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Research Paper

Experimental investigation of alternative robust model predictive control of a heat exchanger

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HIGHLIGHTS

- Robust model predictive controllers are designed using four approaches.
- Software MUP is a tool for robust controller design.
- Robust predictive controllers control a laboratory heat exchanger.
- Robust model predictive control brings energy savings.

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ABSTRACT

Advanced control of heat exchangers is an important task for control engineers, as these devices belong to the key equipment in chemical, petrochemical, food and pharmaceutical industries, and they are energy-intensive processes. This study presents novel robust model-based predictive control (MPC) of a heat exchanger. Influence of uncertain parameters was taken into account to design robust model-based predictive controller. Resulting optimization problem with constraints was formulated in the form of linear matrix inequalities, and the convex optimization problem was solved using semi-definite programming. The proposed alternative robust MPC design method was implemented using the novel software MUP. Extensive case study of heat exchanger control was done to demonstrate effectiveness of the alternative robust MPC. This novel strategy was compared with known robust MPC approaches. Experimental results confirmed that the alternative robust MPC improved control performance and ensured energy savings during the heat exchanger operation.

1. Introduction

Recently, more attention has been paid to energy savings and alleviating environmental problems [1]. As energy prices rise, energy savings are very important in industry with energy-intensive production [2]. To solve this problem, advanced control strategies have been developed [3] that can be used in more complicated control problems to improve process control in comparison with conventional proportional-integral-derivative (PID) control [4]. The generalized predictive control (GPC) [5] was used in the waste heat recovery power plant [1]. Simulation of control showed improved steady-state and transient responses along with the decoupling performance. Moreover, the disturbance rejection was significantly improved. MPC and Linear Quadratic Gaussian (LQG) compensator were numerically compared and used for thermal regulation of a high precision measurement machine affected by four disturbances [6]. The work showed that both, the quality of regulation results and perturbation rejection strongly depend on the parameters in the cost function and the penalization coefficients in LQG and MPC. Optimization of heat and power self-sufficiency can be achieved by applying local renewable resource integration and transformation of the renewable energy [7].

Heat losses can rise up to 50% in heat exchangers. Therefore, it is necessary to optimize their operation and to implement advanced control strategies. The robust stochastic approach for optimization design of air cooled heat exchangers was studied in [8] and the results confirmed that the harmony search algorithm converged to the optimum solution with higher accuracy in comparison with genetic algorithms. Using neural network predictive control (NNPC) with an auxiliary fuzzy controller assured energy savings in operation of a tubular heat exchanger [9]. The experimental

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Nomenclature

Symbols

$\boldsymbol{A}$	system matrix of state space system
$\mathbb{A}$	polytopic set of uncertain system
$\boldsymbol{B}$	input matrix of state space system
c_p	specific heat capacity (J kg^{-1} K^{-1})
$\boldsymbol{C}$	output matrix of state space system
$\boldsymbol{E}^{(\boldsymbol{m})}$	auxiliary matrix of controller design
$\widetilde{E}^{(\boldsymbol{m})}$	auxiliary matrix of controller design
$\boldsymbol{F}$	gain matrix of the controller
$\boldsymbol{H}$	auxiliary matrix of controller design
$\boldsymbol{I}$	identity matrix
i	auxiliary counter
j	auxiliary counter
J	quadratic quality criterion
k	discrete time (s)
$\boldsymbol{K}^{(\boldsymbol{m})}$	auxiliary matrix of controller design
n_m	number of variations of constrained and non-constrained control inputs
n_u	number of control inputs
n_v	number of vertex systems
n_x	number of system states
n_y	number of system outputs
$\boldsymbol{P}$	Lyapunov matrix
q	volumetric flow rate of hot fluid (m^3 s^{-1})
Q	heat consumption (kJ)
$\mathbb{R}$	space of the real-valued matrices
s	operator of Laplace domain
t	time (s)
t_f	number of control steps
t_s	sampling time (s)
T	controlled temperature of heated fluid (°C)
T_h	temperature of hot fluid (°C)
T_r	initial temperature of hot fluid (°C)
$\boldsymbol{u}$	control inputs
$\boldsymbol{u}_{\max}$	constraints on control inputs
$\boldsymbol{u}_{\mathrm{sat}}$	saturated control inputs
U	voltage (V)
$\mathbb{U}$	set of constrained control inputs
v	vertex system
V	volume (m^3)
$V(x)$	Lyapunov function
$\boldsymbol{W}_u$	weight matrix of control inputs
$\boldsymbol{W}_x$	weight matrix of system states
$\boldsymbol{x}$	system states
$\boldsymbol{x}_0$	initial conditions of system states
$\boldsymbol{X}$	inverse Lyapunov matrix
$\boldsymbol{y}$	system outputs
$\boldsymbol{y}_{\max}$	constraints on system outputs
$\boldsymbol{Y}$	auxiliary matrix of controller design
$\mathbb{Y}$	set of constrained system outputs
Z	transfer function gain (°C/V)
$\boldsymbol{Z}$	auxiliary matrix of controller design
0	zero matrix

Greek symbol

γ	auxiliary weight of Lyapunov function
ρ	density (kg m^{-3})
τ	transfer function time constant (s)
τ_F	filter time constant (s)

Superscript

s	steady state
(m)	auxiliary counter
(v)	vertex system
(0)	nominal system

Subscript

h	hot fluid
k	k-th control step

Abbreviations

ACIS	additional control-input saturation
LMI	linear matrix inequalities
LQG	linear-quadratic-Gaussian
LQR	linear-quadratic-regulatory
MPC	model predictive control
NSO	nominal-system optimization
PCM	peristaltic pump dosing cool fluid
PHM	peristaltic pump dosing hot fluid
PID	proportional-integral-derivative controller
RMPC	robust model predictive control
SDP	semidefinite programming

closed-loop control based on two fuzzy controllers improved operation of a heat pump drying system [10]. One way of improving energy efficiency of heat exchanger networks is to perform retrofitting of them. The shifted retrofit thermodynamic diagram that represents a modification of the retrofit thermodynamic diagram was introduced in [11]. The heat exchanger network modification by parallel arrangement can lead to the waste heat utilisation [12].

Industrial processes are affected by various uncertainties, as e.g. parameter variations, measurement noise, disturbances, varying operation conditions. Controllers designed without taking uncertainties into account may result in ineffective control or even fail. Uncertainties also affect quality of production and energy consumption. To resolve mentioned problems, controllers with high performance and robustness are necessary. Advanced optimization in robust control design has been presented in various works in recent years. Robust PID controller for heat pump and plug-in hybrid electric vehicle with uncertainties was developed in a smart microgrid system [13]. The robust controller was designed for air conditioners using optimization based on the mixed H_2/H_∞ control technique [14]. Simulation results showed significant improvement of robustness and control performance in comparison with conventional control approaches. The robust controller was also able to ensure significant energy savings. The H_∞ control strategy was successfully implemented to control the one-stage refrigeration cycle [15]. Better closed-loop performance of the robust controller and reduced coupling between controlled variables were observed. The robust controller was designed also for the higher penetration of photovoltaic generators [16] and their control performance was investigated using simulations. It was demonstrated that the robust controller ensured stability in the presence of uncertainties and the system operating conditions were not violated.

Robust model predictive control (MPC) is an advanced control strategy optimizing the control performance subject to the bounded system uncertainties and the constraints on control inputs and system outputs [17]. The complex optimization problem became tractable via its formulation in the form of LMIs [18]. In order to design robust MPC, the optimization problem with