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Review

Non-linearities in the vibrations of elastic structures with a closing crack: A state of the art review

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ABSTRACT

The main purpose of the present review paper is to illustrate the principal achievements of numerous researchers who have studied the non-linear effects caused by a closing crack in the most common types of structural elements such as beams, shafts and plates, the aim being to assess the potential and future prospects of using non-linear behaviour to detect damage. Indeed, for a wide range of practical applications, in order to avoid catastrophic failure, the development of diagnostics techniques which are sufficiently sensitive to incipient cracks in structures and machines is a crucial issue. The main potential advantage of using vibration diagnostics based on the use of non-linear effects is the relatively high sensitivity to the damage of the closing crack type, especially for application to beam-like structures and rotating shafts; instead the potential for application to plate-like structures has been found to be limited.

After analysing the state-of-art on this subject in detail, a discussion of the respective merits, drawbacks and prospects of a range of non-linear vibration methods for structural damage detection is presented. The general conclusion which can be drawn from the highly encouraging results of recent research is that further development of these techniques for non-destructive testing of structures with closing cracks would be highly worthwhile.

Contents

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Nomenclature

a	crack depth
h	cross-section height
$\gamma = a/h$	relative crack depth
I	second moment of cross section area
I_c	second moment of cracked cross section area
H	Heaviside function
L	length of beam or plate
L_d	delamination length
L_C	crack location
L_p	driving force application point
M_S	bending moment
r	shaft radius
$\mu = a/r$	shaft relative crack depth
Ω	speed of rotation
Ω_0	shaft eigenfrequency
Ω_{cr}	critical speed of rotation
Ω_b	critical backward whirl speed
Ω_f	critical forward whirl speed
Ω_{tr}	frequency of torsional vibration
$\eta = \Omega/\Omega_{cr}$	relative speed of rotation
φ	angular position of imbalance
θ	angle of crack opening
h_{sh}	thickness of a shell
f_{exc}	frequency of excitation
f_{rel}	relative frequency of driving force
R	restoring force
LP	low pressure
3D	three-dimensional
FEM	finite element model
FRF	frequency response function
DOF	degrees-of-freedom
SIF	stress intensity factor
WT	wavelet transform
δ	logarithmic decrement of vibration

1. Introduction

The first works on the impact of local defects on the vibration characteristics of structural elements were performed by Kirmsher [1] in 1944 and Thomson [2] in 1949. In these studies approaches were proposed to the modelling of damage of a fatigue crack type, as well as the methods of determining the natural frequencies of vibrations of beams with a crack. As numerous studies have demonstrated [3], the change of natural frequencies and mode shapes seem insufficient to detect small cracks. A search for vibration characteristics that are more sensitive to the presence of damage and easy to apply still continue today. These characteristics include: the change of damping, the sub- and superharmonic vibrations, non-linear distortion of vibration at the principal resonance, the change of transfer function, the distortion of phase trajectories, antiresonance frequencies, mechanical impedance and static and dynamic compliance [4].

In many studies the slot type model of a crack was used. The crack is supposed to be constantly open regardless of the stress sign (the so called open crack). In this case the characteristic of the restoring force remains linear (Fig. 1a). However, such a simplification of the problem leads to the over estimation of changes in natural frequencies and mode shapes, as compared with the effect of the real crack [5,6]. Moreover, the models with an open crack are not suitable to describe the non-linear behaviour of structures with closing cracks and so are unable to identify the sub- and superharmonic resonances.

Real cracks usually are formed as a result of fatigue and corrosion and have the possibility of opening during the stretching cycle and closing during the compression cycle, thereby changing the stiffness of a body in the process of its cyclic deformation. That is why these cracks are referred to as closing or breathing (Fig. 2). It is assumed that the stiffness of the