50^{th}. Anniversary SPECIAL ISSUE

Review of the paper

J A Brandon **"Some insights into the dynamics of defective structures"**,

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by **I.N. Trendafilova**

Abstract. John Brandon and his paper.

John Brandon has a long standing record of leading and internationally recognised research in the area of structural and nonlinear dynamics as well as on the analysis of the mechanics and dynamics of defective structures. His consistent research in these areas is aimed at in-depth understanding of the dynamics of damaged structures combined with the mechanics of crack development. John Brandon initiated and led the Cardiff research group on nonlinear structural dynamics and damage analysis and detection for a number of years. His paper "**Some insights into the dynamics of defective structures"** is an excellent example of assembling and presenting together a lot of the research in the vibration modelling and experimental testing of damaged structures. It presents and summarises the recent findings and trends in non-linear dynamics of defective structures. The reviewed paper focuses mainly on the modelling and the analysis of nonlinear effects

in structural dynamics as well as in the dynamics of damaged structures, which have mostly been neglected in the recent literature.

1. Introduction. Vibration-based structural health monitoring and the Journal of Mechanical Engineering Science.

During the last 10 years the IMech E Journal of Mechanical Engineering Science consistently published and keeps publishing leading research in damage detection as well as in structural dynamics and vibration-based structural monitoring. It follows the forefront of the research in damage assessment and nonlinear dynamics as well as the application of nonlinear methods in structural vibrations and in structural damage assessment [1-5]. Vibration-based structural health monitoring (VHM) and integrity assessment is the research which examines the vibration-response of structures in order to assess their integrity and ability to perform their functions. VHM has generally been accepted as a tool for damage detection and health monitoring but its practical applications still poses a number of problems and challenges. VHM is based on the fact that any change in a structure including a defect affects its physical properties and this eventually changes its vibration response. VHM examines the dynamics of a structure, which traditionally has been based on the assumption for linearity. A lot of practically applied VHM methods examine the lower natural frequencies of a structure to get a conclusion about the presence of a defect in it [6,7,9]. One of the problems is that the first several modal frequencies are global characteristics and on a lot of occasions prove to be unaffected by damage. Another problem might come from the fact that modal analysis, which is the most common vibration analysis approach, is based on inherently linear assumptions. The updating methods present another alternative for structural VHM [6.8]. On most occasions these methods use a linear model to predict the structural vibration response and try to extract information about the presence of damage by comparing the experimentally measured dynamic response to the modelled one and "update" the model so that it fits the experiment. But if the linearly modelled response differs from the dynamic response of the healthy structure, such a method will give a false alarm just due to discrepancies between the modelled and the actually measured vibration response. The above considerations throw light on the fact that a lot of structures in practice exhibit nonlinear dynamic behaviour. This might be due to nonlinearities in the material properties, the joints and the connections as well as geometric nonlinearities. In general the presence of a defect will add to these nonlinearities and will also contribute to the nonlinear dynamic behaviour of a structure. This is the main focus of the considered paper. It is concerned with the fact that such nonlinearities cannot always be accepted as "small" and there is of course the question of the definition of small. When can we consider a dynamic behaviour as strongly nonlinear and when do we consider it as weakly nonlinear? John Brandon's paper was the first to introduce some definitions and characteristics of nonlinear dynamic behaviour. It also offers a number of circumstances which can justify the assumption of a linear model. As pointed out in the paper a linear model is accepted not only when it provides a sufficiently precise approximation of the structural dynamic response but also because the nonlinear dynamic modelling is not advanced enough to be able to cover a lot of cases of nonlinear behaviour. Nonlinear effects are not rare or insignificant in the dynamics of structures, "rather they are difficult to place in the framework of structural dynamics" which has been constructed mostly for linear structures. The reviewed paper is mostly based on the extensive experience of the Cardiff research group which includes theoretical modelling, simulation and experimental testing of defective structures. The three areas, as rightly mentioned in the paper, have always been in strong and constant interaction and this provides the basis of the author's deep understanding about the dynamics of defective structures.

2. Detailed review of John Brandon's paper

The paper starts with a short theoretical analysis on the modelling of nonlinear vibratory behaviour starting from first principles and using the general differential equation for the vibration of single degree of freedom systems. This reveals the dependence of the general solution of the differential equation on the initial conditions for nonlinear systems. This dependence becomes significant especially for strong nonlinearities and has been investigated for the case of cracked Timoshenko beams in another paper by Brandon and Abraham [4]. The paper then introduces more rigorous and pragmatic criteria for discriminating between strong and weak non-linearities. It points to the fact that defective structures have been treated using linear analysis as well as chaos-based methods, which confirms their controversial nature, because as the author rightly points out none of these studies is "definitively right or wrong". The author suggests some characteristics that can be used for the analysis of defective structures with strongly nonlinear behaviour. Some of them are based on the phase-space representation of the structural vibration response and are similar to features suggested by other authors e.g. [5,10,11,12]. But the author complements these with the frequency domain of the vibratory motion, which he describes as a source for "qualitative information".

The paper goes on to introduce the analytical modelling approach exploited by the Cardiff research group. The structures considered were restricted mainly to Timoshenko cantilever beams. What I find very interesting and attractive in the modelling strategy described is that it combines structural dynamics and fracture mechanics which very few research studies do. The used strategy combines the modelling of the crack development and the beam vibration behaviour and its vibratory modes including the coupling of axial and transverse modes. Most fracture mechanics studies focus on the material properties, while the majority of structural dynamics studies concentrate solely on structural properties, while damage is represented in terms of stiffness and/or damping parameters. Studies that combine both effects- the material behaviour, not only in the sense of fracture mechanics but in terms of material modelling as well, and the structural dynamics- are quite sparse and mainly restricted to very simple structures. The present paper represents an approach which permits further developments for more complicated structures and is consequently very useful in the sense of an enterprise strategy.

The next paragraph deals with the simulation of the dynamic behaviour of cracked structures. It plunges in depths of phase space representation and Poincare maps combined with spectral analysis to emerge with some clear and useful conclusions about the dynamics of cracked beams. The research is concerned primarily with piecewise linear systems for which the two most basic excitation conditions were considered, namely free vibration and sinusoidal excitation. One of the most interesting conclusions from the time-domain phase space analysis of cracked beams that the author suggests is that "the straightforward analytical results for single degree of freedom (DOF) systems cannot be extended to multiple DOF piecewise linear systems". This was based on the research of the group in simulation of the response of cracked beams released from rest with initial displacement of the free end. The Poincare maps obtained for closed and open crack periods were both structured contrary to the expectations while the map for the mean period was unstructured. This conclusion is in agreement with the observations of other authors [5,10,11] suggesting that the introduction of damage makes the dynamics more structured and more predictable rather than the opposite, which is in fact the expected behaviour.

Another very interesting and useful conclusion of the paper concerns the recognition of impulsive behaviour as one of the indicators for the presence of damage. This was suggested by the in depth analysis of the behaviour of vibrating cracked beams by Brandon and Abraham [4] which was confirmed by the experimental studies carried out by the Cardiff research group led by John Brandon. A number of nonlinear effects were observed in the dynamic behaviour of cracked beams some of which indicated the onset of strongly nonlinear or chaotic behaviour. One of the main findings of the experimental work of the author and his research group, which was consistent with their modelling and simulation results as well as with the previously mentioned conclusion about the presence of structure in the dynamics of defective beams, was that period doubling or sub-harmonics were quite rare for cracked beams. The author also observed the dominance of the driving frequency in the spectrum of cracked beams which partly motivated his suggestion for the use of autocorrelation of the structural response. This is a tool which, as the author righteously mentions, is paid small or no attention in the analysis of nonlinear dynamic behaviour and in the interpretation of the vibration response of defective structures. Although a number of authors suggest the use of conventional statistical characteristics [5,11,12] this investigation draws attention to the use of the autocorrelation as another conventional statistical tool which also turned out to be quite useful for the analysis of the dynamic behaviour of defective structures. This is a very interesting and useful tool which leads to important indications about the behaviour of cracked beams, one of which is that the harmonics of the response appear to be generated by the second order sub-harmonics rather than by the driving frequency (which is suggested by the time and the frequency domains of the measured response). The author is thus able to observe long term nonlinear behaviour in the dynamics of cracked beams which enables the presence of bifurcation to be detected in the long term phase space representation. This is again a very interesting conclusion which is pioneered by the research team in Cardiff. This long term nonlinear behaviour can be a key to the development of useful and consistent damage indicators. The paragraph dealing with the experimental studies of the Cardiff research group introduces the results of some parameter variations on the response of cracked beams. A particular finding is the presence of a wide range of sub-harmonics in the response of the cracked beam. The author argues the existence of instability related to some of these sub-harmonics. He tries to clear a misinterpretation of the period-three components in the spectral response, which are often understood as an implication for instability. The paper demonstrates several different cases of period three vibration which clearly show stable chaotic or periodic oscillations. This particular paragraph as well as the whole work shows a deep understanding of the phenomena relating to nonlinear dynamics and chaos.

The paper concludes with some final remarks summarising the practical implications of the research of the Cardiff group. It summarises the principal research questions, which motivated and led the research in Cardiff University. These include the prediction of potential sources of failure, the continuous monitoring of a structure over its life time, the prediction of its residual life once faults have been identified as well as problems concerned with any remedial actions that could be undertaken. These are obviously major questions which go considerably ahead of structural health monitoring. As the author justly mentions the principal aim of the paper (which is motivated by the research in Cardiff) is "to contribute new understandings of the dynamics of defective structures to the subject of structural integrity assessment". These new understandings can be further used in answering the above mentioned fundamental questions.

3. Summary and conclusions

Some of the main contributions of the research performed by John Brandon and his collaborators can be summarised as follows:

- The research was successful in the achievement of considerable linkage between theoretical modelling and experimental identification and the use of theoretical modelling for the prediction of the dynamic behaviour of damaged structures.
- A particularly useful part of this research is the employment of the accumulated experimental data and the understanding gained from it to improve the theoretical modelling. The research uniquely combines the linear modelling in terms of a modal model with a further state space modelling and analysis. The paper also contributes to understanding of the interaction of the driving signal and a defect present in a structure.

- The research promotes an understanding of the relation between the changing structural properties and the health monitoring process. The idea is to be able to take into account the changing structural properties especially in the case of nonlinear structures during a process of damage assessment.
- The paper summarises the main priorities of structural health monitoring stating that the prediction of imminent failure is perhaps the most important question of structural health monitoring. Gaining information about the location and the severity of the fault is essential for any effective remedial action as well as the prediction of the remaining life of the structure.

The reviewed paper as well as the research of the research group in the Cardiff school of Engineering presents a major contribution towards the area of vibration-based structural health monitoring as well as to the field of nonlinear structural dynamics. The main gift of the research is that it promotes a deep understanding of the nonlinear effects and the dynamics of defective structures. It links modelling, simulation and experimental testing to promote a deeper knowledge in the development of defects in structures and their influence on the vibrational properties of the structure combining linear analysis and modelling of non-linear effects.

References.

1. D L McDowell, J D Clayton and V P Bennett, Integrated diagnostic/prognostic tools for small cracks in structures , **2000**, ***Journal of Mechanical Engineering Science, Volume 214, Number 9*** , pp 1123-1140.
2. Y Pu, J Chen, J Zou and P Zhong, The research on non-linear characteristics of a cracked rotor and reconstruction of the crack forces, **2002**, ***Journal of Mechanical Engineering Science, Volume 216, Number 11,*** pp 1099-1108
3. M Sahin and R A Shenoi, Vibration-based damage identification in beam-like composite laminates by using artificial neural networks, **2003**, ***Journal of Mechanical Engineering Science, Volume 217, Number 6*** , pp 661-676.
4. J A Brandon, A E Stephens, E M O Lopes and A S K Kwan, Spectral indicators in structural damage identification: a case study, **1999**, ***Journal of Mechanical Engineering Science, Volume 213, Number 4***, pp 411-415.
5. I Trendafilova, Vibration-based damage detection in structures using time series analysis, **2006**, ***Journal of Mechanical Engineering Science, Volume 220, Number 3***, pp 261-272.
6. S.W.Doebling, C.R. Farrar and M.B. Prime, A Summary Review of Vibration-Based Damage Identification Methods, **1998*, The Shock and Vibration Digest, Vol. 30, No. 2,*** pp. 91-105.

7. N.Hu, X Wang, H. Fukunaga, Z.H Yao, H.X. Zhang and Z.S. Wu, Damage assessment of structures using modal test data, **2001*, International Journal of Solids and Structures, vol.38/18,*** pp.3111-3126.

8. P. Verboven, E. Parloo, P. Guillaume and M. Van Overmeire: Autonomous structural health monitoring-part I: Modal parameter estimation and tracking, **2002,** ***Mechanical Systems and Signal Processing, vol. 16(4),*** pp 637-657.

9. P.Cawley, and Adams, R. D. The location of defects in structures from measurements of natural frequencies., ***J. Strain Analysis***, 1979, **14**(2), 49–57**.**

10. Todd M., J M Nichols, L M Pecora and L Virgin, Vibration-based Damage Assessment Utilizing State Space Geometry Changes: local Attractor Variance Ratio, **2001,** ***Smart Mater. Struct. 10,*** pp 1000-1008.

11. Nichols J.M., Trickey S.T., Seaver M., Damage detection using multivariate recurrence quantification analysis, **2006**, ***Mechanical Systems and Signal Processing 20***, pp 421–437.

12. Sohn H. and Farrar C., Damage diagnosis using time series analysis of vibration signals, **2001**, ***Smart Mater. Struct.*** **10** pp 1–6.