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Unmeasured temperature control in the presence of unknown drifting parameters in a cruise ship application

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ABSTRACT

In cruise ship applications several waste heat recovery systems have been developed over the years in order to harvest the excess heat produced by the diesel engine and is stored in the coolant as thermal energy for instance. In this paper, a detailed model of a Fresh-Water-Cooling system is developed based on first principles and a given circuit scheme provided by the vessel manufacturer. The Fresh-Water-Cooling system consists of multiple interconnected subsystems; in this paper the main focus lies on the heat exchanger, where the waste heat recovery process takes place. Due to the presence of unmeasured states and uncertain model parameters the heat exchanger is modelled as partially measured stochastic system. Further the process is proved to be conditionally Gaussian, which makes the use of a conditionally Gaussian filter possible. It produces optimal estimates for the states and the unknown drifting parameters in the mean square sense. The process state is locally stabilized by the estimated process values using stabilizing feedback control.

1. Introduction

Efficient use of energy is a focal point in any branch of industry due to the finite nature of fossil fuel supplies among other reasons. In marine vessel applications, the diesel engine is the main source of power supply for the entire ship. Although fairly developed, its thermal efficiency is only 50% so that only half of the fuel energy is converted into mechanical work. The other half appears as thermal energy in the form of exhaust gas, coolant and radiation. This is referred as waste heat and considerable of work has been deployed in developing different kinds of waste heat recovery systems. Here one particular system is considered known as the Fresh-Water-Cooling system (FWC).

In this paper the main focus lies on the heat exchanger, where the waste heat recovery takes place. In brief, the heat exchanger is divided into two channels referred as the primary and secondary side. The cold seawater feed on the secondary side is heated up by the hot coolant on the primary side, which contains the excess thermal energy produced by the diesel generator. However, the heat exchanger is subject to several kinds of uncertainties; e.g. its geometrical configuration is not known accurately as it changes from ship to ship. Moreover the heat transfer process strongly depends on the unknown flow conditions inside the heat exchanger, which might cause the associated heat transfer coefficient to fluctuate over a wide range during operation. Many approaches exist across different fields in engineering dealing with the determination of the heat transfer coefficient. A brief outline of those approaches is provided next.

1.1. Thermodynamics/fluid mechanics

Within the thermodynamics and fluid mechanics community, the main objective is the accurate modelling of the governing physical phenomena. That often leads to complex and coupled field problems, where analytical solutions are difficult to obtain; e.g. the Navier–Stokes equations. Empirical and numerical methods have been developed as a consequence and the results have been well reported in literature. For instance, in [1,2], empirical correlations are available to estimate the heat transfer coefficient for numerous geometries in the case of forced convection. The obtained correlations are expressed in terms of dimensionless numbers: the Nusselt (Nu), Prandtl Pr and Reynolds number (Re). However, the analogies are only valid for very specific conditions under which the experiments have been carried out.

With increasing computing power, Computational Fluid Dynamics (CFD) provides an option to solve the Navier–Stokes equations numerically. In [3,4], the heat transfer coefficient is

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Nomenclature

Abbreviations

CFD	Computational Fluid Dynamics
CGF	Conditionally-Gaussian Filter
CV	control valve
EKF	extended Kalman Filter
FWC	Fresh-Water-Cooling system
HT	high temperature
LT	low temperature
MV	mixing valve
SV	splitting valve

Conditionally-Gaussian system, estimation and control

$\bar{\varepsilon}$	innovation process
γ	conditional covariance matrix
μ	unconditional mean of unknown parameter vector θ
Φ	dynamics of drift
Σ	covariance of noise
σ	standard deviation
θ	unknown drifting parameter
$\varepsilon_1, \varepsilon_2$	white noise
φ	indirect control variable; flow rate through the shell-side of the heat exchanger
$a_0(t, y_t), A_0(y_t)$	time-varying vector functions dependent on measurements y_t
$a_1(t, y_t), A_1(t, y_t)$	time-varying matrix functions dependent on measurements y_t
$a_2(t)$	time-varying vector function
b, B	covariance matrices of process and measurement noise
d	stability resource
G	gain of innovation
h	sampling interval
K	upper bound for $T_{E,out}$
K_p	proportional gain of controller
m	conditional mean
T_d	desired constant temperature at the heat exchanger outlet
u	direct control variable; set-point temperature in CV
V, W	independent Wiener processes
y	measurements
z	vector of unmeasured parameters and state

FWC system

κ_1, κ_2	characteristic function for control and splitting valves
Q_j	flow rate through j
T_j	temperatures at j
V_j	volume at j
W_{Heat}	transferred heat from engine to coolant

Physical and geometrical quantities

ρ	density of water and brine
A_i	heat transfer area on the interior surface of the tube bank
A_o	heat transfer area on the exterior surface of the tube bank
c_p	heat capacity of water and brine
h_i	convective heat transfer coefficient on the tube-side
h_o	convective heat transfer coefficient on the shell-side
k	thermal conductivity of walls
L	length of the tube bank

Abbreviations

m_W	mass of the tube bank
r_i	interior radius of on tube
r_o	exterior radius of on tube

Subscripts and superscripts

0	initial
CL	closed-loop
OL	open-loop
$a\,MV_1$	after mixing valve 1
BP	by-pass
E	engine
fix	fixed set-point
$fr\,LT$	from the low-temperature circuit
Hex	heat exchanger
in	at inlet
LT	low temperature circuit
out	at outlet
S	shell
Sea	sea water
T	tube
t	instant in time t
$to\,LT$	towards the low-temperature circuit
$to\,MV_1$	towards mixing valve 1
W, i	interior surface of tube bank
W, o	exterior surface of tube bank
WHR	waste heat recovery

determined in the boundary layer of a wall for laminar and turbulent air flow and in atmospheric flow conditions with low and high Reynolds numbers.

1.2. Control engineering

For several industrial processes, estimation of the heat transfer coefficient is a crucial task; it is evident from the different applications such as chemical reactors, biochemical and food industries or in a turbo-charged diesel engine [5–8]. The well-known extended Kalman Filter (EKF) has been applied in all of those cases, where the posterior filtering densities of the states is assumed to be a Gaussian distribution. These are formed by utilizing Taylor series approximations of the nonlinear state equations. Application of the EKF requires deterministic model coefficients (Jacobians). However, in our case study the model coefficients depend on noisy measurements introducing stochastics to the system. Theoretically, this circumstance is not covered by the EKF framework leading to non-proper solutions as the mean and variance are incorrect biased estimates of the state and unknown parameters. They are biased since the estimation problem is infinite dimensional and the statistical moments do not form a closed system for the calculation of the mean and variance. One must find the probability density first before calculating the mean and variance. The probability density can be found as the solution of the Zakai equation or Kushner equation developed for nonlinear systems. For instance Zakai-filtering has been applied to a nonlinear parameter estimation problem in deposition process control [9]. In less severe cases, when the coefficients are only nonlinear dependent on the measurements, (and not nonlinear regarding the state) the mean and variance can still be calculated in closed form with the conditionally Gaussian filter. We follow this conventional approach in the manuscript.

This paper is organized in eight sections. In Section 2 the control objectives are stated. Based on a given circuit scheme and