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Vibration based condition monitoring of a multistage epicyclic gearbox in lifting cranes

Bassel Assaad [a], Mario Eltabach [a,*], Jérôme Antoni [b]

[a] Centre Technique des Industries Mécaniques, CETIM, 52 av Félix Louat, BP 80067, 60304 Senlis Cedex, France
[b] Vibrations and Acoustic Laboratory, University of Lyon, F-69621 Villeurbanne Cédex, France

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A B S T R A C T

This paper proposes a model-based technique for detecting wear in a multistage planetary gearbox used by lifting cranes. The proposed method establishes a vibration signal model which deals with cyclostationary and autoregressive models. First-order cyclostationarity is addressed by the analysis of the *time synchronous average* (*TSA*) of the angular resampled vibration signal. Then an *autoregressive model* (*AR*) is applied to the TSA part in order to extract a residual signal containing pertinent fault signatures. The paper also explores a number of methods commonly used in vibration monitoring of planetary gearboxes, in order to make comparisons. In the experimental part of this study, these techniques are applied to accelerated lifetime test bench data for the lifting winch. After processing raw signals recorded with an accelerometer mounted on the outside of the gearbox, a number of *condition indicators* (*CIs*) are derived from the TSA signal, the residual autoregressive signal and other signals derived using standard signal processing methods. The goal is to check the evolution of the CIs during the *accelerated lifetime test* (*ALT*). Clarity and fluctuation level of the historical trends are finally considered as a criteria for comparing between the extracted CIs.

This study reveals the most relevant features to be used for damage detection and condition monitoring of the gear system. It is also shown that the proposed procedure using a combination of cyclostationarity and autoregressive modeling enhance the ability to detect and diagnose mechanical wear in multi-staged planetary gears.

1. Introduction

An Epicyclic gear system is a compound gear system with planet gears between a center sun gear and an outer ring gear. It is particularly suitable for industrial applications, especially in lifting machines, where it is able to transmit heavy loads from the driving motor to the driven machine with a large reduction in speed, while retaining a compact design. This configuration is also to be found in helicopter transmission gearboxes, wind turbines, mining machines and many other applications. In the case of a single-stage planetary gearbox, torque is transmitted from the central sun gear through the planets to the planet carrier and from the planet carrier to the main rotor shaft of the driven machine. Planetary gears are susceptible to several defects that reduce their performance and give rise to undesirable phenomena such as noise, vibration

* Corresponding author. Tel.: +33 3 44673325.
E-mail addresses: bassel.assaad@cetim.fr (B. Assaad), mario.eltabach@cetim.fr (M. Eltabach), jerome.antoni@insa-lyon.fr (J. Antoni).

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and cracks. It is therefore crucial to identify faults that may occur within an epicyclic gearbox before a catastrophic failure occurs, resulting at the very least in costly downtime.

The practical monitoring of epicyclic gearboxes in industry is significantly underdeveloped. However, a number of techniques for monitoring the health of machinery can be integrated in the system. These techniques include vibration analysis, thermography, oil analysis and ultrasound.

Vibration analysis has historically been the technique of choice for machinery maintenance and fault diagnosis. However, planetary gearboxes cannot be monitored using traditional vibration techniques, due to the complexity of the gear system. Specialized condition monitoring techniques based on vibration analysis for detecting incipient failures in rotating machinery containing planetary gears, such as time synchronous averaging [1–3], time-frequency analysis [4–8], spectral kurtosis [9,10] and mathematical modeling [11,12], have been described in the literature. Other researchers have developed special techniques to detect planetary gear defects in helicopters [13,14]. It has been shown that *Time Synchronous Averaging* (*TSA*) is a particularly suitable technique for feature extraction from the vibration signal in order to provide pertinent condition monitoring of the planetary gearbox. Features are extracted from the raw signal and from the TSA signal to evaluate the health of the rotating machine. Nevertheless, it may be difficult when using TSA alone to isolate the damage in its early stages. Sometimes it is preferable to combine TSA with other techniques such as auto-regression filtering [15–17] in order to improve the detectability of gear faults.

Since the residual part denoted resAR resulting from the autoregressive process contains only fault signatures, we propose to apply and explore the pertinence of many usual statistical and power indicators to this residual part. Our approach consists in extracting the residual and the difference signal from resAR and then applying a new set of CIs, so that signs of heavy wear like broken teeth, or distributed faults like pitting and scoring, can be clearly revealed.

2. Vibration induced by epicyclic gears

2.1. Vibration signals

Epicyclic gear train vibrations are fundamentally different from vibrations in fixed-axis gear trains. They are difficult to analyze, not only because there are multiple planet gears producing similar vibrations, but also because of the relative motion of planet gears to the transducer located on the gearbox housing. Vibration transmission paths from the gear mesh point to the transducer vary with time, introducing a planet-pass modulation.

Since rotating machines involve cyclical patterns, the transmission of the vibration signal is periodic, and so its spectrum contains components at the fundamental gear mesh frequencies and their harmonics. Generally, modulation may also occur around the *N*th harmonic of the gear mesh frequency. All these frequencies are considered the system's regular components. The model for vibration in a planetary gearbox is given in Eq. (1).

$$V_{gear}(t) = \sum_{n=0}^{N} P_n(1+a_n(t)).\cos(2.\pi.f_e.t+b_n(t))+\omega(t) \tag{1}$$

where

f_e is the *gear mesh frequency*, also denoted *GMF*,
P_n is the amplitude of the nth harmonics of the tooth meshing harmonics,
$a_n(t)$ is the amplitude modulation function of harmonic n,
$b_n(t)$ is the phase modulation function of harmonic n,
$\omega(t)$ is a Gaussian noise.

Each gear mesh harmonic can be subject to amplitude and phase modulation (AM, PM) by any multiple of a rotating component frequency 'f_{rotc}'. The rotating component frequency chosen might be the input shaft rotating frequency, the planet carrier rotating frequency or the planet pass rotating frequency. These modulation functions are periodic with the considered gear rotation frequency. They are expressed by Eqs. (2) and (3)

$$a_n(t) = \sum_{m=0}^{\infty} A_{m,n}\cos(2\pi f_{rotc}mt+\alpha_{m,n}) \tag{2}$$

$$b_n(t) = \sum_{m=0}^{\infty} B_{m,n}\cos(2\pi f_{rotc}mt+\beta_{m,n}) \tag{3}$$

where $A_{m,n}$ and $B_{m,n}$ are the amplitudes of the mth harmonic, and α_n and β_n are the phases.

Note that modulation phenomena may contemporaneously affect gearbox vibrations due to local or distributed faults or to transmission errors to be found in the gear design and/or the manufacturing process.