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Practice article

Fault tolerant system based on non-integers order observers: Application in a heat exchanger

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A R T I C L E I N F O

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A B S T R A C T

This work presents a fault-tolerant (FT) scheme based on the application of non-integer order observers also called fractional observers, the case of study is a double pipe countercurrent heat exchanger (HE). The aim of the FT is to detect sensors faults as soon as possible, and to provide a healthy signal in order to replace the faulty sensor signal by the fractional observer estimation. To develop the FT scheme a bank of high gain fractional order observers (HGFOO) is proposed. The Riemann-Liouville (RL) fractional derivative definition is used to solve each fractional observer. Experimental measures from a HE were used to test the performance of the fractional observers and the control scheme. The results show the robustness of the proposed observers.

1. Introduction

In the last twenty years, the fractional calculus theory has been widely studied and applied to describe the behavior of different processes [1,2] and systems [3], also in automatic control area the fractional calculus has been a powerful tool to solve practical problems [4]. The advantages of the fractional calculus over the ordinary calculus lies in the possibility of using different kernels and its general formulation provides an additional freedom degree because of the derivative order. The fractional derivatives of non-integer orders are used in physics and engineering to describe the processes and systems with spatial and temporal nonlocality (usually called dynamic memory of the system), nonlocality means that fractional differentiation involves integration over time from the past up to the present point of interest [5]. The order of the fractional derivative can be interpreted as an index of memory. Fractional calculus has been adopted by different areas of the engineering mainly automatic control area has given special attention to this field of the mathematics, that is because this method provides more accuracy in the processes and systems modeling and higher robustness in their control.

The FT systems applied to HE devices have been subject of study of different authors [6–8]. However, all these FT schemes were based on integer order models, observers and control systems. Applications of FT systems using fractional calculus have not been strongly explored. In Ref. [9] authors presented a research on robust FT control for uncertain fractional order systems. The authors presented numerical simulations to show the effectiveness of the proposed method. So, FT schemes based on fractional observers are an opportunity area to be explored. The fractional observers theory has been widely studied for different authors. For instance, in the work presented by Ref. [10] the author designed a nonlinear observer to synchronize fractional-order chaotic systems. The author concluded that this approach is simple and global. Related to the design of Luenberger observers in Ref. [11], the authors presented the design of a Luenberger observer for discrete fractional order systems. The equations of the observer were derived and presented in the form of a theorem. In Ref. [12], a fractional order sliding mode observer was developed, the observer was designed to estimate the states variables. Theoretical results of two chaotic systems showed the effectiveness of the observer. Another interesting work based on the fractional order Lyapunov approach was presented in Ref. [13], in this work, simple fractional order observers were proposed for estimating the states variables of linear and nonlinear systems. Authors presented two examples to show the effectiveness of the observers, for the first example a linear system was considered. The case of study was a heat transfer system and for the second example a fractional-order Lü's system was considerate. The authors conclude that both observers guarantee that the state estimation error converges to zero asymptotically. In order to obtain sufficient conditions to ensure the stability of a class of uncertain fractional order linear systems, authors in Ref. [14] proposed simple linear matrix inequalities by means of a fractional-order deterministic observer, simulations results showed the efficiency and the straightforwardness of the design. Authors in Ref. [15],

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designed a state observer to approximate signals by using the concept of fractional variable-order derivative. The author conclude that the fractional spectral observer of variational-order is an excellent option to estimate, reconstruct or fit signals.

A Non-fragile observer for a type of nonlinear fractional order Lipschitz system was proposed in Ref. [16]. The system was designed to solve a chaos synchronization problem. In the field of Fault Detection and Isolation (FDI) and Fault Tolerant systems, the authors in Ref. [17] considered a bank of discontinuous dynamical observers to design a fault detection and isolation system, the authors used the RL definition. The authors proposed a second-order sliding-mode observer for some classes of fractional-order uncertain switched dynamics systems using a Lyapunov function for the convergence of the observers. Regarding Fault Diagnosis systems, in Ref. [18], the authors proposed a fault diagnosis method based on fractional-order models applied in a thermal system, they tested two types of observers, the Generalized dynamic parity space method and the Luenberger observer for residue generation. The results showed the effectiveness of the Luenberger observer in problems that involve a thermal transfer. In Ref. [19], the authors showed a method for Fault detection and synchronization system, the method involves the extension theory with fractional-order chaotic self-synchronization of dynamic errors, using the Chen Lee chaotic fractional-order system to extract the obvious characteristics of signal disturbance applied to a ball bearing signals. In mechanical systems, authors in Ref. [20] presented a fault diagnosis system applied to the rotor and stator of a wind energy conversion system with a self-excited induction generator. The fractional model was represented using the RL definition. For controlling the wing turbine velocity, and for ensuring the stability of the non-linear system with and without failure, a fractional order $PI^{\alpha}D^{\mu}D$ controller was implemented.

In the present work, the FDI system was designed using HGFOO. Non-integer order systems are robust to the parametric uncertainties; also HGFOO provide one more freedom degree to the system allowing a better signal reconstruction. A difference between integer order systems and non-integer order systems is that the non-integer order systems have a kernel associated, this kernel allows to characterize the memory of the system dynamics, also these type of systems are robust due to the integral that involves the derivative. Moreover, non-integer order systems have an additional freedom degree due to the derivate order, all of these characteristics of the non-integer order systems represent an advantage for the reconstruction of signals. This means that non-integer order observer could be a good choice to develop fault detection systems based on analytical redundancy.

The aim of the present research is to show the design of a sensor FT control using fractional observers strategy, as well as to show the performance of the fractional observers using the RL fractional derivative definition in a heat transfer process.

2. Heat exchanger pilot plant

Fig. 1 shows the countercurrent double pipe HE pilot plant. Through the inner pipe flows hot water and by the annular space flows cold water. The aim of the HE is cooling the hot water. The cold water flow is controlled by the actuator 1 and the hot water flow is controlled by the actuator 2. Moreover, the HE has four temperature sensors of the type RTD Pt-100 and two analogical flowmeters.

For the temperature data acquisition and for controlling the pneumatic valves a National Instrument Data Acquisition Card was used, the data acquisition card has four input voltage channels and two output voltage channels. By a linear approximation algorithm and using the voltage signal, the heat exchanger temperatures are estimated. To carry out the control action on the pneumatic valves, the signal is converted from voltage to current, due the pneumatic valves work in a range between 4 and 20 mA.

Fig. 2 shows the countercurrent double pipe heat exchanger scheme, where T_{ci} and T_{co} represent the cold water inlet and outlet respectively and T_{hi} and T_{ho} represent the hot water inlet and outlet respectively. Table 1 shows the dimensions of the heat exchanger's pipes, and the characteristics of the sensors RTD Pt-100 are given in Table 2.

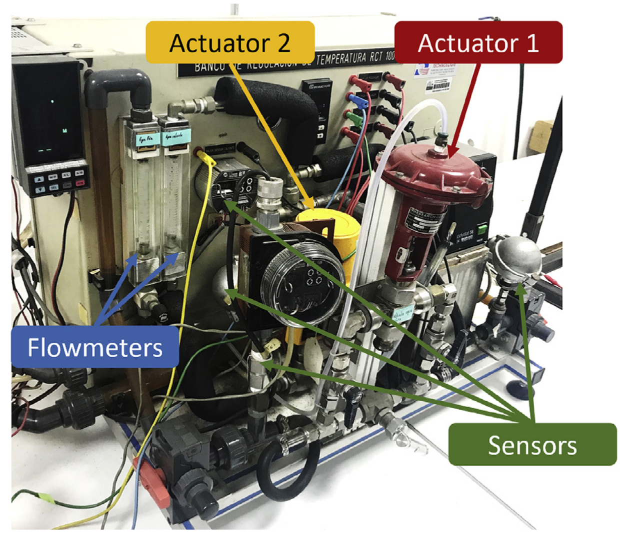

Fig. 1. Heat exchanger benchmark.

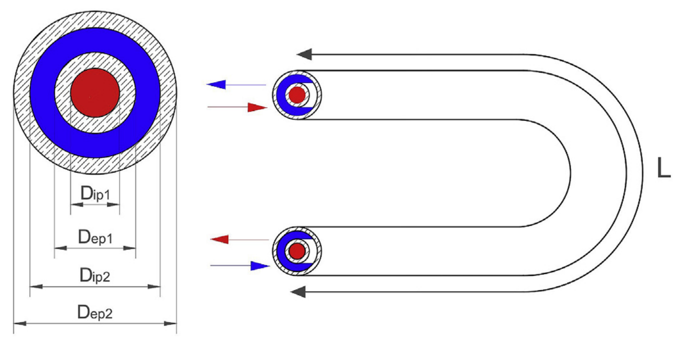

Fig. 2. Configuration of the heat exchanger.

Table 1
Dimensions of the heat exchanger.

Parameter	Value
L	790 mm
D_{ip1}	6 mm
D_{ep1}	10 mm
D_{ip2}	16 mm
D_{ep2}	20 mm

Table 2
Characteristics of temperature sensors.

Specification	Value
Temperature range	0 °C *to* 100 °C
Weight	50 g
Sensor output current	0.2 mA *to* 0.4 mA
Dimensions	44 × 20.2 mm
Diameter	20 mm

3. Mathematical preliminaries

In literature, different fractional derivatives definitions have been proposed, e.g., Riemann-Liouville, Grünwald-Letnikov, Liouville-Caputo, Atangana-Baleanu, among others [21–23]. The convolution of

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