Available online at www.sciencedirect.com
SCIENCE DIRECT®
Nuclear Engineering and Design 236 (2006) 333–349
Nuclear Engineering and Design
www.elsevier.com/locate/nucengdes

Investigation of helix-shaped and transverse crack propagation in rotor shafts based on disk shrunk technology

B. Andrier [a], E. Garbay [a], F. Hasnaoui [b], P. Massin [c,*], P. Verrier [b]

[a] *EDF/GDL, 2 Rue Ampère, 93206 Saint-Denis Cédex, France*
[b] *EDF/DRD, 1 Avenue du Général de Gaulle, 92141 Clamart, France*
[c] *CNRS-EDF, UMR 2832, 1 Avenue du Général de Gaulle, 92141 Clamart, France*

Received 18 April 2005; received in revised form 15 September 2005; accepted 16 September 2005

Abstract

It is known from international feedback that the rotor shafts of the turbo-generators with disk shrunk technology may have transverse cracks located near the keys which maintain the bond between the core of the shaft and the surrounding disks in case of over speed. It was understood that the cracks were initiated by fretting between the keys and the shaft and that they propagated due to a fatigue mechanism generated by the rotational flexion of the shafts under gravity. The destructive observation now correlated to the service history of the shaft shows different mixed modes propagation phases and a stopped circumferential crack evolution during the last months of service of the shaft. Mechanical studies based on the determination of the stress intensity factors provide the evolution of the stress intensity factors during the crack propagation. They give access to information not available otherwise to explain the observed crack profiles. Finally, experimental investigations are needed to obtain the kinetics as a function of the stress intensity factors. The information provided is helpful in determining the possible crack profiles to be detected by the most suitable vibratory surveillance systems before failure in service of the shaft line.

1. Introduction

In October 1998 the ultrasonic inspection of a low pressure shaft revealed the presence of two cracks at the right of two keys of the central spacer, which was confirmed in 2001 by a destructive observation on a deposed shaft. From then on ultrasonic inspections have shown that the cracking phenomenon was generalized to the shafts of the 900 Mwe units equipped with disk shrunk technology. Cracks are almost transverse to the shaft axis.

After initiation in the keys region, cracks propagate under fatigue due to a rotational bending loading. The bending results from gravity, and its variations result from the rotation of the shaft. Two main operating conditions are under investigation: barring at 75 rpm and 20 °C during which rotational bending effects are predominant and normal operating conditions at 1500 rpm and 250 °C during which these rotational bending effects compete with a torsion effect due to the coupling of the line of shafts with the alternator.

A workshop composed of several teams from EDF and ALSTOM helped define a limit crack depth. This threshold was established using the experimental feedback from the deposed shaft, confirmed later by numerical investigations and the exploitation of experimental results. A research program based on mechanical studies and experimental investigations was launched by EDF. The aim of this program was to identify which operating conditions were limiting the life expectancy of the rotor shafts and to identify which margin existed with respect to the brutal rupture of the shafts.

In addition to this program vibratory surveillance systems were investigated in order to know if they are capable of detecting suspected crack profiles in service conditions. Different vibratory detection methods were analyzed amongst which those based on bending or torsion modes and bending harmonics of the rotational speed of the shaft.

2. Description of the cracks

A shaft line is composed of three lined low pressure turbines connected to a high pressure turbine on one end and to the alternator that provides energy on the other end. The low pressure

* Corresponding author.
E-mail address: patrick.massin@edf.fr (P. Massin).

0029-5493/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.nucengdes.2005.09.012

Nomenclature

a	crack depth (mm)
$2b$	circumferential crack extension (mm)
d	diameter of the non-cracked part of the shaft, $d = D - 2a$ for revolution cracks (mm)
D	diameter of the shaft (mm)
K_1	mode I stress intensity factor (MPa m$^{1/2}$)
K_2	mode II stress intensity factor (MPa m$^{1/2}$)
K_3	mode III stress intensity factor (MPa m$^{1/2}$)
$\Delta K_1 = K_{1\,max} - K_{1\,min}$	variation of the stress intensity factor K_1 during a shaft revolution (MPa m$^{1/2}$)
$K_{1\,max}$	maximum value of the stress intensity factor K_1 during a shaft revolution (MPa m$^{1/2}$)
$K_{1\,max\,th}$	threshold on the maximum value of the stress intensity factor K_1 above which fatigue crack propagation occurs (MPa m$^{1/2}$)
$K_{1\,min}$	minimum value of the stress intensity factor K_1 during a shaft revolution (MPa m$^{1/2}$)
$\Delta K_{1\,th}$	threshold on the variation of mode I stress intensity factor above which fatigue crack propagation occurs (MPa m$^{1/2}$)
M	bending torque (MN m)
N	number of shaft revolutions
T	torsion torque (MN m)

turbines are named LP1, LP2 and LP3 as you get closer to the alternator.

A low-pressure turbine model is given in Fig. 1. The middle-zone figures the central spacer. The spacer is linked to the shaft by the means of three keys 120° away from each other. Cracks are located at the right of the keys and several keys may be affected. Cracks develop in the zone between spacer and disk-shrunk regions. Ultrasonic controls show that:

- The number of cracks is more important on the high pressure turbine side than on the alternator side for each LP.
- Crack depth is more important as the shaft distance with respect to the alternator increases from LP3 to LP1.

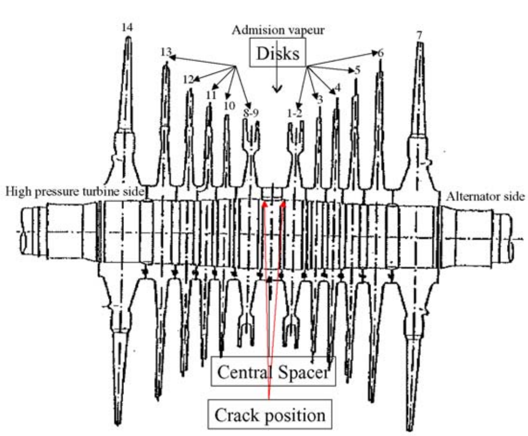

Fig. 1. Position of the cracks on the turbine.

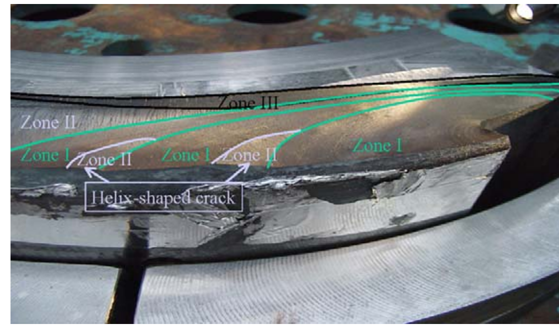

Fig. 2. Propagation zones for the crack in a deposed LP1 turbine.

The position of the cracks on the shaft axis is indicated in Fig. 1. Cracks are almost transverse to the shaft axis. Their depth is measured with respect to the 960 mm diameter of the spacer and may reach one tenth of the diameter size. The crack shape is semi-elliptic warped in helix-like way around the shaft axis.

A complete description of the crack can be found by Capponi et al. (2002). To sum up, three different propagation zones can be distinguished, represented in Fig. 2:

- Zone I: Plane propagation zones transverse to the shaft axis in mode I during barring phases, with both radial and circumferential extension. Numerous stopped lines may be seen. Disk shrunk effect induces a small static mode II that deviates the crack under the spacer. This zone is at the onset of the propagation process.
- Zone II: Helix-shaped propagation zones, with roof like profile when the crack depth is maximal, generated in normal operating conditions with an alternate mode I and a static mode II near the extremities of the crack or a static mode III at the center of the crack. The angle of the propagation plane with respect to the transverse to the axis of the shaft line is about 7° in the case of the deposed LP1 turbine. Propagation is circumferential with very few stop lines. This mode of propagation appears quickly but after the one characterizing zone I.
- Zone III: Roof-like propagation zones in the last propagation band when successive to a zone II propagation type. Quasi-transverse propagation if consecutive to a zone I propagation type with a deviation of the crack towards the spacer. Propagation is essentially radial with numerous stop lines. This propagation occurs during barring because the angle of propagation is not compatible with the torsion torque in the normal operating conditions. Moreover specific experiments were conducted in alternate mode I on non-transverse cracks, inducing a local alternate mode I + III, that showed that such factory roof profiles could be obtained.

3. Static mechanical studies

3.1. Methodology of the studies

The static mechanical studies are based on the determination of the stress intensity factors that will be used to derive the kinetics of the crack propagation and establish the margin with respect