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Bond Graph modeling for fault detection and isolation of a train door mechatronic system

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ABSTRACT

In this paper, monitoring and diagnosis of a new generation of train door mechatronic system is proposed. Bond Graph methodology is applied to obtain a reference model. In addition to this reference model, a global model based-FDI (Fault Diagnostic and Isolation) is developed for the generation of fault indicators and residual thresholds in presence of door failures. The ability of the proposed diagnostic approach to detect train door failures is demonstrated. The main contribution of this paper concerns the implementation of FDI procedure on a train door instead of health monitoring as it is usually performed in maintenance field.

1. Introduction

Technical processes are becoming more and more complex and if a fault occurs, safety may severely be affected, particularly in processes like aircraft, trains, automobiles, power plants and chemical plants (Isermann, 2005; Chen & Patton, 1999). Consequently, Fault Detection and Isolation (FDI) domain has received considerable attention during the last three decades (Patton, Franck & Clark, 2000).

FDI approaches are usually divided in two categories: data-driven and model-based methods. Successful applications of the data-driven FDI methods, in particular the multivariate analysis methods, have recently been reported in the process industry (Venkatasubramanian, Rengaswamy & Kavuri, 2003). The wide integration of powerful Supervisory Control And Data Acquisition (SCADA) systems has also promoted this development. Compared with the model-based FDI schemes, the performance of the data-driven methods is often limited in dealing with dynamic processes and FDI in feedback control loops. Also, most of the reported FDI applications are at the process component level, and limited to these "small-scale" processes (e.g., up to hundred sensors and actuators).

Model-based fault detection includes residual generation and residual evaluation (Svard, Nyberg, Frisk & Krysander, 2014). The major efforts in this area have been dedicated to the FDI in Linear Time Invariant (LTI) systems. As a result, a theoretical framework for design and analysis is well established (Isermann, 2006; Blanke, Kinnaert, Lunze & Staroswiecki, 2006; Ding, 2008). Lately, special attention has been given to fault detection approaches for Linear Parameters Varying (LPV) systems (Ponsart, Theilliol & Aubrun, 2010; Varga & Ossmann, 2014; Nazari, Seron & De Doná, 2013; Henry, 2013).

The current research focus in this area is on robustness (Keliris, Polycarpou & Parisini, 2015), nonlinear and hybrid system issues (Ding, 2008). In the past, efforts have also been made to extend the existing model-based FDI methodology to deal with problems in decentralized control systems (Menhiged, Yamé & Aubrun, 2010). Research has been carried out on those processes which are well modeled as interconnected LTI-subsystems, and the diagnosis is dedicated to the system components (Chun, Speyer & Chen, 2001; Yan & Edwards, 2007; Li, Gui, Xie & Ding, 2009).

Recently, model-based approaches have been successfully applied on railway system. A robust observer-based filter has been developed for a single-phase Pulse Width Modulated (PWM) rectifier for electric railway traction systems in (Youssef, El Khil & Slama-Belkhodja, 2013). An extended Kalman filter and a Luenberger observer have been investigated for electric vehicle power trains, and for a permanent magnet synchronous motors drive for faulty position or speed sensors in (Akrad, Hilarait & Diallo, 2011). Finally, (Dassanayake, Roberts, Goodman & Tobias, 2009) are the

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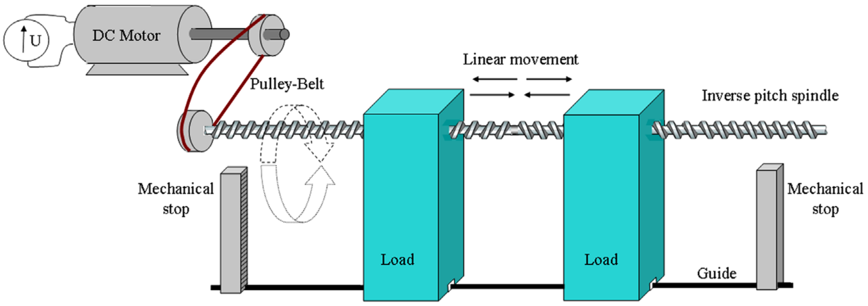

Fig. 1. Description of the mechatronic system.

only one to use parameter estimation for the detection and diagnosis of faults on electric train door systems. However, obtaining an accurate analytical model may be difficult in practice.

An alternative approach consists in establishing a Bond Graph model. Bond Graph modeling is a systematic method for modeling dynamic systems with different energy domains (Paynter, 1959; Borutzky, 2011; Mezghanni, Andoulsi, Mami & Dauphin-Tanguy, 2007), such as electrical, mechanical and hydraulic systems, in a unified framework. Bond Graph is quite intuitive since it is based on the energy conservation principle that generates system equations and graphical representation which facilitate design of FDI algorithms (Rosenberg & Karnopp, 1972).

In the recent research on the FDI of railway system, a fault monitoring framework based on combined use of data-driven and Bond Graph modeling for a locomotive electro-pneumatic brake has been developed in (Niu, Zhao, Defoort & Pecht, 2015).

Statistical studies reported in (Turgis, Copin, Loslever, Cauffriez & Caouder, 2009; Cauffriez, Loslever, Caouder, Turgis & Copin, 2013) point out that doors are responsible from 30% to 40% of the failures in commercial use. This is a problematic area that train manufacturers have to consider as it leads to societal and economical impacts. In particular, it implies not only costs due to delays but also financial penalties that must be paid by the train manufacturer to the railway operator. One of the major reasons is related to the current diagnosis of faulty doors which is made offline and outboard by the maintenance center and results in files containing a high amount of alarms and data. Therefore, this is an approach that takes time and for which it is difficult to find the cause of failures.

Within this context, the aim of this paper is to propose a solution to facilitate the detection and analysis of the door failures. The chosen approach deals with the introduction of a model-based FDI (Fault Detection and Isolation) in addition to the urban train reference model for the generation of fault indicators and residuals thresholds in presence of door failures.

As the modeling of train doors involves several domains of energy, the Bond Graph has been chosen for this study. Among the other multiple benefits provided by the Bond Graph formalism, it allows both causal and behavioral process analysis (Gawthrop, 1991; Borutzky, Dauphin-Tanguy & Thoma, 1995) and it is a graphical tool well adapted for diagnosis (Merzouki, Medjaher, Djeziri & Ould-Bouamama, 2007; Ould Bouamama, Medjaher, Bayart, Samantaray & Conrard, 2005; Samantaray, Medjaher, Ould Bouamama, Staroswiecki & Dauphin-Tanguy, 2006; Roberts, Balance & Gawthrop, 1995; Samantaray & Ghoshal, 2008). Compared to the conventional modeling approaches, the use of Bond Graph model allows dealing with structural control properties (controllability, observability, and invertibility) that are deduced from the causality relationships between causes and effects. Analysis of causal paths can identify problems in formulation of the model equations and also problems than one may face in numerical evaluations. Furthermore, causal properties of the Bond Graph model have been used to determine the origin of the consequences of the faults.

This article can be divided into four parts. First, a reference model for the modeling of the well-functioning of a train door mechatronic system is proposed in Section 2. Section 3 is dedicated to the analysis of current and position signals directly measured on a test bench in order to characterize real train doors behavior and to validate the reference model. Then a global model-based FDI is detailed in Section 4 and contributions to fault detection and isolation are developed. Section 5 focuses on simulation results for the characterization of residuals for certain internal and external failures of the train door. Finally, conclusions about this research work are given, pointing out the ability to detect internal and external failures for the proposed model-based FDI.

2. System reference model

2.1. Mechatronic system description

Fig. 1 illustrates the train door mechatronic system that can be naturally divided in five sub-systems:

1. The input voltage source *U*.
2. The Direct Current DC motor.
3. The Pulley-Belt PB.
4. The inverse Pitch Spindle S.
5. The load parts and guide.

Regarding its functioning, a positive (or a negative) value of the input voltage source *U* leads to a clockwise (anticlockwise) rotation of the “Pulley-Belt /inverse Pitch Spindle” subsystem resulting in a linear movement of load parts. Thus, both load parts are approaching or moving away depending on the direction rotation of the motor. Finally, the guide ensures a longitudinal displacement of loads until mechanical stops are reached.

2.2. Bond Graph modeling

Usually, the Bond Graph modeling requires first establishing the Word Bond Graph of the system. As this representation is a first level toward the energy map description of the system and its composition, a physical analysis of the system and its power interaction are sufficient to determine it. From Fig. 1, it makes sense to decompose the Word Bond Graph into 5 subsystems as shown in Fig. 2. Contrary to the classical block diagrams, the inputs and outputs of each subsystem define here power variables represented by a conjugated pair of effort-flow (e,f) labeled by a half arrow. For this specific application, power variables used are the followings:

$$(\text{Voltage, current}) = (U, i) \tag{1}$$