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Cracked Rotors: A Survey on Static and Dynamic Behaviour Including Modelling and Diagnosis, N. Bachschmid, P. Pennachi, E. Tanzi (2010). 399 pp., ISBN: 978-3-642-01484-0

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Book review

Cracked Rotors: A Survey on Static and Dynamic Behaviour Including Modelling and Diagnosis, N. Bachschmid, P. Pennachi, E. Tanzi (2010). €83, 399 pp., ISBN: 978-3-642-01484-0

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Rotating machines play a paramount role in the technologies of energy, transport, and lots of equipments. Therefore they hold a strategically important position in our modern societies, which require becoming more and more economical and safer. These challenges demand to make the rotating machinery technologies innovative, leading to substantial progress concerning the performances, the cost and the nuisance reduction while continuing to maintain the reliability, durability and safety.

In order to satisfy this latter objective, a great attention has to be paid on the crack propagation due to its negative effect on the rotating machine integrity. This technological risk due to fatigue has motivated a great research interest for the past 40 years. In order to be able to have an early crack detection, *i.e.* to prevent as soon as possible catastrophic failures, many scientific efforts have been invested for developing reliable detection techniques based on discriminating indicators. Many researchers have carried out investigations on cracked rotors experimentally and/or numerically, most of their results have been published in journal articles and conferences proceeding.

In this scientific and technological framework, the book "Cracked rotors" based on a more than 20-year experience of the authors, is a deep, rigorous, and very interesting monograph on the observed phenomena, on the laboratory and in-situ tests carried out on academic and industrial rotors, on simple and more sophisticated modelling. This is due to the great background of the authors on industrial case studies, especially in power generation industries, associated to their relevant expertise in modelling, experimentation and diagnosis. It should be mentioned that the authors have a well known worldwide recognition in rotordynamics.

This 400-page hard cover book is well documented with case histories, and well illustrated by convincing pictures, especially on cracks. The numerous sketches and graphs as well as the derivation of equations show the manifest sake of the authors to be the more pedagogical as possible.

The objective of the authors is clear: it consists in presenting the technical issues and treating them as simpler and more intelligible as possible. All along the book the authors have the way to prove and to illustrate their investigations using industrial applications or observation. The developments use numerous and various references listed at the end of each chapter. They consist of books, articles, proceeding communications and standards.

The book contains eight chapters linked altogether by a judicious inductive presentation: description and explanations of cracks and their consequences on the rotordynamics, experimental means to detect the cracks, existing models and numerical simulations, and finally diagnosis techniques.

- A large set of existing cracks in mechanical parts of industrial rotating machines is fully described in Chapter 1: cracks in the frame of a stator, at the blade root, in shafts, in coupling. The explanations on shapes, positions, extensions and origins are given. Their catastrophic consequence is supported by a long list of accidents occurring on machines installed worldwide.
- In the following chapter, the authors use a condition monitoring system to analyse the lateral vibrations of industrial machines for showing the influence of cracks on the level of harmonic components of the dynamic behaviour and therefore their possible detection. Thus the analyses of the responses in the time domain of turbo-generator and reactor cooling pump running at a constant operating speed of rotation show the influence of a crack growth. In the same way, they observe the effect of the heating and cooling transients on a steam turbine and on a turbo-generator. Finally their investigation concerns the use of run-up and run-down of the same turbo-generator and another generator, as well as the EDF EUROPE test rig to highlight the presence of cracks.
- The third chapter concerns several crack detection tests carried out in laboratory. The static and dynamic experimental analyses are performed on removed rotor equipped with academic boundary conditions. Dynamic tests consist of classical modal analyses. The natural lateral frequencies are analysed while in static test, the deflection is measured. Non destructive tests based either on visual or ultrasonic techniques, round off these laboratory investigations. The authors have taken care to indicate the advantages and drawback of each test.

- In order to study in detail the breathing mechanism of a crack of heavy horizontal rotor and the thermal transient influence on crack effect, the fourth chapter presents original tests, first on cracked shaft and then on the previous turbo-generator equipped altogether of strain gauges. The static tests performed on the shaft equipped with a circumferential set of strain gauges permit establishing a measured axial strain evolution versus the angular position that validates the FLEX model developed by the authors. The transient thermal tests are carried out on the previous turbo-generator either running at constant low speed of rotation or running up. The authors examine the evolution of the harmonic components during the cooling and heating transients.
- Chapter 5 is a very exhaustive bibliography of crack modelling by using several approaches: the elastic strain energy release rate (SERR) and the finite cracked element of the fracture mechanics, the breathing behaviour and thermal influence, the energy balance, the equivalent beam used in the FLEX model and finally the 3D finite element model. Results obtained from the SERR, FLEX and 3D models are compared on an academic cracked shaft. Then, using a simple model, a Jeffcott rotor, the authors explain how to establish the stiffness matrix taking into a breathing steering function. This approach is appreciable because it explains the basic phenomena of cracked rotor in the presence of the gravity. As the lateral behaviour of the rotor is governed by a set of differential equations with time-varying stiffness parameter, the dynamic stability is investigated using the Floquet theory and the stability chart is plotted. Moreover the mass unbalance response is calculated with a special consideration of the forward and backward whirls of the orbits. In the final section the FLEX model is implemented in a finite element model.
- In chapter 6, the two academic rotors of the EDF-EURoPE and Politecnico-di-Milano MODIAROT test rigs as well as others rotors of industrial machines in service are subject to FE modelling and measurements. The comparison of the measured and predicted mass unbalance responses show a satisfactory agreement. The effect of the transverse crack combined also with cooling and heating transients is well reproduced by the model of cracked rotors. Then the validated models permit examining the influence of the depth, position and shape of a crack, and moreover calculating the bending moment in shaft line of turbo generator. Here the final section concerns a detailed investigation on the effect of shear force on bending and torsion behaviour of a cracked overhung shaft.
- Chapter 7 presents co-lateral effects of cracks: first on the axial and torsion behaviour, second on a possible torsion-bending coupling due to helical cracks, and third on the nonlinear behaviour. Here also academic and industrial cracked rotors are investigated. In particular the 3D and FLEX models are used to prove the axial and torsion deflections due to bending-torsion couplings. The helical crack of an overhung shaft is modelled with 3D finite elements and the use of slave and master degrees of freedom. The authors estimate that a helical crack can have an influence only in the absence of driven torque *i.e.* when the rotor runs down. The nonlinear analysis is carried out using finite element simulations of an academic rotor mounted on hydrodynamic fluid film bearings: the lateral instabilities and the sub-harmonic components of the response of the cracked rotor subject to its own weight can occur under the assumption of light damping.
- The final chapter falls in the area of excellence of the authors. The first approach presented consists in a knowledge based system using a fault matrix. Membership functions, symptoms, fault descriptions, and fault versus symptom tables are presented. The EURoPE test rig permits presenting results obtained with the qualitative approach for different crack depths and speeds of rotation. This is a very useful exhaustive qualitative data base. The second approach based on a multi-degrees-of-freedom modelling permits localising the cracks and its severity. It uses parity equations to perform the crack diagnosis: the input variables affected by the crack defaults being not measurable, the approach focuses on the comparison of output measured and predicted variables. Consequently external forces equivalent to the crack effect are to be predicted. The FE model of a steam turbo generator is used to apply this approach and to show how to identify a crack depth. In order to compare predicted and measured mass unbalance responses, the academic rotors of MODIAROT and EURoPE test rigs bring one and three configurations of cracked rotors respectively. Generally speaking, the crack identification can be considered successful even in the case of small cracks.

In conclusion, the subtitle of the book defines very well the content: this is an excellent survey on static and dynamic behaviour including modelling and diagnosis with the main sake to clarify the technological challenges, the experimental and modelling approaches and the existing diagnosis techniques.

Undoubtedly this book is a major contribution to the dynamics analysis of rotating machines and more particularly of the cracked rotors.