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A sensitivity analysis of vibrations in cracked turbogenerator units versus crack position and depth

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ABSTRACT

The dynamic behaviour of heavy, horizontal axis, turbogenerator units affected by transverse cracks can be analysed in the frequency domain by means of a quasi linear approach, using a simplified breathing crack model applied to a traditional finite element model of the shaft-line. This allows to perform a series of analyses with affordable computational efforts.

Modal analysis combined to a simplified approach for simulating the dynamical behaviour allows to predict the severity of the crack-excited vibrations, resolving the old-age question on how deep a crack must be to be detected by means of vibration measurements of the machine during normal operating conditions.

The model of a 320 MW turbogenerator unit has been used to perform a numerical sensitivity analysis, in which the vibrations of the shaft-line, and more in detail the vibrations of the shaft in correspondence to the bearings, have been calculated for all possible positions of the crack along the shaft-line, and for several different values of the depth of the crack.

1. Introduction

A very special case of damage in mechanical structures is the development and propagation of transverse cracks in rotating shafts. Transverse cracks are cracks in which the crack surface is orthogonal to the rotation axis of the shaft. The obvious difficulty in inspecting a rotating shaft during the operation of the machines makes the detection of cracks in these structures much more difficult than in static (non-rotating) structures. Therefore, symptoms are needed that can easily be measured (which are typically the vibrations) and that are able to indicate clearly the presence of a crack in a rotating shaft. If these symptoms arise in a machine, the machine can be stopped, the shaft can be removed and inspected with standard procedures and catastrophic failures of the complete set can be avoided. The accurate modelling of cracked shaft dynamical behaviour allows simulating the vibrations of a shaft affected by a transverse crack in different positions and with different depths. More in detail, the vibrations can be calculated in correspondence to the bearings of the machine, where they are measured in real machines, and its severity allows to predict the possibility of detecting the presence of the crack. A crack in rotating shafts is most likely to appear in correspondence to sharp changes of diameter or of the geometry of the shaft (presence of holes, slots for keys, threads and so on) in regions of high stress concentration.

Thermal stresses that develop in thermal machines, like steam turbines, and thermal shocks are also responsible for generating high local stress intensity factors that can cause the starting of a crack and its propagation.

In rotating shafts, the cracks propagate generally in a plane perpendicular to the shaft axis, when the axial bending stresses are prevailing, generating a transverse crack. The propagation velocity in a rotating shaft may change from case to

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case. Very frequently the crack moves by steps, alternating progresses to stops: both can be seen on the cracked surface pattern where rest lines called *beach marks* are recognizable. Generally, when the crack is approaching to a dangerous depth, it propagates more quickly, with a propagation velocity that increases exponentially, as can be deduced also by the so-called Paris law [1]. The final growth up to a critical dangerous depth takes sometimes only few days of operation. Cracks in power station and industrial plant machinery, steam turbines, generators and pumps have been discovered and documented in many European power plants as well as in the Far East and in the USA [2–22]. They have generally been discovered by analysing the monitored vibrations and the machines have been stopped before the occurrence of a catastrophic failure, but in some cases the symptoms have not been recognized in time and the machines burst. As far as the authors know only one published paper [23] deals with the possibility of discovering from vibration measurements the presence of cracks in 900 MW turboset units, for a *given position* of the crack and for different crack depths and circumferential extensions.

In the following the effects of transverse cracks with rectilinear tips and different depths (in this case the circumferential extensions are defined directly from the depth) that have developed in *any position* of a shaft-line are analysed.

2. Model of the breathing crack

The breathing mechanism is a result of the stress and strain distribution around the cracked area, which is due to static loads, like the weight, the bearing reaction forces and so on, and dynamical loads, like the unbalance and the vibration-induced inertia force distribution. Accurate modelling of the breathing mechanism has been generally disregarded in the literature. When the static loads overcome the dynamical ones, the breathing is governed by the angular position of the shaft with respect to the stationary load direction, and the crack opens and closes again completely once each revolution. The transition from closed crack (full) stiffness to the open crack (weak) stiffness has been generally considered in the literature abrupt (for the first time in [24]) or represented by a given cosine function (for the first time in [25]), but can be calculated step by step in an iterative procedure. Different approaches are compared in [26].

3D non-linear finite element calculations allow the breathing mechanism to be predicted accurately, when the loads are known, but extremely cumbersome, costly and time consuming (due to the need of a refined mesh in the crack region and to the non-linear contact conditions).

A simplified model, which assumes linear stress and strain distributions, for calculating the breathing behaviour, has been developed by the authors and proved to be very accurate [26]. The determination of the breathing behaviour is a non-linear iterative procedure. The breathing mechanism is affected also by transient thermal stresses, which can arise in rotating shafts during a change in operating conditions, and by pre-stresses, which can develop during the crack propagation. These pre-stresses can further open the crack or can tend to hold the crack more closed, influencing the breathing behaviour (as described in [27]). Also these aspects have been generally completely disregarded in previous investigations.

The proposed model is as follows: the initial position of the main inertia axes of the supposedly partially open crack surface is assumed as well as a linear axial stress distribution due to the bending load to which eventually also thermal stresses are superposed. Then the compressive and tensile stresses are defined: cracked surfaces where tensile stresses should appear are "open" areas, where compressive stresses appear are "closed" areas (see Fig. 1).

Indeed open and closed areas define also the main inertia axes position. Therefore the procedure has to be repeated iteratively, until the position of the main axes remains stable.

With this simplified model accurate results have been found, despite the fact that the proposed approach assumes linear stress distribution where in reality the stress distribution is strongly non-linear, as it is well known from Fracture Mechanics and from 3D finite element non-linear analyses.

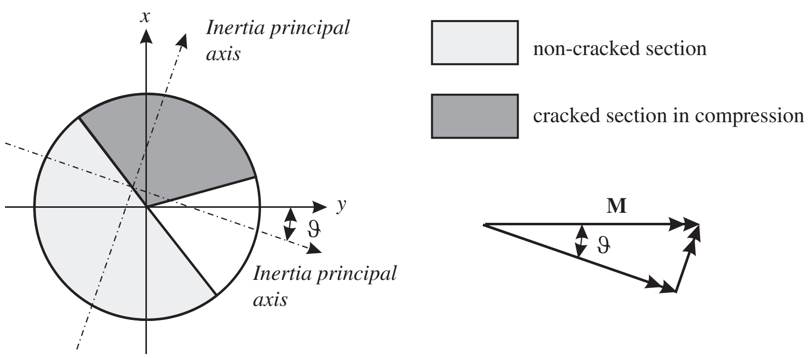

Fig. 1. Main axis of inertia and the bending moment decomposition in a generic position of the cracked section.