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Health monitoring system for transmission shafts based on adaptive parameter identification

I. Souflas, A. Pezouvanis, K.M. Ebrahimi *

Department of Aeronautical and Automotive Engineering, Loughborough University, Loughborough, UK

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ABSTRACT

A health monitoring system for a transmission shaft is proposed. The solution is based on the real-time identification of the physical characteristics of the transmission shaft i.e. stiffness and damping coefficients, by using a physical oriented model and linear recursive identification. The efficacy of the suggested condition monitoring system is demonstrated on a prototype transient engine testing facility equipped with a transmission shaft capable of varying its physical properties. Simulation studies reveal that coupling shaft faults can be detected and isolated using the proposed condition monitoring system. Besides, the performance of various recursive identification algorithms is addressed. The results of this work recommend that the health status of engine dynamometer shafts can be monitored using a simple lumped-parameter shaft model and a linear recursive identification algorithm which makes the concept practically viable.

1. Introduction

Transmission shafts are responsible for transferring kinetic energy between rotating components and machines. Applications can be found in different engineering areas such as power generation plants, machine tool spindles, robotics, marine, aeronautical and automotive propulsion systems. Depending on the purpose of the application, coupling shafts can be designed with different characteristics to satisfy the needs of the user. One of the absolute minimum requirements for every application is the safe and reliable operation of the shaft. Therefore, it is of major importance to be able to monitor the health status of rotor shafts to avoid catastrophic damages.

The condition monitoring of coupling shafts is a well investigated area, and as a result numerous reliable solutions can be found in literature. More specifically, the effectiveness of signal-based techniques using vibration measurements and spectrum or wavelet analysis has been reported in several studies [3,24,27,6]. Various model-based approaches have also been presented, Castejón et al. [5] presented the use of artificial neural networks and multiresolution analysis for the automatic detection of rotor cracks. Sekhar [18] showed an online model-based condition monitoring approach based on a rotor-bearing system redundant model using a Finite Element Model (FEM). The combination of FEMs and online system identification procedures has also been proven to be an effective tool for the detection of shaft damages [16,17]. State of the art fault detection techniques are based on the identification of parameters with physical interpretation that can be found commonly in FEMs using various type of the Kalman filters [28,9,26,4]. In addition, several articles have demonstrated the effectiveness of non-linear estimators [8,12,13] for monitoring the state of mechanical and electro-mechanical systems [7,21,22].

* Corresponding author.
E-mail address: K.Ebrahimi@lboro.ac.uk (K.M. Ebrahimi).

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This paper focuses on the use of physically oriented models and linear Kalman filtering for the health monitoring of engine dynamometer shafts. However, the proposed coupling shaft health monitoring methodology is significantly simpler than the previously reported approaches. In particular, instead of using FEMs and non-linear recursive identification algorithm e.g. Extended Kalman Filter (EKF) or Unscented Kalman Filter (UKF), a simple lumped-parameter coupling shaft model and a linear recursive identification algorithm are employed. This makes the monitoring system practically viable and more robust. Additionally, it is important to highlight that the proposed solution does not require any model training exercise compared to FEMs where experiments are need prior to the application to parameterise the models.

As aforementioned the proposed method is based on the on-line identification of two physical characteristics i.e. stiffness and damping coefficients, of a coupling using measurements that can be found commonly in industrial engine testing facilities. More specifically, these measurements are the speed and position of the dynamometer and engine separately, and the torque acting on the shaft. A schematic overview of the suggested monitoring system is presented in Fig. 1.

The paper is arranged as follows. Firstly, a lumped-parameter dynamic model of a transient engine testing facility is derived. Secondly, candidate adaptive parameter identifications algorithms are introduced. Thirdly, details on the practical implementation of the suggested condition monitoring system are discussed. Then, experimental and simulation results are presented, verifying the functionality of the proposed shaft health monitoring system. Finally, based on the faced challenges and the results of this work, some conclusions and potential future directions are outlined.

2. Theoretical principles

The theoretical preliminaries that are required for the successful practical implementation of the proposed system are discussed in this section.

2.1. Engine dynamometer shaft modelling

The suggested on-line condition monitoring system is based on a simple engine dynamometer shaft lumped-parameter model and the continuous tracking of its physical parameters using recursive identification algorithms. Considering the engine dynamometer shaft as a two degree of freedom rotating system, the free body diagram is drawn as in Fig. 2.

Assuming that the dynamometer is the primary source of the system and that the moment of inertia of the shaft is smaller than the moment of inertia of the dynamometer and the engine [23], the principle governing equations of the system can be expressed using state-space formalism.

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) \\ y(t) &= Cx(t) \end{aligned} \tag{1}$$

here, system's output (y), inputs (u) and states (x) are:

$$y = \tau_{sh}, \quad u = [\,\tau_{dy} \quad \tau_{en}\,], \quad x = [\,\tau_{dy} \quad \theta_{dy} \quad \omega_{dy} \quad \theta_{en} \quad \omega_{en}\,]^T$$

whilst, the parameters of the state-space coefficients are given bellow:

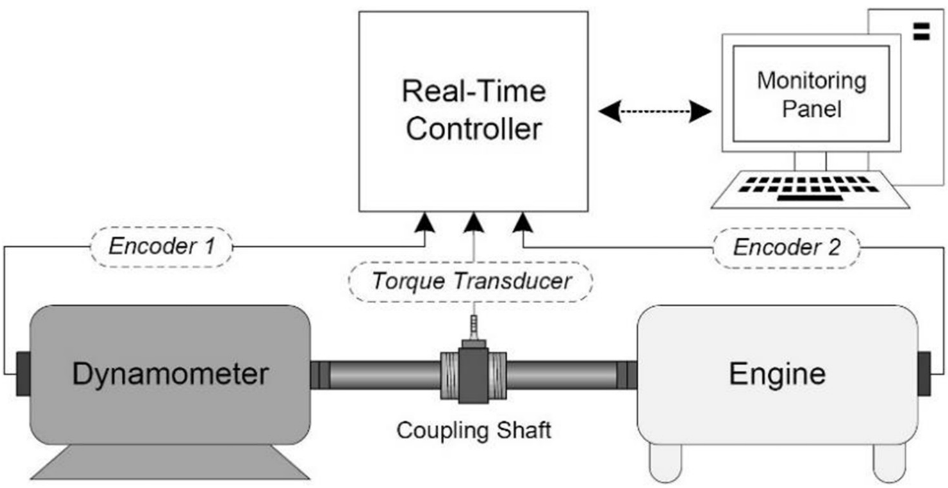

Fig. 1. Conceptual diagram of the engine dynamometer shaft health monitoring system.