Mechatronics 47 (2017) 14–23

Contents lists available at ScienceDirect

Mechatronics

journal homepage: www.elsevier.com/locate/mechatronics

Design methodology of a reduced-scale test bench for fault detection and diagnosis[☆]

E. Esteban[a], O. Salgado[b,*], A. Iturrospe[c], I. Isasa[d]

[a] Mechanical and Manufacturing Department, Mondragon Unibertsitatea, Loramendi 4, 20500 Mondragon, Spain
[b] Mechanical Engineering, IK4-Ikerlan, J. M. Arizmendiarrieta 2, 20500 Mondragon, Spain
[c] Department of Electronics and Computer Sciences, Mondragon Unibertsitatea, Loramendi 4, 20500 Mondragon, Spain
[d] Mechanical Engineering, Orona EIC S. Coop., Orona Ideo, Jauregi bidea s/n, 20120 Hernani, Spain

ARTICLE INFO

Article history:
Received 30 July 2015
Revised 27 June 2017
Accepted 4 August 2017

Keywords:
Test bench
Dimensional analysis
Scaling law
Similarity
Diagnosis

ABSTRACT

Condition monitoring is a crucial task for electromechanical system reliability and quality enhancement, which leads to early electrical and mechanical faults detection. In this paper, the design of a scaled test bench including its main subsystem components at initial stage is presented for the assessment of new methods dedicated to electrical and mechanical faults detection and diagnosis in electromechanical systems. In this paper a design methodology is proposed for developing a reduced-scale test bench dedicated to condition monitoring. Dimensional analysis is applied for ensuring the similarity between the scaled test bench and the full-size systems to be emulated. In addition, the scaled test bench includes the required instrumentation as well as an acquisition platform for development of condition monitoring strategy to batch condition monitoring of full-size systems. Finally, the similarity is evaluated by comparing both the simulation and the experimental results.

1. Introduction

Condition monitoring for electromechanical systems has received increasing attention both from academia and industry during the last decade [1]. This development is motivated by the growing demands on cost efficiency, reliability and product quality of industrial electromechanical systems [2], being essential to reduce unscheduled downtimes and minimize operation and maintenance costs. In general, implementing condition monitoring in electromechanical systems requires to understand the dynamic behavior of the global system and its faults [3,4]. For this purpose, system identification techniques combined with experimental testing is usually required [5]. These techniques can be classified according to model-based or data-driven approaches [6,7]. Data-driven approaches [8] are suitable for applications where a limited *a priori* knowledge of the monitored system is available [9,10]. The performance of data-driven approaches is also highly dependent on the quality and the quantity of the available data [11,12]. Regarding model-based approaches, they rely on the availability of a mathematical model for the monitored system, which can be derived from physical modeling principles [13]. The performance of model-based techniques depends on a large extent on the accuracy of the model when describing the dynamics of interest [14]. Model-based approaches have been successfully employed for electromechanical systems monitoring and control applications [15–18]. Nevertheless, both model-based and data-driven approaches make use of data from available sensor measurements.

In this paper the studied electromechanical system is a roped 1:1 elevator [19]. An elevator installation comprises both a mechanical subsystem and an electrical subsystem, as it is shown in Fig. 1. The mass of the elevator car is balanced by a counterweight in order to reduce the torque demanded by the machine. An electrical machine drives the system through a pulley onto the suspension ropes which interconnect the elevator car and the counterweight. Both the car and the counterweight move vertically, constrained by a pair of rails each. The installation shown in Fig. 1 is driven by an electrical machine which is controlled using a field oriented control (FOC), where the velocity signature profile is generated for each ride, depending on the starting car position and its final destination.

Despite of several attempts, the application of novel signal processing methods for condition monitoring of elevator installations are still an active field of research. The development of new methods dedicated for elevator condition monitoring needs a validation before its installation on a real elevator. Currently, there is a wide range of elevator dimensions and the validation of new methods

[☆] This paper was recommended for publication by Associate Editor T. H. Lee.
* Corresponding author.
E-mail address: osalgado@ikerlan.es (O. Salgado).

http://dx.doi.org/10.1016/j.mechatronics.2017.08.005

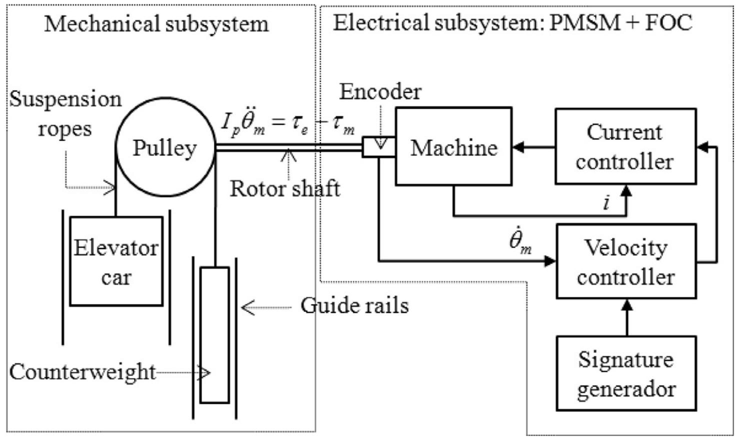

Fig. 1. Simplified schematic description of an elevator installation.

Table 1
Value range of the elevator dimensions.

Range	l [m]	m_l [kg]	v [m/s]	a [m/s^2]	j [m/s^3]	t [s]
min	3	0	1	0.7	1	5
max	45	630	1	0.7	1	35

in them can be laborious or even time-consuming to perform [20]. The range of 1:1 elevator dimensions to be validated is summarized in the following Table 1. The dimensions of these elevator installations range from one floor building (3 [m]) up to fifteen floor buildings (45 [m]) whereas the range of the car load varies from 0 [kg] up to 630 [kg]. The rated speed, acceleration and jerk of the electrical machine are assumed to be equal for all 1:1 elevators.

In order to reduce the effort of performing test and facilitating the validation of new methods, a test bench can be designed with the capacity of emulating all the elevator dimensions of Table 1. The specifications of this table involves that the test bench needs to be designed for emulating different mechanical subsystems dimensions while maintaining the electrical subsystem.

Designing a test bench based on the aforementioned requirements cannot be done in an *ad-hoc* manner as demonstrated in other test bench designs with similar requirements in transportation systems [21–25]. In these test bench designs, the dimensional analysis [26] is proposed as a tool for designing scaled test benches which are equivalent to real systems. The reason to use dimensional analysis is that it is strongly based on concepts of similarity and that similitude has been proved to play a central role in designing equivalent systems [27–32].

This paper aims to design a scaled elevator test bench for performance assessment of condition monitoring techniques. With the application of dimensional analysis, could be possible to form dimensionless groups and formulate scaling laws in order to ensure the similarity between the test bench and the full-size elevator installation to be emulated [33]. In addition, the design of the scaled elevator test bench includes the design solution of both the mechanical and the electrical faults which are going to study using the developed condition monitoring techniques [34]. Regarding the faults, the electrical type of faults included in the design of scaled test bench are the torque ripple [35] and the encoder phase error, whereas the mechanical type of faults are the elevator car-rail and counterweight-rail misalignment [36], the sliding shoe friction conditions [37], rope prognosis [38], and the elastomeric mount characterization [39].

The rest the paper is organized as follows. Section 2 describes the similarity conditions required to design a versatile elevator scaled test bench. In Section 3 the dimensional analysis are obtained and the scaling laws are derived. Section 4 addresses the design solution of the scaled test bench. Finally, in Section 5, fifteen real elevator are emulated in the scaled test bench and they are evaluated by equivalent elevator simulations.

2. Similarity

A scaled test bench is similar to a real application if both the scaled test bench and the real application share geometric, kinematic and dynamic similarity [40]. Similarity is achieved when testing conditions are created such that the test results are applicable to the real design. The following three criteria are required to achieve the similarity:

- Dynamic similarity. Dynamics deals with forces. Two bodies are dynamically similar if their corresponding bodies experience the same forces in corresponding times. The force includes mainly concentrated force, distributed forces and torques. The physical modeling principles is usually employed to describe the system dynamic response [41].
  In the use case selected, the dynamic similarity criteria can be obtained by modeling the dynamics of the elevator installations. A simple vertical dynamic model of an elevator [42], is shown in Fig. 2. This model comprises two lumped masses (the car and the counterweight), a mass-less driving pulley and two springs.
  The imbalance between the elevator car and the counterweight exerts a torque in the pulley that is actively balanced with the electromagnetic torque applied by the machine. The mechanical and electrical subsystems are coupled by the following torque balance equation,

$$\tau = r\,(f_w - f_c) \tag{1}$$

where τ is the torque exerted by the machine and the rope tensile force on the car side and counterweight side are denoted by f_w and f_c respectively. Based on the force balance in each inertial element, the equations that govern the system dynamics are expressed as,

$$f_c = m(g + a) + f_{rc} \tag{2}$$

$$f_w = m_w(g - a) - f_{rw} \tag{3}$$

where the car-rail and counterweight-rail friction forces are denoted by f_{rc} and f_{rw} and the elevator car and counterweight