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Sensors and actuator fault tolerant control applied in a double pipe heat exchanger

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ABSTRACT

In this work, we present the design of a Fault-Tolerant Control (FTC) system, applied in the outlet temperature sensors and in the control valve (actuator) of a concentric double pipe counter-current flow heat exchanger. The FTC consists in a sensors Fault Detection and Isolation (FDI) system and an actuator FDI system. The sensors FDI system is based on analytical redundancy, in such a way that a bank of modified Kalman filters is developed in order to estimate the two outlet temperatures of the heat exchanger. To develop the modified Kalman filters a multi-linear models approach is used. So that, if a sensor fault is detected by the FDI system the measured temperature signal is replaced by the temperature estimation provided by the modified Kalman filter. Moreover, to detect an actuator fault a comparison between the control valve behaviors (the control valve voltage is used to estimate the water flow rate) and a predefined flow rate for each linear model is carried out. In order to keep the continuous operation of the heat exchanger even in fault presence a model-following control law is introduced, such that, when an actuator fault occurs, the FDI system detect the fault and immediately the model-following control makes the fault accommodation in order to compensate the actuator fault. The proposed scheme is presented with experimental data on-line. The successful tests are presented and discussed.

1. Introduction

Nowadays, faults on industrial processes occur frequently, whether in sensors and/or in actuators and conventional controllers are not able to counteract the effects of such faults. Also, if these faults are not detected and corrected immediately after their occurrence, process performance would be deteriorated and could cause deep damage to the process and endanger the operating personnel. For this reason, Fault Detection and Diagnosis (FDD) [1,2] and Fault Tolerant Control (FTC) systems have grown in importance for study and research [3–5].

A widely used heat transfer device in the industries is the heat exchanger since it is used in chemical processes, refineries, petrochemical, pulp and paper, pharmaceutical, to mention some of the most important; it is typically required for use in various stages of these processes, operating points can be chosen based on the required production or quality of the raw material [6,7]. Due to its importance, different authors [8,9] have proposed works on control area and fault diagnosis [10–13] for heat exchangers.

In [14] a robust predictive control is designed, using a heat exchanger model with uncertainty on parameters to counteract the effect of disturbances, measurement noise (disturbance) and parameter variation. In [8] an optimal control system for a heat exchanger network is designed and seeks to solve the performance decrease due to its operation. In both [14,8], it is considered that the design of a control for a heat exchanger is a challenge due to the presence of nonlinearities in the system.

In the framework of multi-model approaches different works about modeling, control and fault diagnosis have been presented, in [15] multi-models approaches based on neural network, fuzzy logic and analytical cases are studied. In [16] the authors proposed multiple-model and multiple-controller methods based on the divide-and-conquer strategy [17], in this strategy the operating range of the system is partitioned into different operating regions. So, local models and/or controllers are applied for each operating region. A difference between multi-linear models and others techniques proposed in the literature [18,19], as compartmental or

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neural network approaches, is the type of function used to switch between models, in multi-linear models approach we used a probabilistic function for it. In the other approaches it can be used sigmoidal or sigmoid functions [19], other cases use logic functions to switch between models [18].

In the framework about diagnosis faults by multi-models, [20] proposed a method to detect and locate faults during the period of transition from one model to another. In [21] showed how the detection and fault location is achieved when the models are accurate and through the decomposition of residual. Finally, in [22] the authors presented a fault uncoupled filter to estimated and detect faults.

In literature, different works have been proposed in fault diagnosis applied in heat exchangers, in [23] the authors proposed a real-time fault diagnosis, in this work, sensors and parameters faults are detected using observers. In [11], the authors present a sensor fault detection and isolation system for a counter-current flow double pipe heat exchanger, the FDI system was designed using a bank of nonlinear high-gain observers, the results showed the good performance of the proposed scheme. Other techniques have been proposed to detect a fault in sensors and/or actuators, in [24] the authors proposed a neural network to detect a fault in sensors and/or actuator, in [25] the authors proposed sliding-mode observers in order to detect sensors faults.

In this work, we show the design of a sensor and actuator FTC scheme for a heat exchanger. The FTC scheme consists of sensors and actuator FDD system and an actuator FTC system based on a model-following control law. The sensor FDD is based on an analytical redundancy, which is designed from a multi-models strategy and the design of modified Kalman filters. An advantage of using multi-models is that we can work in a wide temperatures region, without using complex nonlinear systems. Furthermore, the approach seeks a good relationship performance vs simplicity.

To detect an actuator fault we will compare the behaviors between the control valve (the control valve voltage is used to estimate the water flow rate) and a predefined flow rate for each linear model. If the actuator fault is detected, then the model-following control law will make the fault accommodation in order to compensate the actuator fault.

The goal of this work is the validation of the proposed FTC scheme with experimental data of a heat exchanger. Showing that it is possible to keep under controlled operating conditions, with a minimal degradation of the heat exchanger even in a sensor or/and actuator fault occurrence, which will allow the continuous operation.

2. Heat exchanger model

The heat exchanger objective is cooling hot water, it is configured in counter-current flow, where, the hot water flows through the inner pipe and the cooling water flows through the annular section (outside of the inner pipe).

The heat exchanger model is based on a lumped parameters model [26,6,27], which consists of two ordinary differential equations. The model considers the division of the heat exchanger in a finite number of elements, called sections, where for each section corresponds one pair of differential equations. In this work, we consider only one section and the following assumptions:

- $\mathcal{A}1$ A constant volume in the heat exchanger pipes.
- $\mathcal{A}2$ Global heat transfer coefficient (U) depends on the flow rate and the temperature of the system.
- $\mathcal{A}3$ Physical properties of the fluid are constant.
- $\mathcal{A}4$ There is not heat transfer with the environment.
- $\mathcal{A}5$ There is not calorific energy storage on pipes wall.
- $\mathcal{A}6$ Inlet temperatures are measured.

Table 1
Nomenclature.

Nomenclature	
V_c	Volume in external side, m^3
V_h	Volume in the inner side, m^3
υ_c	Flow in the cold stream, cm^3/min
υ_h	Flow in the hot stream, L/min
C_{pc}	Specific heat of cold water, J/kg °C
C_{ph}	Specific heat of hot water, J/kg °C
ρ_c	Density of cold water, kg/m^3
ρ_h	Density of hot water, kg/m^3
A	Heat transfer surface area, m^2
U	Global heat transfer coefficient, W/m^2 °C
T_{ci}, T_{hi}	Inlet temperatures in the cold and hot streams, respectively, °C
T_{co}, T_{ho}	Outlet temperatures in the cold and hot streams, respectively, °C
Sub-index	
c	Cold
h	Hot
i	Inlet
o	Outlet

The dynamic system of the counter-current flow double pipe heat exchanger is obtained via energy balance as shown in Eqs. (1) and (2)

$$\dot{T}_{co} = \frac{\upsilon_c}{V_c}(T_{ci} - T_{co}) + \frac{UA_1}{\rho_c c_{pc} V_c}(T_{ho} - T_{co}) \tag{1}$$

$$\dot{T}_{ho} = \frac{\upsilon_h}{V_h}(T_{hi} - T_{ho}) - \frac{UA_2}{\rho_h c_{ph} V_h}(T_{ho} - T_{co}) \tag{2}$$

where each variable is defined in Table 1. A low order model as Eqs. (1) and (2) has shown to be useful (observation or control) for synthesis purposes [6].

3. Fault diagnosis system

The idea to use multi-linear model approach, in order to represent a nonlinear system lies on smoothing the nonlinearities of the system, this approach is profitable to work in any operating region of the system, which will depend on the operational requirements. This approach is ideal to apply in diagnosis systems. In this work, a modified Kalman filters bank based on multi-linear model approach is developed. Following, we show the general formulation of the modified Kalman filter design. In Eq. (3) it is shown the representation of a nonlinear system in discrete time state space form.

$$\begin{aligned} X(k+1) &= g(X(k), U(k)) \\ Y(k) &= h(X(k), U(k)) \end{aligned} \tag{3}$$

where $X \in \Re^n$ is the state vector, $U \in \Re^p$ is the input vector and $Y \in \Re^m$ is the output vector. Functions g and h are assumed to be smoothing functions in X and U.

By using Eq. (4), we can represent a nonlinear system by modeling a set of multi-linear systems considering the possible faults of the system.

$$\begin{aligned} X(k+1) &= A_j X_{(k)} + B_j U_{(k)} + \Delta_{X_j} + F_j f(k) \\ Y(k) &= C_j X(k) + \Delta_{Y_j} \end{aligned} \tag{4}$$

where j represents the linear model ($\forall j \in \{1, \dots, M\}$) and M is the total number of linear models used, A_j, B_j and C_j are invariant matrices defined around the jth operating point with appropriate dimensions, generally obtained from a first-order Taylor expansion, Δ_{X_j} and Δ_{Y_j} are constant vectors that depend on the jth linear model, F is the fault distribution matrix and f is the fault vector.