Available online at www.sciencedirect.com
ScienceDirect
Mechanical Systems and Signal Processing 22 (2008) 1092–1106
Mechanical Systems and Signal Processing
www.elsevier.com/locate/jnlabr/ymssp

Vibration-based damage detection in plates by using time series analysis

Irina Trendafilova[a,*], Emil Manoach[b]

[a]Department of Mechanical Engineering, University of Strathclyde, Glasgow, UK
[b]Institute of Mechanics, Bulgarian Academy of Sciences, Sofia, Bulgaria

Received 25 October 2007; received in revised form 12 November 2007; accepted 13 November 2007
Available online 13 February 2008

Abstract

This paper deals with the problem of vibration health monitoring (VHM) in structures with nonlinear dynamic behaviour. It aims to introduce two viable VHM methods that use large amplitude vibrations and are based on nonlinear time series analysis. The methods suggested explore some changes in the state space geometry/distribution of the structural dynamic response with damage and their use for damage detection purposes. One of the methods uses the statistical distribution of state space points on the attractor of a vibrating structure, while the other one is based on the Poincaré map of the state space projected dynamic response.

In this paper both methods are developed and demonstrated for a thin vibrating plate. The investigation is based on finite element modelling of the plate vibration response. The results obtained demonstrate the influence of damage on the local dynamic attractor of the plate state space and the applicability of the proposed strategies for damage assessment. The approach taken in this study and the suggested VHM methods are rather generic and permit development and applications for other more complex nonlinear structures.

Keywords: Vibration-based structural health monitoring; Nonlinear time series analysis; Nonlinear dynamics; State space representation of dynamical systems; Dynamic system attractor; Poincaré maps

1. Introduction and motivation

Vibration-based health monitoring methods are based on the fact that any changes in a structure in turn introduce changes in its vibration response. The problem for damage diagnosis seeks to extract information about the presence, the location and the extent of damage from the vibration response of the structure. The simplest way to do vibration health monitoring (VHM) is using the first several natural frequencies of a structure, which are easy to determine from experiment. But they are global characteristics and thus, in a lot of cases, may remain unaffected by damage and especially by localised damage. Mode shapes are in general more sensitive to damage but they are difficult to measure and/or estimate from measured quantities [1]. Another alternative are the updating methods, which are based on comparison of the measured and the modelled

*Corresponding author. Tel.: +44 141 5482322.
E-mail addresses: Irina.Trendafilova@strath.ac.uk (I. Trendafilova), e.manoach@info.imbm.bas.bg (E. Manoach).

0888-3270/$ - see front matter
doi:10.1016/j.ymssp.2007.11.020

response of a structure. The application of these methods is limited by the need of a precise enough model of the structural vibration response.

The above limitations clearly call for an alternative approach, which emerged and developed in a recent trend in structural VHM. It suggests the use of purely data-based methods which make use of the measured structural vibration response signal [2–7]. There are different ways to use the measured structural vibration response. A straightforward possibility is to use the frequency response functions. Such methods suffer the limitations of the excessively large number of frequency lines in the spectrum, which make any further analysis and application very difficult before any preliminary data reduction is made [8].

Nonlinear dynamics methods present another possibility to use the measured vibration response. Observation-based nonlinear dynamics draws its applications from nonlinear signal analysis. Most nonlinear signal analysis methods operate in a phase space. One of the reasons for using phase space is that nonlinear signals are slightly predictable in time, but they have structure which can be observed in phase space. Such methods are relatively new and insufficiently explored for structural dynamics and VHM purposes but the existing research proves their capabilities and potential [2–7]. The application of such methods is especially appropriate when the structure is subjected to large amplitude vibrations, which enhance the influence of any nonlinearities present in the structure, and as a result the structural vibration response is represented by a nonlinear signal. Under large amplitude dynamic loads, even small changes in the structure (like cracks and other local damage scenarios) can have a big effect on the structural response in the time domain, which can give indication for the presence of damage. Damage which induces very small changes in the natural frequencies and the mode shapes may result in phase shifts between the vibration response of the healthy structure and the damaged structure in the time domain.

This study suggests the use of large amplitude vibrations and develops two viable methods for damage diagnosis in structures, which are based on nonlinear time series analysis. Here, the methods are developed for a thin square plate and their capabilities are demonstrated for a thin aluminium plate.

Thin plate structures have gained special importance and notably increased application in recent years. Complex structures such as aircraft, ships, steel bridges, sea platforms, etc. all use metal plates. Metal plates are subjected to different kinds of damage that can be due to environmental factors, corrosion/erosion and/or collision. The presence of crack and other damage can alter considerably the dynamic behaviour of a thin plate. A number of authors suggest the use of nonlinear methods to analyse thin plate vibrations especially in the presence of damage [9,10]. In many applications vibrating plates are subjected to dynamic loading leading to large amplitude vibrations. In such cases the small deflection plate theory cannot assure the adequate simulation of the plate response and therefore the large deflection plate theory, where the geometrical nonlinearities are included, should be used [11,12]. On the other hand, large amplitude vibrations can allow small defects (which will not influence the response in the case of small deflections in the plate) to affect substantially the dynamic behaviour of the plate and in this way to be easily identified. For the above reasons the geometrically nonlinear version of the so-called Reisner–Mindlin plate theory (the first order plate theory) was used to model the plate behaviour [13,14]. It is out of the scope of this paper to concentrate on the details of this theory and on the method of the solution of the equation of motion. The governing equations and the idea of the used method for rectangular plates are presented very briefly in the Appendix.

It has been found in several studies that the lower natural frequencies of plates might be insensitive to damage [9,15]. This paper also explores the sensitivity of the first several natural frequencies of the plate to damage but it only confirms the previous findings that the changes in the lower natural frequencies of the plate considered are insufficient to be used as damage indicators. The paper then goes on and examines the difference between the two types of vibration responses (in undamaged state and in the presence of damage) in a state space to extract features that can be used for damage detection and localisation.

The next section introduces the idea of the state space approach and its use for damage detection. Section 3 is dedicated to the two damage diagnosis methods. The specific case of a thin square aluminium plate is considered next. Section 5 introduces and discusses the results of some numerical experiments. The paper finishes with some conclusions.