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DAMAGE INDICATORS FOR DIAGNOSTIC OF FATIGUE CRACKS IN STRUCTURES BY VIBRATION MEASUREMENTS – A SURVEY

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The paper presents a survey of damage indicators which can be used for diagnose of fatigue cracks in constructional elements. The advantages and disadvantages of the presented damage indicators are described in the paper. The list more than 100 papers connected with this subject is given.

1. Introduction

Nowadays, the majority of structural elements of machines and facilities are operated in the range of limited fatigue strength, which gives rise to cracks in overstressed areas. From the point of view of the right and safe exploitation of the machine it is of great importance to know whether the constructional elements have any cracks, and it is also necessary to enable their magnitude and location determination. Typical methods for crack detection in large constructions (e.g., bridges, truss constructions, drilling platforms), or in constructional elements in motion (e.g., rotating shafts, disks and turbine blades) are often useless. For this reason in many scientific centers investigation programmes are conducted with the intention to work out methods enabling crack detection on the basis of measurement of dynamic characteristics of damaged constructional elements.

The basic idea of vibration diagnostic systems is to use the changes in dynamic behaviour of a structure due to crack as a basis for detection of this crack. The dynamical behaviour of a structure can be represented by various dynamic characteristics, which in diagnostic systems are called damage indicators. These damage indicators are determined during the lifetime of the structure and compared with indicators received for the "virgin" state. By this way it is possible to indicate the crack existence in the analysed structure.

The aim of this paper is to present different damage indicators which can be potentially used in diagnostic systems. Main advantages and disadvantages of the aforementioned indicators are described. The presented damage indicators refer to steel structures. However, the damage indicators described in this paper can be used in other kinds of structures as well, e.g. concrete structures.

2. Natural frequencies

The drop in natural frequencies is without any doubt most often used damage indicator both formerly and nowadays. It is due to the fact that natural frequencies are easy to measure with a relatively high level of accuracy. For example, Fig.1 illustrates the changes in first bending natural frequency of a cantilever beam as a function of location and depth of the crack and also the slenderness ratio of the beam. The detailed descriptions of diagnostic systems which used changes in natural frequencies for detection fatigue cracks in constructional elements are given by: Adams et al. (1978); Adams (1983); Araujo Gomes and Montalvao e Silva (1990); Cawley and Adams (1979a,b,c); Chang et al. (1993); Dimarogonas (1982); Feng et al. (1989); Fox (1992); Hearn and Testa (1991); Hu and Liang (1993; Ju et al. (1982a,b); Ju and Mimovitch (1988); Kam and Lee (1992); Krawczuk (1992), (1993); Kujath (1988); Liang et al. (1991), (1992); Ng (1984); Ostachowicz and Krawczuk (1992), (1993), (1995); Penny et al. (1993); Richardson and Mannan (1990), (1992), (1993); Samman and Biswas (1994a,b); Sekhar and Prabhu (1992); Soeffer et al. (1993a,b,c,d); Springer et al. (1988); Stubbs (1985).

The changes in natural frequencies are proportional to the square root of the stiffness change. For this reason some investigators reject them as damage indicator. Alampalli (1992); Fox (1992) and Sunder and Ting (1985) concluded that natural frequencies are insufficient for detection of fatigue cracks when used alone. Other limitations are due to the fact that changes in natural frequencies are functions of external loads, temperature, and others. The interesting effect, which reduced the use of natural frequencies as damage indicator in prestressed concrete beams, was reported by Maguire (1990). Traditionally the growth of fatigue cracks in constructional elements caused the reduction of natural frequencies. In prestressed concrete beams the increase of natural fre-

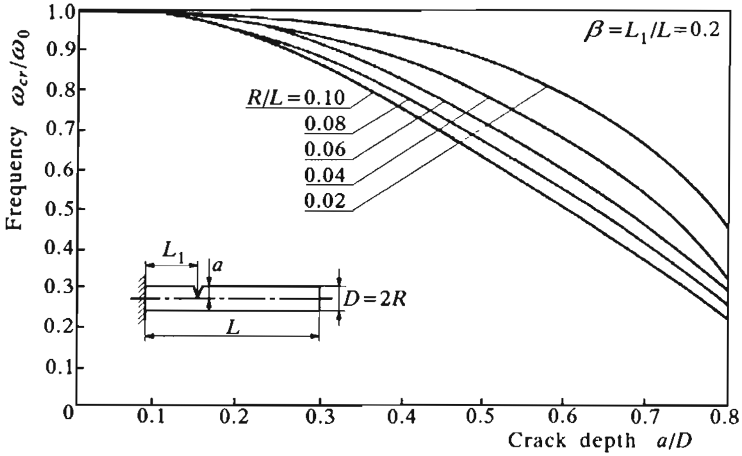

Fig. 1. Relative changes ω_{cr}/ω_0 in the first natural bending frequency of a cantilever beam as a function of relative depth a/D and slenderness ratio of the beam R/L – Dimarogonas and Papadopoulos (1988)

quencies is observed. This increase is due to the fact that modulus of elasticity of the concrete increases as the prestressing decreases. However, a decrease in natural frequencies must occur, when fatigue cracks appear in concrete. In result the natural frequencies are the same for the damaged state and for the undamaged one, and they can not be used as damage indicators. Also the crack closure effect is another, which can make the use of natural frequencies as damage indicators unreliable. If the crack is closed during vibration the measured decrease in natural frequencies is much lower than if the crack is open all the time – Ju et al. (1982b); Actis and Dimarogonas (1989).

Nevertheless, the literature showed that the changes in natural frequencies are most often used in diagnostic systems based on vibration measurement.

3. Mode shapes

It is well known that the fatigue crack cause changes in mode shapes – see Fig.2. For this reason many of investigators try to use the changes in mode shapes as a damage indicator: Anifantis et al. (1983), (1987); Bastadzhan et al. (1990); Davini et al. (1993); Dimarogonas and Papadopoulos (1988); Fox (1992); Hajela and Soeiro (1990); Irretier (1993); Luongo (1992); Ostachowicz and Krawczuk (1990), (1994); Pandey et al. (1991), Rizos and Dimarogonas

(1988); Rizos et al. (1990); Sekhar and Prabhu (1992); Shen and Taylor (1991); Srinivasan and Kot (1992); Yuen (1985).

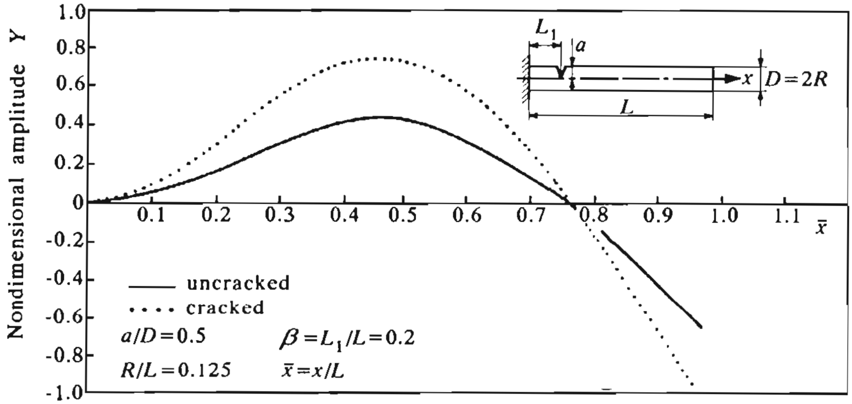

Fig. 2. Changes in the second mode of bending vibration of a cantilever beam due to the transverse crack – Dimarogonas and Papadopoulos (1988)

The main disadvantage in using the mode shapes as the damage indicator are measurement problems. Deflections should be measured at many points for the mode shape estimation to be performed. Thus the duration of a measurement session will increase considerably. On the other hand numerical investigations showed that the mode shape related for rotation degrees of freedom (cf Yuen (1985); Ostachowicz and Krawczuk (1990); Pandey et al. (1991); Gounaris and Dimarogonas (1988)) is more sensitive than the displacement mode shape. However the measurement of rotation mode shape is more complicated than the measurement of displacement mode shape, which means that their applicability as damage indicator is rather poor.

In several papers their authors suggested that it is possible to apply other criteria based on measurements of mode shapes. The first one is the modal assurance criterion (MAC) and the second one is the so-called coordinate modal assurance criterion (COMAC).

The MAC has been used as damage indicator for example by Alampalli et al. (1992) and Biswas et al. (1990). The MAC-value between two eigenvectors ϕ_i, ϕ_j is defined by

$$\mathrm{MAC}(\phi_i,\phi_j) = \frac{|\phi_i^{\mathrm{T}}\phi_j|}{\phi_i^{\mathrm{T}}\phi_i\phi_j^{\mathrm{T}}\phi_j}$$

If the constructional element is uncracked the value of MAC is equal to 1. The MAC-values different from 1 suggested that any damage occured in element.

The changes of MAC-values received from numerical calculations for cantilever beam are shown in Fig.3. From Fig.3 it follows that it is possible to diagnose even relatively short cracks by modal assurance criterion.

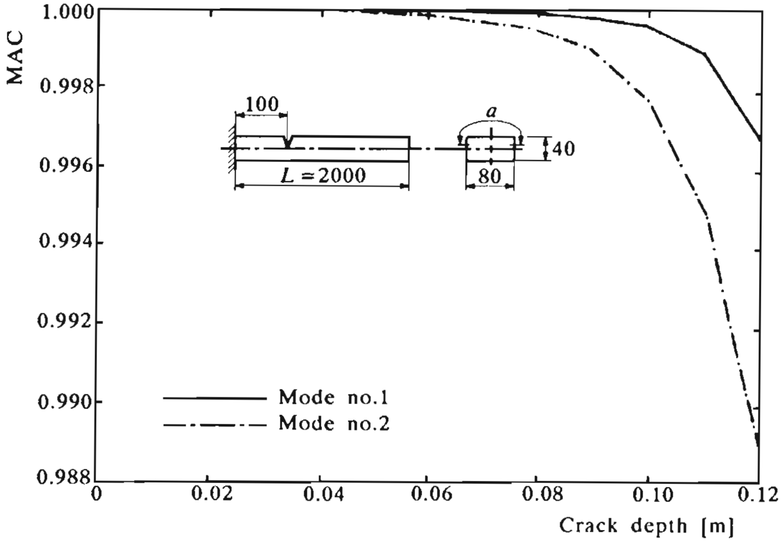

Fig. 3. Changes in MAC(1,1) and MAC(2,2) of the cantilever hollow beam as a function of the crack length – Rytter (1993)

The COMAC has been applied as damage indicator by Alamplalli et al. (1992) and Biswas et al. (1990). The COMAC-factor at a point i between two sets of the mode shape in state $A(\phi^A)$ and $B(\phi^B)$ is defined as

$$\mathrm{COMAC}(i) = \frac{\Big(\sum\limits_{j=1}^{N} |\phi^A_{i,j}\phi^B_{i,j}|\Big)^2}{\sum\limits_{j=1}^{N} (\phi^A_{i,j})^2 \sum\limits_{j=1}^{N} (\phi^B_{i,j})^2}$$

where: N is the number of mode shapes, $\phi^A_{i,j}$, $\phi^B_{i,j}$ denote the values of jth mode shape at a point i for the states A and B, respectively.

The changes in COMAC for cracked cantilever beam are shown in Fig.4. From Fig.4 it follows that the COMAC can be used for crack detection when the relative length of the crack is more than 20%.

From the literature (cf Pandey et al. (1991)) emerges that the MAC and COMAC are highly dependent on the geometry of structure and the location of damage. The numerical simulations performed by Rytter (1993) have shown,

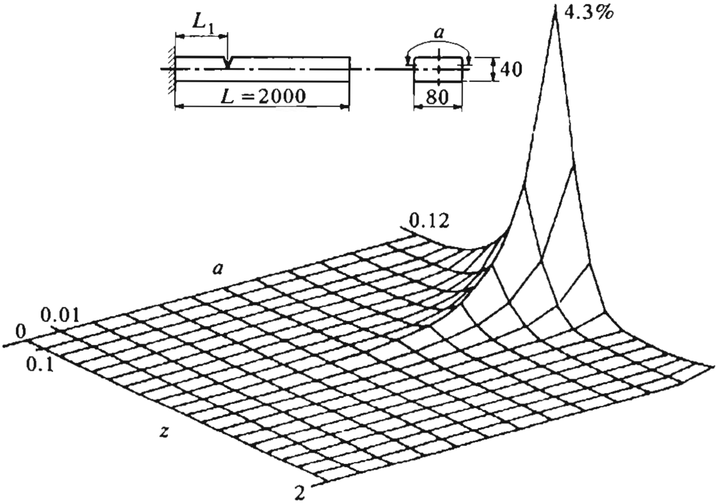

Fig. 4. Changes of COMAC received for the cantilever hollow beam with crack – Rytter (1993)

that these criteria are not sensitive enough to detect damage at the earlier stage.

4. Damping

Cracks in constructional elements cause an increase in damping. This increase is due to the fact that the plastic region arises around the crack tip and friction forces are generated on the crack surfaces during vibration of the cracked structures. The damping is mentioned as a potential damage indicator in many papers (cf Agbabian et al. (1988); Hearn and Testa (1991); Hochrein and Yeager (1978); McGuire et al. (1993); Rytter (1993); Sanlitruk and Imregun (1994); Tsai et al. (1988)). The changes in damping ratio due to the crack in cantilever beam are shown in Fig.5. From Fig.5 it follows that the damping ratio of cantilever beam is extremely sensitive to crack, even small ones.

On the other hand, it is well known that damping is a function on environmental conditions as, e.q., temperature, load history etc. Further, the damage dependent changes in damping are often only a relatively small part of the total damping. Thus, a change in damping due to damage can easily be

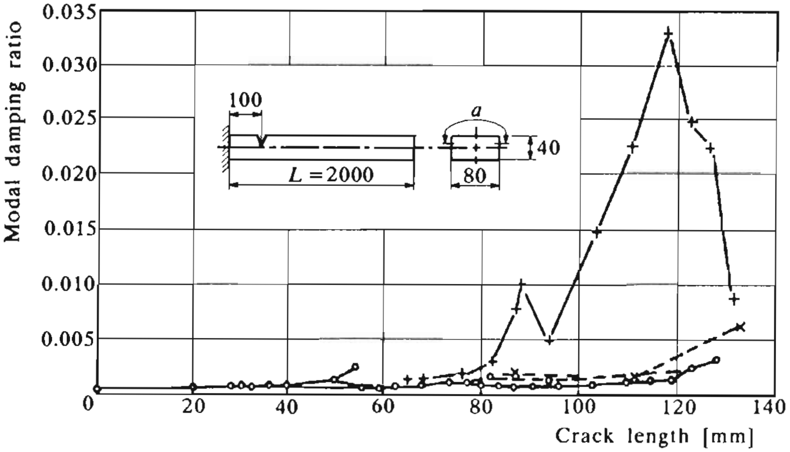

Fig. 5. Changes in the modal damping ratio for the first bending mode as a function of the crack length – Rytter (1993); + line – location of the crack – 100 mm from the clamped end, o line – location of the crack – 1000 mm from the clamped end, × line – location of the crack – 800 mm from the clamped end

missed. For these reasons some investigators reject damping as a potential damage indicator – Turner and Pretlove (1984); Askegaard and Mossing (1988); Alamplalli et al. (1992). The other researches concluded that damping was applicable and recommendable as damage indicators but it should never be used as the only damage indicator.

5. Anti-resonance frequencies

Anti-resonance frequencies are those which correspond to the minimal amplitudes of forced vibrations on the amplitude-frequency response plot, Fig.6. The anti-resonance frequencies can be found by solving a reduced version of the eigenvalue problem, where the jth column and row. The number of removed column and row corresponds to a number of loading global degrees of freedom removed

$$\mathbf{M}^{-1}\mathbf{K}\boldsymbol{q} = \lambda\boldsymbol{q}$$

$\mathbf{M}$ – mass matrix
$\mathbf{K}$ – stiffness matrix
$\boldsymbol{q}$ – displacement vector.

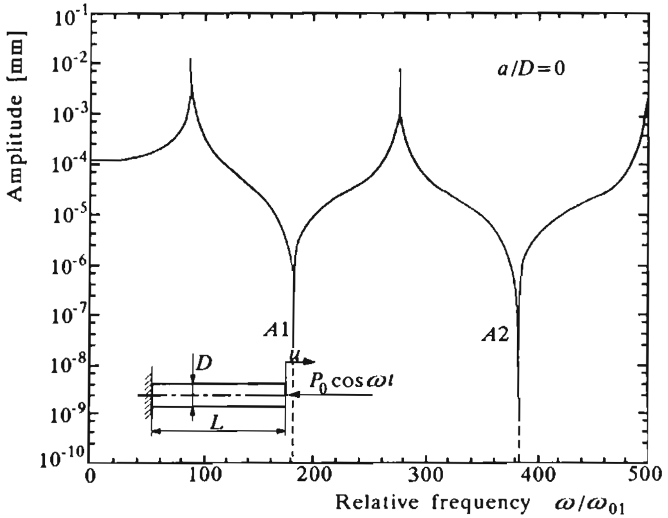

Fig. 6. Anti-resonance frequencies for the cantilever cracked beam – Krawczuk (1992); $A1$ – first anti-resonance frequency, $A2$ – second anti-resonance frequency

The anti-resonance frequencies have been suggested as a potential damage indicator by Afolabi (1987) and Rytter (1993). Afolabi makes numerical calculations on a 3-degree-of-freedom-model of a cantilever. He observed that "as the point of measurements gets closer to the location of the defect, fewer and fewer anti-resonances are shifted from their original values until one gets to the location of the defect, at which all the anti-resonaces are exactly as they were in the undamaged state". By this way it is possible to detect location of the damage.

The main disadvantage in using anti-resonance frequencies as damage indicator is that measurement of response and load at a large number of points of the structure has to be performed.

6. Amplitudes of forced vibrations

The changes in amplitudes of forced vibrations due to the fatigue cracks were applied as damage indicator by Akgun et al. (1985); Akgun and Ju (1987), (1990); Collins et al. (1991), (1992); Gounaris and Dimarogonas (1988); McFaden (1986); Nezu and Kidoguchi (1980); Ostachowicz and Krawczuk (1990); Rogers and Hollingshead (1988).

Akgun et al. (1985) proposed to use the so-called relative transmissibility function as a damage indicator. The transmissibility is defined as the non-dimensional ratio of the response amplitude of a system in steady-state forced vibration to excitation amplitude. The response can be displacement, velocity or acceleration. The relative transmissibility function is defined as

$$R_T = \frac{T_d}{T_u} - 1$$

where T_d and T_u are the transmissibility functions of the damaged and the undamaged structures, respectively.

Theoretically, the relative transmissibility function takes values within the interval $[-1, \infty]$. When the value of R_T at measurement points increases it can be treated as the diagnostic indicator which informs that damage has appeared in the construction. The changes of R_T for frame constructions obtained from numerical calculations are shown in Fig.7.

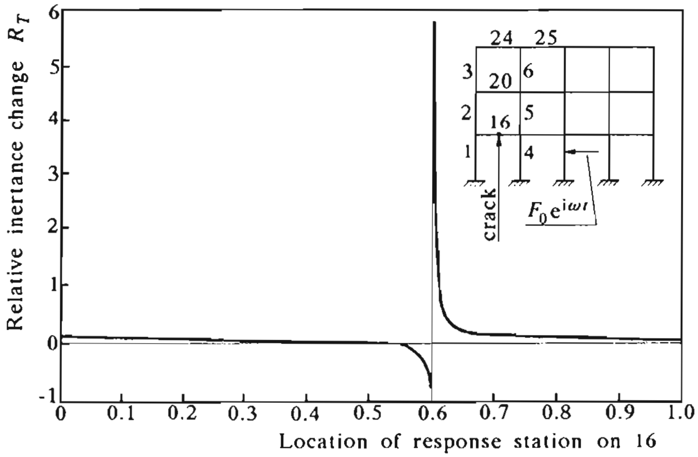

Fig. 7. Changes of relative transmissibility function for the cracked frame – Akgun and Ju (1990)

In several papers (Saneyi and Onipede (1991); Ben Haim (1992)) the transmissibility function received from vibration measurements was replaced (with a good result) by static displacements.

7. Sub or superharmonic peaks in the spectra

The sub or superharomic peaks in the spectra are due to the non-linear behaviour of the construction. The fatigue crack during one period of vibration can be opened and closed. In result the changes in stiffness of the construction due to the crack are non-linear. For this reason the fatigue crack can introduce sub or superharmonic peaks into the spectra. The spectra for cantilever beam with closing crack are presented in Fig.8. This effect has been proposed as a damage indicator by Actis and Dimarogonas (1989); Huang et al. (1993); Ismail et al. (1990); Krawczuk (1994a); Friswell and Penny (1992); Ratan et al. (1993); Tsyfanskiĭ et al. (1985), (1993).

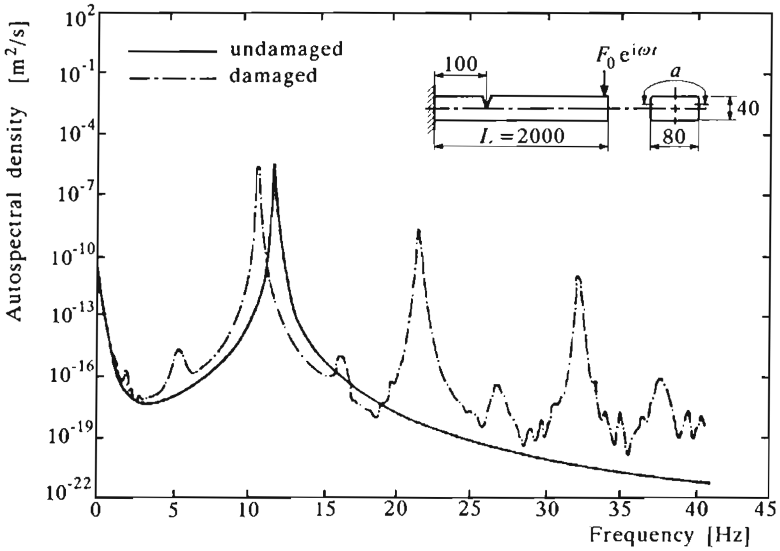

Fig. 8. Changes in spectra of vibration due to the closing crack - Rytter (1993)

From the practical point of view it is very important to known that in rotating constructional elements the crack is always open. For such elements the sub or superharomic peaks will not appear in the spectra. On the other hand, for heavy shafts this effect is very strong and allow detection of even small cracks - Huang et al. (1993).

8. . Additional resonance frequencies

Additional resonance frequencies can appear in the spectra of vibration of cracked structures the stiffness of which in two perpendicular directions is the same. From a theoretical point of view such structures have two eigenfrequencies, which have the same value for vibrations in two perpendicular directions. When the fatigue crack appears in such a constructional element changes these stiffness and instead of one eigenfrequency two eigenfrequencies appear in the spectra. This effect was proposed as a damage indicator by Rytter (1993). The main disadvantage of this indicator is the fact that it can be applied only to constructional elements with the same stiffness in two perpendicular directions – circular shafts, beams with circular and square cross-sections, square plates, etc. For this reason additional resonance frequencies should be treated as an auxiliary damage indicator only in mentioned structures.

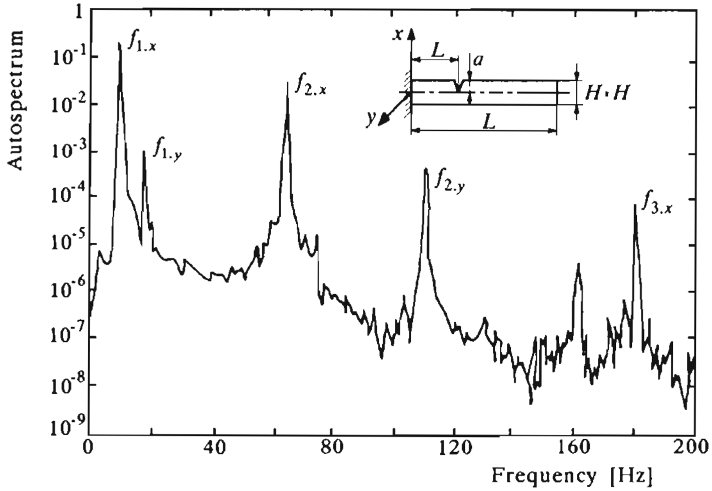

Fig. 9. Additional natural frequencies f_{1y}, f_{2y} due to the transverse crack in the cantilever hollow beam – Rytter (1993)

The additional resonance frequencies received from measurements by Rytter (1993) are shown in Fig.9.

9. Coupled vibrations

Coupled vibrations are widely proposed as damage indicator for detection of cracks in rotating shafts (cf Collins et al. (1992); Krawczuk (1994c); Ostachowicz and Krawczuk (1992); Papadopoulos and Dimarogonas (1987a,b,c), (1988a,b), (1989), (1992); Steigleder and Kraemer (1994)). The spectra of coupled bending-torsional vibrations due to the fatigue crack are presented in Fig.10.

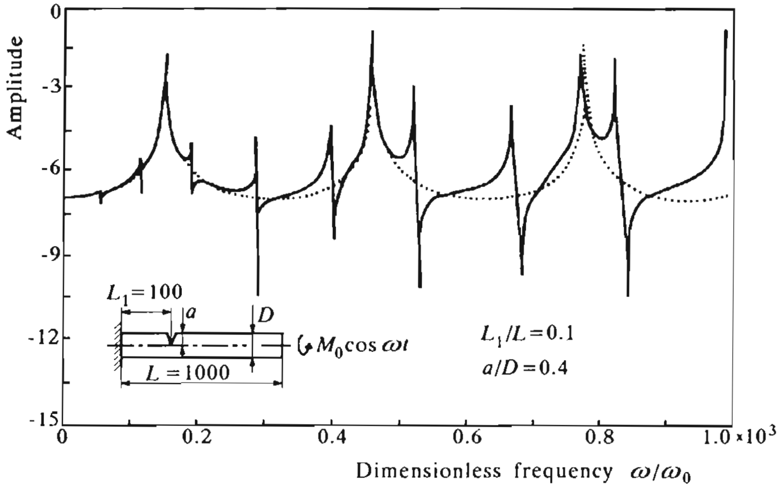

Fig. 10. Spectra of coupled bending-torsional vibrations due to the transverse crack in shaft – Papadopoulos and Dimarogonas (1987); dotted line – spectra for uncracked structure, continuos line – spectra for cracked structure

The effect of coupled vibrations is due to the fact that the fatigue crack in rotating shaft changes its symmetry. From a theoretical point of view this effect allows one to diagnose even very small cracks, less than 10% of the cross-section area. Practically, technological imperfections which appear in shafts make detection of such small cracks very difficult.

10. Phase plane plot

As it was mentioned above the fatigue crack makes a dynamic behaviour of a structure non-linear. This means that also the phase plane plots can be used to reveal the existence of cracks – Krawczuk (1994b). Typical changes in the phase plane plot for cantilever beam are shown in Fig.11.

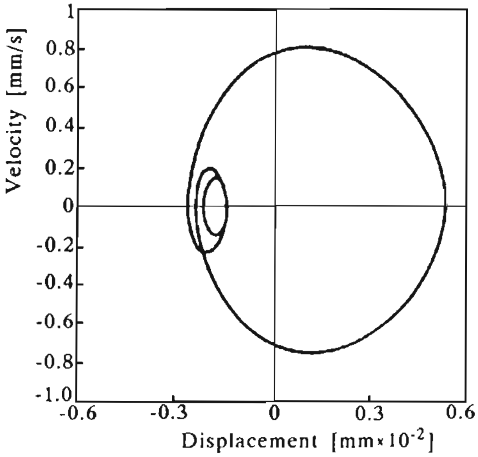

Fig. 11. Phase plot of the cantilever beam with a crack – Krawczuk (1994b)

A phase plane plots are frequently used as damage indicator in rotating machinery (cf Kolzow (1974); Henry (1978); Kottke (1981); Muszyńska (1982); Bently (1986); Jenkins (1985); Bently and Muszyńska (1986a,b), Bently et al. (1988); Diana et al. (1986); Dimarogonas and Papadopoulos (1988); Allen and Bohniack (1990)).

11. Conclusions

From the presented survey follows that some of the cited damage indicators are more efficient than the others ones in particular cases considered. However, a generally fixed order of priority for applicability of the presented damages indicators has not been made, because such a list will vary from structure to structure. It is due to the fact that applicability of damage indicators depends on several different factors. For this reason the choice of the damage indicators to be applied to a given structure should be based on the results of sensitivity studies. In other words, all the potential damage indicators are "equal" at the start of the sensitivity analysis, which will give a fixed order of priority for the applicability of the different damage indicators.

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Wskaźniki uszkodzeń stosowane do diagnostyki pęknięć zmęczeniowych konstrukcji metodami wibracyjnymi – przegląd literatury

Streszczenie

W pracy przedstawiono przegląd wskaźników uszkodzeń, które mogą być wykorzystane w diagnostyce pęknięć zmęczeniowych elementów konstrukcyjnych przy wykorzystaniu metod wibracyjnych. Opisano zalety i wady poszczególnych wskaźników. Podano przegląd ponad 100 prac związanych z zagadnieniem.

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