Nondestructive Testing and Evaluation

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To cite this article: Grzegorz Litak , Jerzy T. Sawicki & Rafał Kasperek (2009): Cracked rotor detection by recurrence plots, Nondestructive Testing and Evaluation, 24:4, 347-351

To link to this article: http://dx.doi.org/10.1080/10589750802570836

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Cracked rotor detection by recurrence plots

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(Received 25 July 2008; final version received 3 October 2008)

Recurrence plots (RPs) analysis has been used to distinguish cracked and healthy rotor responses. It has been shown that the recurrence criteria of the dynamical systems defined by the RPs can indicate the damages of the rotating shaft using relatively short time series.

Keywords: rotor dynamics; cracks detection; recurrence plots; active magnetic bearings

1. Introduction

Horizontal rotors working over extended periods of time in various temperature regions are often subjected to large loads. They are also periodically forced by the gravitational field which can lead to a fatigue crack.

Such a crack, represented as an internal clearance in the shaft, produces characteristic piecewise linear restoring force leading to an additional parametric excitation, induced by the so called breathing effect of the crack [1–3].

The presence of the crack can be detected in the Fourier spectrum by the appearance of an additional peak at various resonances as superharmonic, subharmonic, and combination resonances. The difference between healthy and cracked responses could be magnified by using additional excitation applied by active magnetic bearings (AMBs) [1,4,5]. The rotor crack detection test rig with active magnetic actuator is shown in Figure 1(a). The actuator is an 8-pole radial design and is equipped with four variable reluctance type position sensors. It can provide specified force actuation in two perpendicular axes, which are rotated 45° from the vertical. The schematic plot of the experimental standing is shown in Figure 1(b).

Although this method enables to produce very unique crack signatures that could be used to detect cracks in the rotor, one should examine very carefully the changes in positions as well as magnitude variations of responses. Apart from that, one needs long time series to draw any constructive conclusions [4,5]. Recently, to overcome it, there appeared new considerations based on the nonlinear properties of the time series [6].

In the present paper we propose to use a novel method of recurrence plots (RPs) [7]. By using this method one considers the state of a dynamical system using the time versus time diagrams instead of doing Fourier analysis. In the following sections we show that relatively short time series can be also successfully used for crack identification.

The examples of time series including the healthy and cracked rotor responses are presented in Figure 2. Note that these measurements have been carried out in absence and presence of the magnetic actuator, respectively.

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ISSN 1058-9759 print/ISSN 1477-2671 online
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DOI: 10.1080/10589750802570836
http://www.informaworld.com
2. Recurrence plots

We start the recurrence analysis from reconstructing a phase space. After Takens [8,9], the state of the system can be represented by the corresponding time-delayed vector

\[ y_i = (y_i, y_{i-\Delta}, y_{i-2\Delta}, \ldots, y_{i-(M-1)\Delta}), \]

where \( M \) is the embedding dimension (in our case \( M = 5 \)) and \( \Delta \) is the appropriate time delay.

In our case, taking into account possible \( x \) and \( y \) displacements with possible modes, we assumed that \( M = 5 \), while \( \Delta = 65 \) is related to one fourth of the main period average (Figure 2).

The RP is constructed from the distance matrix \( R \) with its element \( R_{ij} \) given by [7,10–14]:

\[ R_{ij} = \Theta(\varepsilon - ||y_i - y_j||). \]  

Here \( \varepsilon \) is a threshold value, and \( \Theta \) is a Heaviside step function. In a RP, the elements 0 and 1 of the matrix \( R \) are represented by an empty space and a coloured dot, respectively. The recurrence rate (RR) [7,10] expressing the measure of system regularity, has the following definition:

\[ RR = \frac{1}{N^2} \sum_{i,j=1}^{N} R_{ij}, \quad \text{for} \quad |i - j| \geq 1. \]
This quantity determines the fraction of recurrences in an RP (excluding the central line of identical points $i = j$) and is the probability that the system will recur.

It should be noted that originally the method RP was invented to present signal data as patterns on a two dimensional (time versus time) figure [15]. After supplementing by the method of recurrence quantification analysis (RQA) it became an alternative to standard frequency analysis [6,16,17].

We have analysed experimental data [1] gathered on a cracked rotor. Looking for the signature of crack we plot RR versus $\varepsilon$ in Figure 3 for all four considered time series. In Figure 3(a) we observe characteristic line splitting effect, visible in the region of $\varepsilon \in [0.3, 0.7]$. Note that this effect is visible only in the presence of magnetic excitation (curves ‘d’ and ‘c’ are split) while for non excited cases is negligible (‘a’ and ‘b’ coincide). One can draw the following conclusions: firstly, the regularity of healthy and cracked rotor responses represented by the parameter RR is very similar for the cases without magnetic excitation. Secondly, this regularity is considerably changed in the presence of magnetic actuators. Namely, cracked rotor shows more regular response than the healthy system. This could be also interpreted that the response is more periodic as a result of extra coupling.

Figure 3. RR versus the threshold value $\varepsilon$ for the healthy and damaged rotors (cases ‘a’–‘d’ as in Figure 2).
by breathing action of the crack. Consequently, the response of the cracked rotor excited by an AMB should contain combinational resonances.

To clarify the origin of this splitting we show in Figure 4a–d the corresponding RPs. Here by using the definition of the distance matrix $R$ (Equation (2)) we illustrated the recurrences for $\varepsilon = 0.4$. Note that Figures 4(a,b) (no magnetic excitation) show rather periodic character while this periodicity is smeared considerably in Figure 4(c,d) (with magnetic excitation). Clearly, among the all four cases, Figure 4(c) is the most affected by magnetic force excitation. This indicates that the presence of crack recovers partially the original periodic character of the basic response.

3. Conclusions

Using embedding approach, RPs and RQA by calculating RR for short experimental time series, we have identified the cracked rotor in the presence of an additional magnetic excitation. It should be noted that this method yields similar results for different values of embedding parameter $M$ and $\Delta$.

The identification procedure may be useful for developing more sophisticated methods of health monitoring including the transient time series. However, before doing it one has to explore systematically the effect of varying magnetic actuator frequency.
References


