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Vibration-based fault detection of meshing shafts

Victor Girondin [*,**] **Herve Morel** [*] **Jean-Philippe Cassar** [**]
Komi Midzodzi Pekpe [**]

[*] *AIRBUS HELICOPTERS F-13725 Marignane Cedex, France*
[**] *LAGIS - UMR CNRS 8219 Université Lille 1 Boulevard Langevin 59655 Villeneuve d'Ascq*

Abstract: In this article, vibration-based monitoring of cracked shafts is addressed in the context of mechanical transmission of helicopters. The approach developed is based on the detection of cyclostationary components produced by a crack. The cyclostationary theory is first presented on a mechanical point of view. Then a signal processing indicator, the spectral coherence, is introduced in order to quantify the second order cyclostationary content of a signal. The characteristics of the vibration produced in the faulty case are explained from a mechanical model of a cracked shaft. It is then shown that small variations in the structural parameters of the crack creates cyclostationary modulations around the meshing frequencies. This justifies the spectral coherence as a relevant indicator to monitor the crack. The spectal coherence is successful applied on bench data reproducing a crack propagation on an actual helicopter shaft.

Keywords: vibration, helicopter, health monitoring, shaft, HUMS

1. INTRODUCTION

Early fault detection is a crucial problem in helicopter maintenance strategy. Actually, one miss-detection of a small fault could lead to its propagation and to system breakdown and eventually to an accident. Health monitoring methods are effective ways of performing Condition Monitoring. In the helicopter field, the Health function is part of the HUMS (Health and Usage Monitoring Systems) and is specified by the 'CAP753" Group [2012] and the EASA [2014]. Among Health Methods, vibration analysis using non-intrusive sensors matches well with helicopter requirements. Accelerometers are the most suitable sensors for non-intrusive health monitoring of helicopters in terms of space, cost and qualification Randall [2011].
Among helicopter elements, the health of shafts bearings plays a key role for the power transmission chain integrity. Its monitoring is therefore worth to be carried out with the most effective methods. One of the most catastrophic failure modes of shafts is the transverse crack leading to the complete failure of the power transmission. A crack is in general caused by fatigue in heavily loaded parts and where local notch may occur (corrosion, fretting, matting coups…). Crack propagation can be decomposed into three stages presented in diagram 1 (Clavel and Bombard [2009]).

This diagram represents the crack growth rate against the variation of the stress intensity factor [1] (Bachschmid and Pennacchi [2008], paragraph 5.2.3.1). The first stage is the initiation and is very fast. The second stage is the propagation and the crack tends to propagate steadily and linearly. The last stage is the failure and is, as initiation, very fast. The crack trajectory cannot be found with this diagram and is in general hard to guess since it depends strongly on intrinsic (geometry, young modulus) and extrinsic factors (cycles, temperatures, load). The crack can also open and close dynamically due to the deflation of the shaft itself. This phenomenon is called "'breathing"'.

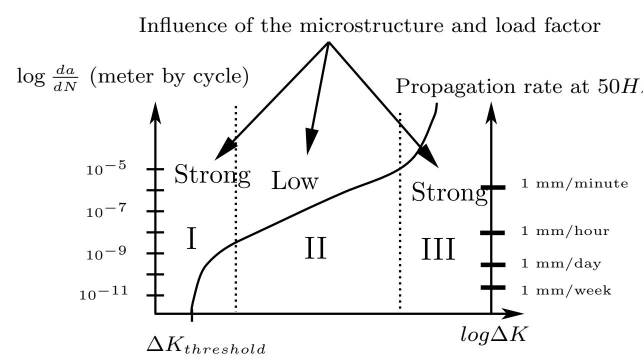

Fig. 1. Log/log diagram of a crack's length as a function of the applied stress intensity factor. The first part of the curve corresponds to the initiation and the last part of the curve corresponds to to the destruction the shaft Clavel and Bombard [2009]. ΔK is the stress intensity factor.

Papadopoulos presents in Papadopoulos [2008] an overview of the crack modeling methods for vibration monitoring. Cracks have many consequences on the dynamics of shafts: change or appearance of coupling between modes, new vibration components, new resonances during run-ups…The authors classify the methods into two groups:

[1] This parameter represents the strain field around the crack.

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→ signal processing: detection of new resonance, modes identification using the free response function, active controlling. . .
→ model-based: Kalman filter, adaptive filters. . .

In Carneiro [2000], the author presents a model of cracked rotor (breathing or non-breathing) and deduce the vibration signatures for known quasi-periodic excitations. Then he proposed to detect a crack using a temporal distance between the recorded data and reference signals. The author argues that frequential monitoring is not feasible with this approach because of the non-linear effects. However no real theoretical or practical clues are presented. In general the temporal methods require a high signal-to-noise ratio. In the helicopter field the signal-to-noise ratio is very low and potentially variable, moreover parasitical components are numerous. The performances of temporal methods in this context are very poor since they require a controlled excitation and a high signal-to-noise ratio.

In the thesis Mani [2006], the author proposes Laval-Jeffcott and Euler-Bernoulli models. The crack is monitored using the response of the system subject to resonances. The author utilizes a periodic excitation to maximize the signal-to-noise ratio and concludes with wavelet analysis to monitor the pattern of the fault. These excitations may not be easily reproduced on helicopters due to the additional workload on operations.
In Bigret and Féron [1994], a Laval model allows deducing that superharmonics of shaft' rotation speed occur when the speed is constant. Bench tests carried in Bigret and Féron [1994] prove that the angular position of the shaft with respect to the unbalance modifies highly the fault pattern. Classic condition indicators are presented to monitor the shaft such as RMS, crest-to-crest, shaft harmonics. . . . In the same reference, the author supposes that these fault patterns are uniquely caused by a crack. However, high bending or rotor-stator contact may cause the same issue. Fault identification is then compromised. For example, even harmonics of shaft' rotation are used as indicator of shaft misalignment Bigret and Féron [1994] Pennacchi et al. [2012] Randall and Antoni [2011] Wiig [2006] or for spline monitoring Bechhoefer and Bernhard [2006]. The authors of Bachschmid and Pennacchi [2008] et Bigret and Féron [1994] suggest to rely on trend monitoring to allow fault isolation without further explanations.

These references rely strongly on a pre-existent historic and lack a joint vibration and signal processing approach that is of vital importance to design indicators used for monitoring. The next paragraphs will introduce cyclostationary theory and how it connects with the vibrations of cracked shafts.

2. CYCLOSTATIONARY ANALYSIS

2.1 Mechanical sources of cyclostationarity

Standard models of mechanical signals recorded on rotating transmission assume that the recorded signals can be decomposed into a periodic and a random part (background noise independant from the periodic part). This model implies that the dynamic response of the system, generating the first part, is purely deterministic, or in other words that the statistical properties of the system are constant. However, for rotating machines like helicopters, the structural parameters of the system are actually periodic. These features can be linked to some excitations of the structural parameters. The author of Antoni [2000] classify excitations into 3 groups: periodic excitations (inertia, meshing), random excitation with possible amplitude or frequency modulation and localized excitations created by repetitive impacts (shocks, explosion...). The last two classes produce periodic uncertainties in the vibrations due to the phenomena causing these signals. The transfer function between the excitations and the accelerometer may also vary periodically, causing periodic amplitude or frequency modulation. The statistical properties of the signal change periodically with the periods attached with the different sub-systems. These periodic variations reflect some mechanical uncertainties like the instantaneous load, the surfaces in contact, and small differences in the geometry. These signals are called cyclostationary.

2.2 Definitions

The mathematical expectation is noted $\mathbb{E}$, the Dirac distribution is δ, x is a stochastic process as defined in Gardner and Spooner [1994] and x^* is its conjugate.

Cyclostationary is now presented for the first two orders using the concept of temporal and spectral cumulants Gardner and Spooner [1994] Spooner and Gardner [1994]. It is possible to define cyclostationary for higher orders but its application is more difficult and not necessarily more fruitful according to Antoni [2000]. Yet the use of the first two orders is enough to extract the vibration patterns useful for monitoring.

(1) The process $\{x(t)\}$ is first order cyclostationary (CS1) with respect to the period $T \neq 0$ when:
$$\mathbb{E}\{x(t)\} \text{ is } T \text{ periodic} \tag{1}$$
The quantity $\mathbb{E}\{x(t)\}$ is called the first order temporal cumulant of $x(t)$.
(2) The process $\{x(t)\}$ is second order cyclostationary (CS2) with respect to the period $T \neq 0$ when:
$$\mathbb{E}\left\{\left[x\left(t+\frac{\tau}{2}\right)-\mathbb{E}\left\{x\left(t+\frac{\tau}{2}\right)\right\}\right] \times\left[x^*\left(t-\frac{\tau}{2}\right)-\mathbb{E}\left\{x^*\left(t-\frac{\tau}{2}\right)\right\}\right]\right\}$$
$$\text{is } T \text{ periodic with respect to the variable } t \tag{2}$$
This quantity is noted the second order temporal cumulant of $x(t)$. The formula is quite close to the autocovariance function. The main difference is that the two signals in the expectation are centered on t for the cumulant and on $t-\frac{\tau}{2}$ for the autocovariance function. The variable τ has a role of temporal shift.

A typical CS1 signal is a additive mixture of a periodic signal and a noise. A typical CS2 signal is a multiplicative mixture of a periodic signal and a noise. In Antoni et al. [2004], the authors propose a cyclostationary classification of gearbox vibrations: meshing and inertia vibrations are mainly CS1 and bearing vibrations are mainly CS2.

2.3 Spectral representation of cyclostationarity

Fourier transform It is possible to rewrite $x(t)$ with the first order temporal cumulant defined in paragraph 2.2: