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An improved electromechanical spectral signature for monitoring gear-based systems driven by an induction machine

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ABSTRACT

Even under normal operating conditions, Gear-based systems naturally generate four particular frequencies: the input and output mechanical speeds as well as the gear meshing and the hunting tooth frequencies. Thereby, through amplitude monitoring of these components and their harmonics, the gear state can be easily monitored and successfully assessed. Based on this fact, this paper discusses the fitness of the vibration data and the load torque (mechanical signature) to detect these frequencies. Furthermore, when the system is driven by an induction machine these frequencies will affect the stator currents. Thus, the appropriateness of the spectral analyzing techniques based such amounts as alternate for monitoring gear-based systems will also be discussed. Moreover, for improving the sensitivity detection of these particular frequencies an original preprocessing technique is proposed and its effectiveness is evaluated for spectral analysis of mechanical as well as electrical experimental data.

1. Introduction

For a long time, gearboxes have been involved in several mechatronics systems for adapting the movement transmission of a driving to a driven shaft. Given this key role in many kinematic drivelines, the state assessment of gearboxes has become a challenging industrial task to detect any possible incipient abnormality that can occur before spreading and affecting the shaft scraps. Most known defects that may affect gearboxes are shaft misalignment, gear eccentricities, and tooth fatigue. Under such conditions, the performance of the affected gear system deteriorates and the desired motion transfer deviates from the intended one. Moreover, when a gear fails for any reason the resulting damage may affect either all the teeth on a gear or only a few ones.

For a preventative condition-based maintenance, the early fault detection prevents an extended period of breakdown caused by the extensive system failures, and allows a better arrangement of curative maintenances during scheduled downtimes. Thereby, it is crucial to detect any possible failure occurrence through online measurements. Indeed, condition monitoring techniques let increasing availability and performance, reducing consequential damage, increasing machine life, reducing spare parts inventories, and reducing breakdown maintenance. An efficient condition monitoring scheme should be able to provide warnings and to predict failures at early stages. For this main purpose, many methods have been proposed and reported in the literature.

Traditionally, gearbox has been monitored by tracking the meshing frequency magnitude through various processing techniques of the vibration data. Hence, time–frequency (TF) amplitude and frequency demodulation analysis have been proposed to identify the characteristic frequency of gear faults, while avoiding complex time-variant sideband analysis [1]. In [2], the authors have proposed a TF technique based on Kalman filter and higher order energy separation for extracting the fault symptoms and distinguishing the time-varying behavior of the characteristic fault frequencies from complex non-stationary vibration data. Also, the TF techniques have been proven efficient for speed monitoring of three-phase synchronous generators [3]. Furthermore, a transient feature extraction technique based on sparse representation in wavelet basis has been suggested for gearbox fault diagnosis [4]. Other diagnosis methods have been entrusted to the empirical mode decomposition techniques order to decompose vibration data into meaningful

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signal components associated with specific frequency signal bands [5]. In [6], authors propose the independent angular re-sampling technique using vibration to diagnose gearbox faults under non-stationary conditions. The angular domain signals, each representing one revolution of the gearbox-driving shaft, are then decomposed with continuous wavelet transform. In [7], a single piezoelectric strain sensor is used for planetary gearboxes fault diagnosis. In [8], an acoustic emission sensor-based planetary gearbox fault diagnosis method is presented.

Despite the proven efficiency of vibration analysis for monitoring gearbox faults, the involved sensors are of relatively high cost and their mounting on the frame of the target equipment is not always simple. Hence, in the particular case of a gearbox driven by an induction motor, other fault signatures based on the motor current signature analysis (MCSA), the mechanical torque, and the stator current space vector (SCSV) have been proposed in the literature. These techniques have been widely used for the induction motors fault diagnosis. However, in [9] the authors propose an induction motor fault diagnosis method using a condition monitoring architecture based on stator current measurements and high-resolution spectral analysis techniques, also known as subspace techniques. The effectiveness of MCSA as an alternate that could replace the conventional vibration data-based analysis for monitoring multistage transmission gearbox has been widely investigated. In [10], the authors have shown the effectiveness of MCSA technique for diagnosing multistage gearboxes. Within this context, they have proposed demodulation techniques of the amplitude and the frequency for detecting the rotating shaft frequencies as well as the gear meshing frequency (GMF) related to the gearbox. In this context, the authors of [11] have shown that while high frequencies of the vibration signature are difficult to be detected, low frequencies have involved sidebands close to the line frequency of the stator current. On the other hand, effects of torsional vibrations on the electrical signature of an induction machine involved in a simple gearbox-based electro-mechanical system have been studied through a modeling approach. From this perspective, in [12] the authors have shown that MCSA is accurate enough to be used as a function of gearbox parameters and can give information about mechanical stresses. Moreover, under a damaged surface condition of a gear-tooth, an oscillation of the motor torque profile may occur. Thereby, in [13] the authors have proposed a theoretical framework based on the torque oscillations initiated by the characteristic torsional vibrations of a gearbox. They have particularly presented the source of the mesh and the rotating frequency components into the machine stator current. Furthermore, by considering the instantaneous frequency of the SCSV a non-invasive fault diagnosis technique has been suggested in [14]. The authors have proposed a fault index based on the energy initiated by the frequency modulation effect observed in the SCSV related to a gear tooth with damaged surface. In [15], a fault detection scheme has been proposed, based on the line current and the electromagnetic torque estimation, which tracks mechanical faults known as backlash phenomena appearing between the pinion and the girth gear of a single cement kiln drive. But this method generates an additional cost and size of the monitoring system, given the use of a large number of sensors. This may degrade the reliability of the proposed scheme. In [16], doubly-fed induction generator stator and rotor current signals are processed in time and frequency domain. These features are used as the inputs of multiclass support vector machines for gearbox fault mode identification. In [17], the resonance residual method is applied to MCSA, around the resonance frequency, to detect planetary gearbox faults.

Given the above-discussed literature context, this paper proposes to analyze the effects of gearbox faults on the frequency responses related to the vibration data, the load torque, the MCSA, the zero-sequence component (ZSC), and the SCSV. Moreover, a new analyzing technique based on the data preprocessing by calling for discrete cosine and sinus transforms (DCT & DST) will be proposed to monitor gear-based systems.

2. Basic theory

2.1. Gearbox characteristic frequencies

For a given gear-based systems (i.e. gearbox), if we assume that the two gears are with Z_i and Z_o teeth, respectively, and rotating with the respective frequencies f_i and f_o, the related GMF will be expressed by [13]

$$f_m = Z_i. f_i = Z_o. f_o \tag{1}$$

2.1.1. Gear tooth profile

Ideally, gearing system is intended to transmit mechanical power between two close together shafts at constant angular velocity ratio. To obey the fundamental law of gearing, this constancy must be ensured throughout the contact between two teeth. In this respect, the gear geometry is appropriately designed to guarantee continuous motion while avoiding collision. To satisfy these conditions, the involute gear profile still be the most commonly used system. Indeed, with such geometrical form the contact between a pair of gear teeth occurs at a single instantaneous point moving along the tooth flank (profiles are conjugate: i.e. are constantly tangent). Thereby, when teeth are supposed absolutely rigid and with no geometrical errors, under assumption of no friction the torque will be perfectly transmitted and no force variations would occur during the contact cycle. Thereafter, no vibrations can be initiated [18]. Yet, since the contact stiffness cannot be infinite, the tooth deflection resulting from the load effects is added to the geometrical profile errors caused by wear or by the initial machining process and contributes to the tooth profile deviations [19]. These sources of deviation constitute the two main components of the gear transmission error (TE) that is inevitable even for a healthy state of the gear.

2.1.2. Gear vibration spectrum

Given the gear contact ratio, the load will be shared between different teeth numbers. Hence, following the variation of the number of tooth pairs in contact, the compliance will be no longer constant yet it will undergo periodic change leading to oscillation at the meshing frequency. Indeed, whenever a tooth of the pinion engages into the driven wheel, a cyclic load occurs at the teeth engagement rate. Therefore, the driven wheel will undergo self-excited angular vibration leading to time-varying of the couple of forces jointly acting along the line of action and at the driven shaft support point. Thus, the gearbox housing will be excited and generates vibrations [20]. Hence, the vibration spectrum related to a healthy gear will show the GMF and its harmonics. Indeed, at each time period $1/f_m$ one tooth is being in contact with the meshing point and during its passage it generates a tooth meshing signal $d_m(t)$ of stepped shape [19], which is transient by its nature [21]. Since the TE constitutes the primary cause of gear vibrations, the $d_m(t)$ can be viewed as a weakened shock signal [22] modeling the TE effect during one cycle. Therefore, the meshing waveform $x_m{}^0(t)$ may be described by an infinite sum of shifted and regularly spaced waves expressed by:

$$x_m^0(t) = \sum_{k=-\infty}^{+\infty} d_m(t-k/f_m) \tag{2}$$

This signal can be viewed as the succession of a filter impulse-response to a cadence of $d_m(t)$. Hence, to express its periodicity the Dirac comb (δ) can be used to rewrite (2) through a convolution product:

$$x_m^0(t) = d_m(t) * \sum_{k=-\infty}^{+\infty} \delta(t-k/f_m) \tag{3}$$

In the following, we note $D_m(\nu)$ (respectively $X^0{}_m(\nu)$) the Fourier transform of $d_m(t)$ (respectively $x^0{}_m(t)$). Rewritten into the frequency domain, the previous equation gives: