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Detection of cracks in shafts with the Approximated Entropy algorithm

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ABSTRACT

The Approximate Entropy is a statistical calculus used primarily in the fields of Medicine, Biology, and Telecommunication for classifying and identifying complex signal data. In this work, an Approximate Entropy algorithm is used to detect cracks in a rotating shaft. The signals of the cracked shaft are obtained from numerical simulations of a de Laval rotor with breathing cracks modelled by the Fracture Mechanics. In this case, one analysed the vertical displacements of the rotor during run-up transients. The results show the feasibility of detecting cracks from 5% depth, irrespective of the unbalance of the rotating system and crack orientation in the shaft. The results also show that the algorithm can differentiate the occurrence of crack only, misalignment only, and crack + misalignment in the system. However, the algorithm is sensitive to intrinsic parameters p (number of data points in a sample vector) and f (fraction of the standard deviation that defines the minimum distance between two sample vectors), and good results are only obtained by appropriately choosing their values according to the sampling rate of the signal.

1. Introduction

Rotating machines are heavily employed in industry and, specifically in some fields (e.g. the energy industry), they represent vital elements in the production chain. From the point of view of reliability, such machines shall work with high availability and low probability of failure to avoid significant financial losses. For this reason, the constant monitoring of such vital machines is common practice. Among all the malfunctions that a rotating machine can present, cracks in the shaft represent a very dangerous operating condition because failure is often sudden and catastrophic. Thus, the early identification of cracks in the shafts of such machines is an important issue.

It is well known in the literature that the presence of a crack introduces an additional flexibility to the shaft, which reduces the overall stiffness of the shaft [1,2]. The reduction of shaft stiffness reduces the critical frequency of the system, but this information is not reliable for identification purposes. Even in the presence of deep cracks, one can only observe slight changes in the critical frequency [3]. A more noticeable change in the system is the higher vibration harmonics that appear during shaft rotation [4,5]. These harmonics become more noticeable during the passage through sub-harmonics of the critical frequency, when vibration amplitude of the shaft increases. Complex orbits of the shaft and orbit phase shifts are also observed in the presence of cracks [4–6]. In general, the deeper the crack is, the more pronounced such effects are.

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Nomenclature

$\overline{a}$	crack depth (m)
ApEn	Approximate Entropy value
d	rotor damping coefficient (N s m^{-1})
D	shaft diameter (m)
E	Young modulus of the shaft material (N m^{-2})
f	fraction of the standard deviation of a sample vector
f_s	sampling rate (Hz)
g	acceleration of gravity (m s^{-2})
g_i	shaft flexibility in the i-th direction (m N^{-1})
I	moment of area of the shaft cross section (m^4)
k_ξ	shaft stiffness in the direction of the crack (N m^{-1})
k_η	shaft stiffness perpendicular to the crack (N m^{-1})
$k_{\xi\eta}, k_{\eta\xi}$	cross-coupling stiffness coefficients of the shaft (N m^{-1})
L	shaft length between bearings (m)
m	rotor mass (kg)
Q_ξ, Q_η	bending forces acting on the shaft (N)
r	maximum distance between data points
SIF	Stress Intensity Factor
$\mathbf{x}$	sample vector of data points
β	angle between the centre of gravity and the centreline of the crack (rad)
ε	mass eccentricity (m)
ξ, η	rotating coordinates
Ω	rotating speed (rad s^{-1})

Considering the effects that a crack can produce in the dynamic behaviour of the shaft, many different identification procedures have been investigated in the literature. According to [1], one can classify these crack identification methods in Vibration Based Methods (signal-based or model-based), Modal Testing Methods, and Non-Traditional Methods. The Vibration Based Methods take into account the vibration signal of the machine in time domain (steady state or transient) to detect and identify the cracks. For example, frequency components of the signal can be monitored as indicators of the presence of the crack in the shaft [7–9]. Modal Testing Methods take into account the dynamics characteristics of the machine in frequency domain to detect and identify the cracks. For example, the natural frequencies of the system and mode shapes can be monitored, and variations can be associated to the presence of a crack [10]. One can also excite the system and observe its dynamic behaviour regarding coupling mechanisms between different types of vibrations (axial, radial, or torsional) in cracked shafts [11–14]. Non-Traditional Methods are those that do not fit entirely in the previous two types of methods, although they can take into account time or frequency domain information for detecting and identifying cracks in shafts. For example, optimisation procedures can be used to compare the dynamic response of a real shaft (suspected to have a crack) to that of a finite element model of the system [15]. Neural networks can also be used in the inverse problem of identifying the location and depth of the crack in shafts [16]. Other works use wavelet transform [17] and Wigner–Ville transformation [18]. Although the Approximate Entropy (ApEn) is applied to signals in time domain (signal-based method), it can be classified as a non-traditional method due to the non-conventional signal processing involved.

The ApEn is a statistical value used to quantify the irregularity of a temporal series [19]. This value, obtained by an algorithm applied to the data, has been widely used in the areas of Biology and Medicine to extract information from signals related to the presence and characteristics of pathologies [20–22]. In Engineering, there are few works applying the ApEn for machine health monitoring and diagnosis. Most applications are related to the identification of faults in ball bearings [23–26]. Nevertheless, the method can also be used to detect oscillations in energy transmission systems [27], and to detect instabilities in machining processes [28]. The question is whether the ApEn is suitable for detecting cracks in shafts. The present work shows that it is indeed.

In the present work, the ApEn is applied to the vibration signals of a cracked shaft for detecting the presence of the crack and its depth. The vibration signals used in the analysis are obtained from numerical simulations of the mathematical model of a de Laval rotor with a breathing crack modelled from the theory of Fracture Mechanics [29]. Such crack model was chosen because it presented good correlation to experimental results [6]. The present results show the feasibility of detecting breathing cracks as small as 5% of shaft diameter, irrespective of the unbalance of the rotating system and crack orientation in the shaft, during system run-up. The main disadvantage of the method is its high sensitivity to the intrinsic parameters p and f, whose values must be appropriately chosen for achieving good results in the identification.

2. Cracked shaft model

The ApEn algorithm will be applied to vibration signals of the system, more specifically vertical displacements of the shaft, to detect cracks in the shaft. Considering that it is difficult to create cracks with controlled depth experimentally, one will rely on the results of a mathematical model to have the vibration signals of a cracked shaft in this analysis. The mathematical model of the cracked shaft adopted in this work is the model presented in [29]. In this case, one considers a transverse crack (perpendicular to the shaft) in a breathing mechanism, where gravity and centrifugal forces are responsible