avoid the formation of liquid droplets that could damage the expander. To this end, a multivariable Model Predictive Control (MPC) strategy with improved disturbance rejection capabilities is proposed, its performance is compared to the one of PI controllers for the case of variable waste-heat source profiles.

ORGANIC RANKINE CYCLE

The ORC system considered in this paper is characterized by an evaporator where the heat source is used to heat and evaporate the organic fluid. The fluid drives a single screw expander for power generation, and is then condensed into liquid in the condenser. The Organic fluid is collected in a receiver, introduced to avoid pump surge, and then pumped back to the evaporator. The evaporator, as the energy exchange device, transfers the energy from the heat source to the cycle fluid. Its parameters and performance have a major impact on the efficiency of the system. In the proposed cycle regeneration is used to increase the efficiency of the cycle. In Fig. 1 a schematic overview of the system is given. Each component of the ORC cycle has been modeled following the approach proposed in (Quoilin, 2011), and implemented under Modelica language in Dymola®using the 'CoolProp2Modelica' library.

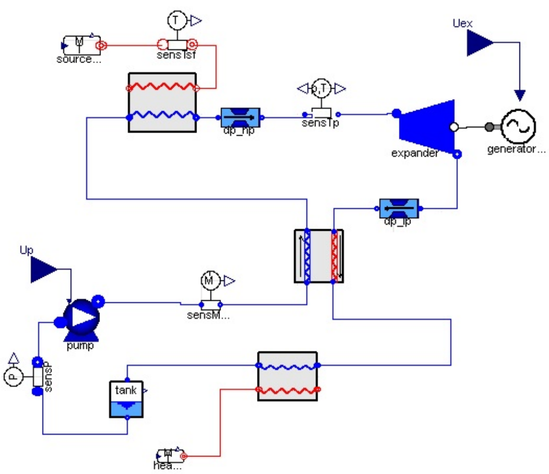

Figure 1: Schematic of the setup

Parametric Identification

In this study we are interested in controlling the superheating and evaporating temperature; hence, transfer function will be identified between the inputs speed in the pump (U_p) and expander (U_{exp}) given in Hz and the outputs superheat ($\Delta T_{ex,ev}$) and evaporating temperature (T_{ev}) given in K. The identification was performed using a multisine excitation signal and the prediction error method (pem) (Lung, 1999). The sampling time $T_s = 5\,\mathrm{s}$ was chosen according to the fastest dynamics of the system. The identified transfer function matrix is presented in (1). Each transfer function gave a data fitting of about 90%.

$$\begin{bmatrix} \Delta T_{ex,ev}(s) \\ T_{ev}(s) \end{bmatrix} = \begin{bmatrix} \frac{-4.5036}{(141.2s+1)} & \frac{1.0351}{(104.56s+1)} \\ \frac{1.37}{(134.2s+1)} & \frac{-0.48}{(54.14s+1)} \end{bmatrix} \begin{bmatrix} U_p(s) \\ U_{exp}(s) \end{bmatrix} \tag{1}$$

CONTROL DESIGN

In recent years, studies on ORC systems have been focused on the optimization of the ORC system and the selection of working fluids, but the results about modeling and control strategy were few. In (Quoilin et al., 2011) were proposed three different control strategies for varying heat source profiles, concluding that the best strategy was the one which made use optimization of a steady-state model to find the optimal operating points of the system for a wide range of conditions. The strategy proposed in this paper consists in considering the varying-heat source as a disturbance to the system; hence, making more important to improve the disturbance rejection capabilities of MPC to avoid the need of an off-line steady-state optimization.

Two **PI controllers** were tuned using the CAD tool FRTool in Matlab and used as a reference to the MPC performance. The parameters tuned to control the superheating $\Delta T_{ex,ev}$ are $Kp = -1.095$, $Ti = 103.22$ and the PI parameters to control the evaporating temperature T_{ev} are $Kp = -2.25$, $Ti = 8.63$.

In this study the **Model Predictive Control** strategy has been implemented following the Extended Prediction Self-Adaptive Control (EPSAC) (De Keyser, 2003) for MIMO systems. The MPC control for the superheating $\Delta T_{ex,ev}$ was tuned as follows, coincidence horizon $N_1 = 1 ..., N_2 = 6$ and control horizon $N_u = 1$; while the control evaporating temperature T_{ev} was tuned as coincidence horizon $N_1 = 1 ... N_2 = 7$ and control horizon $N_u = 1$. An important element of this study is the choice of the disturbance model, first the 'default' filter $\frac{C(q^{-1})}{D(q^{-1})} = \frac{1}{1-q^{-1}}$ was chosen leading to zero steady-state error. However, if some knowledge about the frequency content of the disturbance is known a priori, then a 'smart' filter can be designed following the approach suggested in (De Keyser 2003b), giving as result the disturbance model $\frac{C(q^{-1})}{D(q^{-1})} = \frac{1}{1-2.5995q^{-1}+2.2395q^{-2}-0.64q^{-3}}$.

SIMULATION RESULTS

In this section are presented the results obtained with the PI controllers and the two MIMO MPC methodologies with 'basic' and 'intelligent' filter. As mentioned earlier the present study focuses on the accurate regulation of the superheating $\Delta T_{ex,ev}$, where a small amount of superheating represents a higher efficiency (Wei, 2008) and zero represents an undesired effect (i.e. formation of liquid droplets that could damage the expander).

The performance for PIs as well as the MPC controllers is depicted in figure 2. Although, the temperature variations coming from the heat source affect the three control strategies, it is noticeable that the PI control performs the worst as the superheating drops to zero at 1250 s, while the MPC controllers are able to keep the superheating into the desired range. From those the MPC with 'intelligent' filter reacts before the disturbance appears, decreasing its final effect and consequently, making possible to decrease the setpoint of the superheating to increase the efficiency of the cycle.

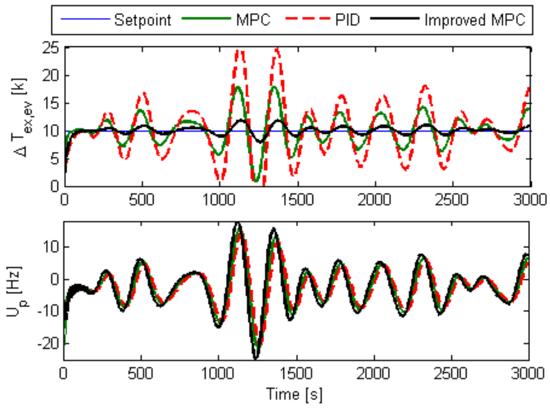

Figure 2: Disturbance rejection performance of PIs and MIMO MPC

CONCLUSIONS

In the present contribution an effective and efficient Multivariable Predictive Control strategy with improved disturbance rejection capabilities has been evaluated and compared to PI controllers. The results obtained suggest that it is possible to work with an small amount of superheating without endangering the expander, thus increasing the efficiency of the cycle even in the case of variable heat source profiles. In practice, the 'intelligent' disturbance filter can be designed after getting information of the bandwidth of the disturbance. This can be achieved by implementing a frequency analysis of previous measured temperature data, or by means of the forecast information in the case of solar applications.

ACKNOWLEDGEMENTS

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