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Unified Multi-speed analysis (UMA) for the condition monitoring of aero-engines

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For rotating machinery in which speeds and dynamics constantly change, performing vibration-based condition monitoring can be challenging. Thus, an effort is made here to develop a Unified Multi-speed fault diagnosis technique that can exploit useful vibration information available at various speeds from a rotating machine in a single analysis. Commonly applied indicators are computed from data collected from a rig at different speeds for a baseline case and different faults. Four separate analyses are performed: single speed at a single bearing, integrated features from multiple speeds at a single bearing, single speed for integrated features from multiple bearings and the proposed Unified Multi-speed analysis. The Unified Multi-speed approach produces the most conspicuous separation and isolation among the conditions tested. Observations made here suggest integration of more dynamic features available at different speeds improves the learning process of the tool which could prove useful for aero-engine condition monitoring.

1. Introduction

It is recommended that machine speed remain constant when conducting vibration-based condition monitoring (VCM) of rotating machinery. Typically, during the VCM process, diagnostic features are extracted at a particular speed and compared to a healthy (baseline) feature previously generated at the same speed. This is necessary because features may be sensitive to machine speeds and changes in these relative to the baseline could signify the presence of a fault. Thus, it is imperative to ascertain whether a change in the feature is due to a fault or speed fluctuations by mitigating the effects of any speed fluctuations [1]. However, on complex machines like aero-engines where speeds constantly change under normal operating conditions, performing VCM during constant speed is a fundamental challenge.

Current practice shows the selection of data in the most steady state condition available; say during idle or cruising [2], but accurate fault diagnosis (FD) is not guaranteed; since fault signals are oftentimes fleeting and replete with noise [3]. Normalization of diagnostic features with respect to speed is also often employed, but this can be complex and usually leads to less accurate or less robust fault detection [2]. In a review of aircraft engine health monitoring systems, Tumer and Bajwa [4] cited that tools which better discriminate engine healthy from faulty states using the wealth of data available from existing aero-engine management systems are lacking. More recently, to bridge this gap, numerous works have been done

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on improving aero-engine vibration-based FD [5–8]. These, however, still remain somewhat digressed from the current needs of industry [6].

Of the readily accessible literature, few researchers have sought to develop methods that are applicable during transient operations. Barragan [9] proposed a vibration monitoring system (VMS) that processes data acquired during engine acceleration and deceleration for the diagnosis of unbalance and misalignment faults. Fault detection was achieved by comparing "vibration patterns" from several selected indicators generated in time waveform and waterfall diagrams to a library of known patterns of engine faults. The method relies on a Finite Element Model for FD. Thus, the method may not be robust; since it is widely held that generating a FE model which accurately reflects the true dynamics of a machine for confident FD is difficult. Modgil et al., [10] suggested an advanced vibration diagnostic system for engine test cells which sampled data from engine idle to full power. Similar to Barragan [9], FD was achieved predominantly with Waterfall diagrams of the spectrum. VCM techniques based on transient operations are good during aircraft landing and takeoff, but efforts based on the waterfall diagrams are grouping data generated in the amplitude spectra at different speeds with diagnosis being based at a single speed, which may not be useful in continuously changing speed conditions. On a slightly different note, Grabill, et al. [11] developed an advanced airborne Turbine Engine Diagnostic System (aTEDS) for the C17/F117 aero engines. The system automatically triggered vibration data collection and processing during acceleration, deceleration and steady state speeds for the diagnosis of a comprehensive list of faults. Though the system was intelligent, its FD capabilities were predominantly based on normalization of time domain features at a single speed and on features extracted from the amplitude spectra, both of which do not guarantee accurate fault detection [2].

Despite the promising developments of efforts based on transient operations, the fundamental techniques used for processing of data may not be useful during continuous operations with varying speeds. Hence, a technique which is insensitive to changing speeds is warranted. Therefore, an effort is made in the current study to develop a simple but confidence inspiring approach that fuses data acquired at different steady state speeds in a single analysis step.

Experiments were done on a small ball bearing laboratory rig [13,14] with rigidly coupled dissimilar length shafts. A healthy (baseline) condition was first tested followed by the separate introduction of crack, misalignment and rotor rub faults. On-bearing vibration data were collected at different subcritical steady state speeds. Recent developments [13–15] used fewer sensors than standard practice for vibration fault diagnosis at a single speed. Similarly, for all conditions tested, only one vibration measurement per bearing is employed in the current study. These vibration signals were processed to compute commonly applied condition indicators (features) for each bearing location. Fusion of these indicators and subsequent classification of the different faults, with respect to a healthy state, was achieved with a Principal Component Analysis (PCA) based algorithm. Brotherton et al. [16] and Nembhard et al. [13] demonstrated the potential for rotating machinery fault classification with PCA, and as such it is employed in this study. To demonstrate the robustness of the multispeed technique it was compared to other analyses done at a single speed and multi-speed. It was observed that the Unified Multi-speed approach produced improved separation and isolation of the conditions tested than other analyses done.

A brief description of the experimental set up and data collection method is given in Section 2. This is followed by an overview of the effects of speed change on the simple amplitude spectra in Section 3. The theoretical basis for the method introduced in the present study is highlighted in Section 4. Section 5 provides a synopsis of the data processing done. In section 6, the results of proposed Unified Multispeed method is given in addition to its comparison with other analyses done at a single speed and multi-speed. Lastly, a brief discussion of results is given and concluding remarks are made in Sections 7 and 8 respectively.

2. Experimental set up

Fig. 1 shows a photograph of the small experimental rig, located in the University of Manchester (UK) Dynamics Laboratory. The rig consists of two 20 mm nominal diameter rigidly coupled (Coupling 2) dissimilar length shafts of 1010 mm (Rotor 1) and 500 mm (Rotor 2) that are secured to a steel lathe bed by four pillow block ball bearings (Model: SKF SY504M). Machined sections that accommodate balancing disks (125 mm in diameter and 14 mm thick) are mounted on each shaft. System drive is produced by a 3000 rpm 0.70 kW 3 phase motor that is coupled to the rotating assembly via a semi-flexible coupling (Coupling 1). The impulse response method of modal testing [17] was done to identify the dynamic characteristics of the test rig. The first two natural frequencies were identified at 67.14 Hz and 142.2 Hz. The mode shapes corresponding to these natural frequencies are provided in Fig. 2. A sample of the measured Frequency Response Function (FRF) obtained from the modal analysis is shown in Fig. 3.

Experiments were conducted at steady state rotating speeds of 600 rpm (10 Hz), 1200 rpm (20 Hz), 1800 rpm (30 Hz), 2400 rpm (40 Hz) and 3000 rpm (50 Hz), to evaluate the impact of steady state speed changes on the results obtained. Note that all experiments were conducted below the first critical speed of 4028.4 rpm (67.14 Hz). With one condition tested at a time, a total of three different fault conditions were introduced to the rig; crack, misalignment (M) and rotor rub. Rub condition was simulated near Bearing 4 (R4). Cracked rotor was tested in three different locations; near Bearing 1 (C1), near Bearing 2 (C2) and near Bearing 3 (C3). Additional details of the experimental set up, including instrumentation can be found in [13].