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On the identification of the angular position of gears for the diagnostics of planetary gearboxes

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ABSTRACT

Generally, in planetary gearbox diagnostics, vibration transducers are placed on the gearbox case near the ring gear. The relative angular position of the planet gears with respect to the transducer is a useful information for the evaluation of vibration signals related to planet/sun gears. This angular position is usually unknown, or it is known with a large tolerance causing serious difficulties in both gears and bearing diagnostics. In fact, noise and spurious component from healthy planets could overhang the informative content about incipient faults. The present work seeks to propose two alternative methods for the identification of the angular position of the planet gears with respect to the transducer. The first one is based on the study of how the power flows inside the Time Synchronous Average of the ring gear, whilst the second method is based on a modified statistical parameter such as the Crest Factor. The effectiveness of these methods is assessed on the basis of actual vibration signals acquired from a faulty planetary gearbox. The knowledge of the exact angular position of the planet gears allows the diagnostics of both gears and bearings, as proven by extensive experimental activities reported in the paper.

1. Introduction

Bearings and gears are probably the most common components in rotating machines. Since they are functional for the dynamics of the rotating parts, an incipient fault could lead to a sudden break of the machine. Thus, possible consequences are safety problems, irreparable damage of the machine, and high costs of non-production that normally exceed the cost of the machine. Consequently, the diagnostics of these components has always played a great interest in both academy and industry. The study of failure detection in bearings started over two decades ago, embracing a crowd of signal processing techniques which deals with several domains, from time to time–frequency. An emerging interest has been reported on modelling rotating machine signals as cyclostationary [1], which embodies a particular class in the realm of non-stationary stochastic processes [2]. From the pioneering work of McCormick and Nandi [3] the principles of cyclostationarity have become the state-of-art in bearing diagnostics [4]. Above all, Antoni in [5] discusses which cyclic spectral tool is the most suitable for the localised fault detection in ball bearings. In particular the operator that describes how the power flows within the signal was introduced by Antoni a few years ago [6]. Diagnostics becomes more complex when bearings and

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gears are coupled together as in gearboxes. Among them the class of planetary gearboxes is probably the most challenging. The difficulty of extracting the bearing characteristic fault frequencies of a planetary gear bearing stems from two factors. First, transducers may only be placed on the exterior of the gearbox, usually rather far from bearings. Second, the rotational axes of the planet gears are not fixed, i.e. they move with respect to the gearbox housing and thus to the transducers. As a result, the vibration signature of the planet gear bearings can be altered by the variable transfer path. In this scenario, standard signal processing techniques fail, and the characteristic bearing fault frequencies cannot be extracted from the vibration signals. For example envelope analysis, which is a widely used technique, could fail due to spurious components that overhang the fault signature. Indeed the working conditions of a specific gearbox could increase or reduce the fighting chance of the standard technique. Time synchronous averaging (TSA) has been shown to be a useful tool for extracting gear mesh vibrations from composite vibration signals since it enables the extraction of periodic signals from noise-polluted signals [7–9]. The resulting vibration signal corresponds to one complete revolution of the gear under consideration, and thus changes in the vibration waveform due to damage on individual teeth can be identified. The application of the TSA for the extraction of periodic waveforms in ordinary gearbox was proposed by Braun in the mid-70s [7]. However, such TSA techniques relate to gears with fixed vibration transfer paths from the source of the vibration to the transducer. In planetary gearboxes, the vibration transfer path is not fixed but it is subjected to variation due to the relative motion of the planet gears with respect to the transducer.

A technique for the evaluation of the TSA vibration signals associated with the sun and planet gears of a planetary gearbox was proposed by McFadden in the early 90s [10]. Such a work demonstrates that, for planetary gearboxes with certain geometric properties, the averaged vibration signals can be extracted from a vibration signal captured by a single fixed-frame transducer. Subsequent studies validated McFadden's research and presented slight variations on the technique [11,12]. Samuel and Pines [12] incorporate the use of multiple sensors in the evaluation of planet and sun gear TSAs. The use of multiple sensors overcome several limitations such as (i) capturing all the teeth of planet and sun gear in planetary gearboxes with non-appropriate geometric properties, (ii) reduce the time required for performing the planet and sun gear TSAs and (iii) increasing the robustness of the extraction method in case of sensor failure. However, the fundamental methodology remains unchanged; moreover [12] does not focus the attention on the evaluation of the relative position between planet gears and transducer.

The TSA of the planet/sun gears can be obtained if and only if, the relative position of the planet gears with respect to a transducer placed on the ring gear is known a priori. In [13] McFadden suggested that the position of each of the planet gears with respect to the transducer could be estimated directly from the TSA of the ring gear by identifying the locations of the maximum vibration amplitude. This identification could be more effective from the amplitude modulated signal of the ring gear. For small planetary gearbox, this approach could be not effective and the planet position cannot be identified leading to a poor evaluation of the planet gear TSA, as outlined in the following.

This paper focuses on fixed ring gear epicyclic gear train working on the hypothesis of steady speed. In particular two alternative methods are proposed for the precise identification of the position of each of the planet gears with respect to the transducer. Once the vibration signal related to each gearbox components is determined, diagnostics of gears is straightforward by means of anyone of the established method proposed in the literature. Moreover, also the diagnostics of the gearbox bearings is now possible, since Cyclic Power technique works on a vibration signal which is free from components other from the one under study. The aim of this paper is to propose a methodology for the diagnostics of a planetary gearbox as a whole, including both gears and bearings.

The paper is organised as follows. After a brief introduction and problem statement given in this section, the TSA algorithm proposed by McFadden is outlined in the next. The two proposed methods for the evaluation of the planet gear positions are presented in Section 3. The effectiveness of the proposed diagnostics methods is discussed on the basis of real data in Section 4 for both gears and bearings. Section 5 addresses the concluding remarks.

2. Background on TSA in planetary gearbox

McFadden and Smith [14] have demonstrated that as a given planet gear approaches the transducer, the measured vibration level increases, while as the planet gear moves away from the transducer the measured vibration level decreases. Let introduce $h(t)$ the transfer function between the transducer and the planet gear, with a period of one carrier revolution T_c, Fig. 1. Thus, planet signal $x(t)$ as seen by transducer j is given by $h_j(t)x(t)$.

In order to extract the planet/sun signal McFadden stated that [14]: "*when a given planet gear is near a transducer, the vibrations measured by the transducer are dominated by the meshing of that specific planet gear with the sun and ring gears*." Thus, during each passing of a given planet, a small data window can be collected. It can be assumed that over the width of such a window, the transfer function between the accelerometer and the region of tooth contact will remain constant. The planet gear teeth in mesh can be determined at each carrier revolution, and the window of data can be stored in a buffer according to the meshing tooth. This process is then repeated several times, in order to obtain a window of data for each tooth of the planet gear. The so arranged buffer includes the vibration signal for a complete revolution of the planet gear. Several buffers can then be averaged in order to obtain the TSA signal of the gear of interest, Fig. 2.

Mathematically speaking, let define a windowing function centred at time $t = nT_c$, where n is an integer number. The time at which $h_j(t)$ reaches its maximum is defined by $v(t - nT_c)$, Fig. 1(c). The subsequent windowed vibration signal is given by