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Fatigue damage detection using cyclostationarity

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ABSTRACT

In this paper, we present the second-order of cyclostationarity to detect and diagnose the fatigue damage of the stainless steel 316l subjected to low cycle fatigue (LCF). LCF is defined by repetitive cycling in a low stress and a short period. The vibration response of material subjected to LCF provides information linked to the solicitation and to the fatigue damage. Thus, we considered a cantilever beam with breathing cracks and assumed that under the solicitation, breathing cracks generates non-linearity in the stiffness of the material and this one decreases with the damage. We used the second-order of the cyclostationarity to reveal this non-linearity and showed that the fatigue provide a random component in the signal, which increases with the fatigue damage. Thus, in the specific case of a material subjected to LCF, with a non-linear stiffness, we propose a new methodology to detect and diagnose the fatigue damage using a vibration signal. This methodology is based on the second order of the cyclostationarity.

1. Introduction

Fatigue damage is one of the main causes of machine defects found in industry. The detection of this type of damage is very difficult and affects maintenance scheduling. During fatigue damage, we observe the appearance of microcracks that grow until the effective damage of the structure and change its stiffness and damping properties [1]. In the case of a cantilever beam subjected to alternating bending, these cracks present two states: (1) opening crack and (2) closing crack, which define the breathing crack model. The breathing crack impacts the stiffness of the material, which becomes non-linear. In fact, the presence of breathing cracks in a beam results in non-linear dynamic behavior which gives rise to superharmonics in the spectrum of the response signals. The amplitude of these ones depends on the location and depth of any cracks present [2]. Many researchers have performed vibration measurements and analysis techniques to detect this non-linearity caused by the breathing crack. Indeed, in [3], the authors detected this non-linearity using bispectral analysis. Prime and Shevitz [4] have employed instantaneous frequencies and time frequency transforms to detect and locate the crack, making use of the non-linearity. Loutridis et al. [5] have also used the instantaneous frequency for the study of forced vibration behavior and crack detection of cracked beam. Crespo and Ruotolo [6] demonstrated that damage identification is possible using the so-called higher order frequency response functions (FRFs) based on the Volterra series. Rizos et al. [7] suggested using the vibration modes for the identification of crack location in a cantilever beam. In [8], a new concept of

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Nomenclature

$\mathcal{P}\{\cdot\}$	time-averaging operator for extracting all periodic components
$\mathcal{R}\{\cdot\}$	residual operator
α	cyclic frequency variable
$\mathcal{P}_0\{\cdot\}$	time-averaging operator for extracting a constant value
ω	excitation force pulsation
ω_0	crack breathing pulsation
τ	time-lag variable
$\vartheta(F)$	magnitude linked to the excitation force
a_0, a_n	Fourier coefficient
$b(t), b_{ij}$	Gaussian white noise
c	damping of the specimen
$DCS_x^\alpha(N)$	magnitude of the cyclic frequency α at the number of cycles N
f	(spectral) frequency variable
$F(t)$	excitation force
f_n	natural frequency
$I_{CS2}(\alpha, N)$	new cyclostationary fatigue damage indicator
$k(t)$	non-linear stiffness
m	mass of the specimen
$m_x(t)$	synchronous average
N	cycle number variable
N_0	cycle number corresponding at the start of the test
$P_x^\alpha(f;\Delta f)$	cyclic modulation spectrum
$P_x(t,f,\Delta f)$	instantaneous power envelope
$R_{x_r}^\alpha(\tau)$	cyclic autocorrelation function of the residual signal $x_r(t)$
$R_{x_r}(t,\tau)$	instantaneous autocorrelation function of the residual signal $x_r(t)$
T	time period
t	time variable
$x_r(t)$	residual part or random part of the signal $x(t)$
$x_{\Delta f}(t,f)$	filtered signal in the frequency band $[f-\Delta f/2; f+\Delta f/2]$

non-linear output frequency response functions (NOFRFs) is exploited to detect cracks in beams using frequency domain information. Benfrattello et al. [9] used higher order statistics to locate a fatigue crack on beams vibrating under Gaussian excitation.

In this paper, the non-linearity provided by the breathing crack is considered and a novel non-linear technique for crack detection in mechanical structures is investigated. We propose a robust diagnostic of damage based on vibrational measurement with particular regard to the second-order of cyclostationarity and a new damage indicator. Cyclostationarity is a signal processing tool which allows us to characterize in a signal a coupling between random phenomenon (typically in our case the fatigue damage) and non-linear phenomenon (due in our case to the stiffness). Thus, our study was carried out on the dynamic response of fatigue cracks and we used the second-order of cyclostationarity to reveal this non-linearity and showed that the fatigue provide a random component in the signal, which increases with fatigue damage.

2. Dynamic response of an cantilever beam subjected to alternative bending

2.1. Breathing crack model and dynamic equation

Most researchers have used open and close crack models in their studies and have claimed that the change in natural frequency might be a parameter used to detect the presence of a crack [10,1,2,11]. In their model, the structure has only two characteristic stiffness values: (i) a larger value corresponding to the state of crack closing and (ii) a smaller value for crack opening. Therefore, the stiffness of a structure containing a real fatigue crack may change continuously with time as the load oscillates. Examining the dynamic response of a fatigue crack at its first mode in a single-degree-of-freedom system, the stiffness may be expressed as [12]

$$k(t) = k_0 + k_{\Delta c}(1+\cos\omega_0 t), \tag{1}$$

where ω_0 is the crack breathing frequency, k_0 is the stiffness of the structure when the crack is fully open, and the amplitude of the stiffness change is given by

$$k_{\Delta c} = \tfrac{1}{2}(k_c - k_0), \tag{2}$$

$$k(t) = \begin{cases} k_c & \text{if } \omega_0 t = l,\ l \in \mathbb{N},\ \text{the crack is completely closed.} \\ k_0 & \text{if } \omega_0 t = l - 1/2,\ l \in \mathbb{N},\ \text{the crack is in the fully open state.} \\ & \text{if not, it is partial closure.} \end{cases}$$

The coefficients k_c and k_0 are determined from the stiffness properties of the structure when the crack is completely open and completely closed respectively (Fig. 1).

For the sake of simplicity, a cantilever beam is modeled as a one-degree-of-freedom as shown in Fig. 2. Under the action of the excitation force $F(t)$, alternate crack opening and closing causes the equation of motion of the cracked beam to be non-linear. This single-degree-of-freedom system is governed by an equation for forced vibration expressed as

$$m\ddot{x}(t) + c\dot{x}(t) + k(t)x(t) = F(t), \tag{3}$$

where m is the mass, c is the damping coefficient, $k(t)$ is the non-linear stiffness, $F(t)$ is an external force (periodic excitation of pulsation ω) and $x(t)$ is the displacement.