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Numerical Analysis of Effect of Crack Location on the Crack Breathing Behavior

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Abstract**—**In this work, a three-dimensional finite element model was developed to investigate the crack breathing behavior at different crack locations considering the effect of unbalance force. A two-disk rotor with a crack is simulated using ABAQUS. The duration of each crack status (open, closed and partially open/closed) during a full shaft rotation was examined to analyse the crack breathing behavior. Unbalanced shaft crack breathing behavior was found to be different at different crack locations. The breathing behavior of crack along the shaft length is divided into different regions depending on the unbalance force and crack location. The simulated results in this work can be further utilised to obtain the time-varying stiffness matrix of the cracked shaft element under the influence of unbalance force.

Keywords**—**Crack breathing, crack location, slant crack, unbalance force, rotating shaft.

I. INTRODUCTION

BREATHING of the fatigue cracks is considered to be one of the key rotor faults for rotating machinery. In literature, it has a great deal of attention as one of the main causes of dangerous damages in rotor systems [1]. A wide variety of analytical and practical methods have been used or developed for the detection of transverse rotor cracks [2], [3]. At the beginning of the research, the crack was considered to be always fully open [4], [5]. However, this type of model does not represent the actual breathing of a fatigue crack. Improvements on the non-linear nature of crack breathing are seen through a switching crack model [6]. In this crack model, the crack is considered either fully open or fully closed. Further, these crack models are associated with chaotic and quasiperiodic vibrations that are not seen in experimental testing. Recently, realistic trigonometric functions are used to describe the crack breathing mechanism of a rotating shaft [7].

As mentioned above, numerous studies on cracked rotors are formed on the basis of a crack breathing mechanism under gravitational load, which disallows accurate modelling of crack breathing behavior under unbalance force. A few studies have examined some facets of non-linear crack breathing [8]-[10]. Researchers found that rotor with unbalance can restore the stability [7] and unbalance can amplify the influence of the breathing behavior of the crack [11], [12]. Further, the key aspect of any crack model is the reduction in stiffness introduced by the crack. The localized reduction in stiffness is directly related to crack depth, whereas the global reduction in stiffness is influenced by both crack depth and crack location along the shaft. Unfortunately, all researchers opt to either ignore crack location or mitigate its effects. This paper aims to investigate crack breathing behavior considering the effect of crack location under unbalanced force. The simulation is performed by using the commercial finite element code ABAQUS. Crack breathing, represented by crack closing percentage, is presented for numerous crack locations and unbalance configurations. The results from the unbalanced shaft model are also compared with those of the balanced shaft.

II. 3D FINITE ELEMENT MODEL

The crack section is simulated by joining two shafts together using ABAQUS 'Tie constraint' function that constitutes the intact part of the cracked section. Crack surfaces are defined by surfaces to surfaces contact interaction properties as displayed in Fig. 1. The upper part is the intact section, while the lower area corresponds to the cracked section. The shaft is meshed by using an element named C3D8R, and around the crack surfaces in both, the mesh density is much higher, see Fig. 1.

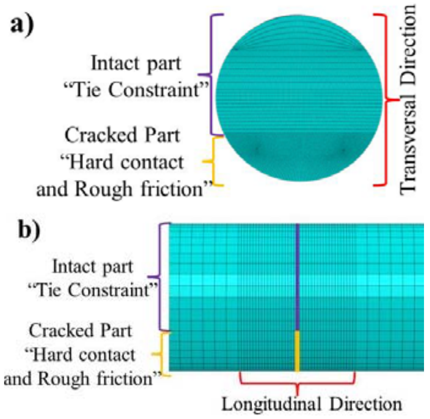

Fig. 1 Simulation details for the crack cross section and mesh around the crack in a) transversal direction and b) longitudinal direction

The simulation is conducted as a series of static problems considering the following configurations of crack location and unbalance force:

a) 40 different crack locations along the shaft length varying from 0 to L with an increment of 0.025L, where L is the shaft total length.
b) 24 different angular positions of the crack or shaft

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rotational angles, θ, varying from 0o to 360o with an increment of 15o and

c) Five different ratios of unbalance force to the rotor weight (two disks and shaft), i. e. η = 5, 10, 20, 100 and ∞ (balanced).

d) Five different crack depth ratios, μ=0.25, μ=0.5, μ=0.75 and μ=1. The crack depth ratio, μ, is the ratios of crack depth, h, to the shaft radius, R, see the Fig. 2.

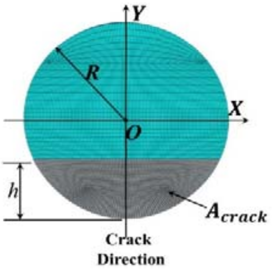


Fig. 2 Schematic diagram of the crack cross section area

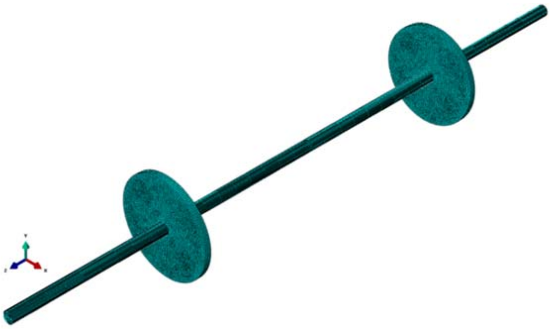


Fig. 3 Schematic diagram of the 3D two-disk rotor model

A full 3D two-disk rotor model is simulated with fixed end supports since the rotor symmetry no longer exists in the unbalanced shaft as shown in Fig. 3. The parameters of rotor model are given in Table I. The shaft self-weight and two disk weights have been applied as a gravitational force. Two disk weights have been applied at 181 mm from the two side ends. Unbalance force has been also applied as a concentrated force in horizontal and vertical directions of the shaft cross section at the right disk.

TABLE I
PARAMETERS OF THE ROTOR MODEL

Shaft Parameters	
Description	**Value**
Shaft Length, L	724 mm
Shaft Radius, R	6.35 mm
Disk Parameters	
Description	**Value**
Disk Inner Radius, R_i	6.35 mm
Disk Outer Radius, R_0	55 mm
Shaft and Disk Material Properties	
Description	**Value**
Density, ρ	7800 kg/mm^3
Poisson ratio, ν	0.3
Young's Modulus, E	210 GPa

III. Results and Discussion

The statuses of the crack in a balanced shaft along the shaft length for a full shaft rotation are shown in Fig. 4. For the balanced shaft, the percentage of closing remains constant but has sharp jumps at crack locations 0.2 and 0.8. This behavior can be easily understood from Figs. 5 and 6, where the slope of the shaft deflection curve at either 0.2 or 0.8 is zero and shaft bending direction changes by 180° across either one of two inflection points. Crack status for the balanced shaft has two types, but both are symmetrical about the first half and second half of the shaft rotation. When the crack is located in 0.2 to 0.8, the crack statuses follow a sequential change from fully open, partially open/closed, fully closed, partially open/closed and then fully open again. When the crack is located outside this region, the crack in the balanced shaft follows a sequential change beginning with fully closed than partially open/closed, fully open, partially open/closed and then fully closed again.

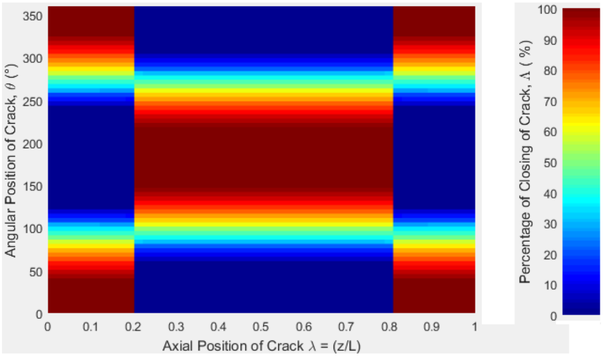


Fig. 4 Statuses of the crack in the balanced shaft along the shaft location

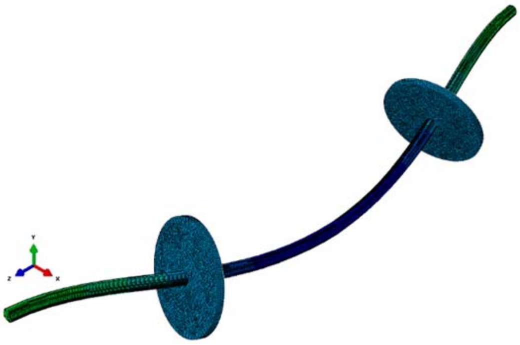


Fig. 5 Deflection of balanced shaft

For an unbalanced shaft, notably different crack breathing behaviors along the shaft length have been identified. However, at crack location 0.2 for all unbalanced cases, the crack is fully closed, never open, during shaft rotation, it is just like an uncracked shaft. The shaft will have a maximum stiffness and it becomes virtually identical to an intact shaft. On the other hand, at around crack location 0.8 for all unbalanced cases, the crack is fully open, never closed, during shaft rotation, it behaves just like a notch. The shaft will have a minimum stiffness. As discussed previously (referring to Fig. 6), this is because rotor weight does not introduce any shaft bending at these two locations and crack opening and closing are determined by the unbalance force only. Moreover, these two special crack locations in the unbalanced shaft are independent of the force magnitudes. For the other crack locations, percentage of closing progressively approaches that of the balanced shaft as unbalanced force ratio increases (unbalanced force decreases), see Fig. 7.

Effect of crack depth ratios on crack breathing behavior has been shown in Fig. 8. It is clearly found that crack statuses of unbalanced shaft highly depend on crack depth ratios. Regardless of the axial position of crack except crack locations 0.2 and 0.8, as crack depth ratios increase, the percentage of closing decreases. Thus, the stiffness of an unbalanced shaft with bigger crack depth would have lower stiffness from an unbalanced shaft with lower crack depth.

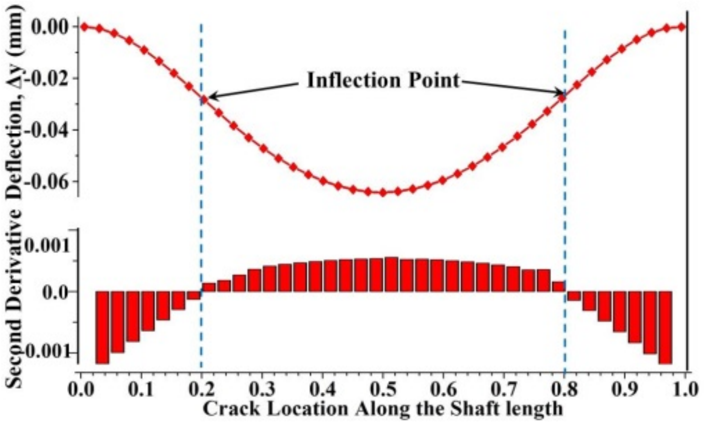
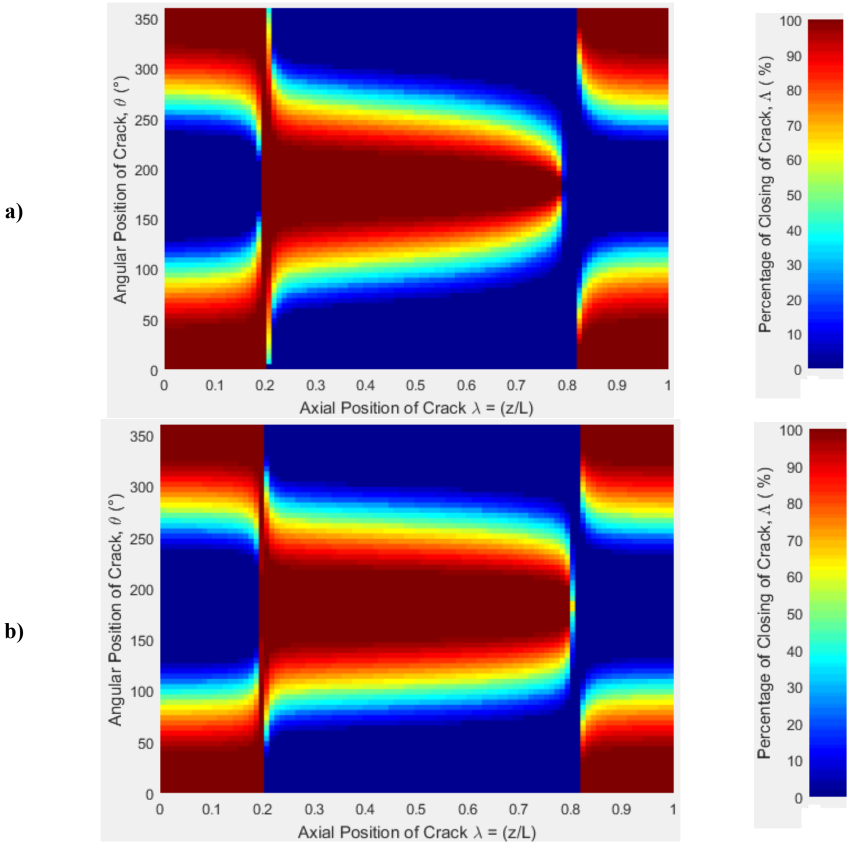


Fig. 6 Deflection curve and second derivative of deflection curve for balanced shaft



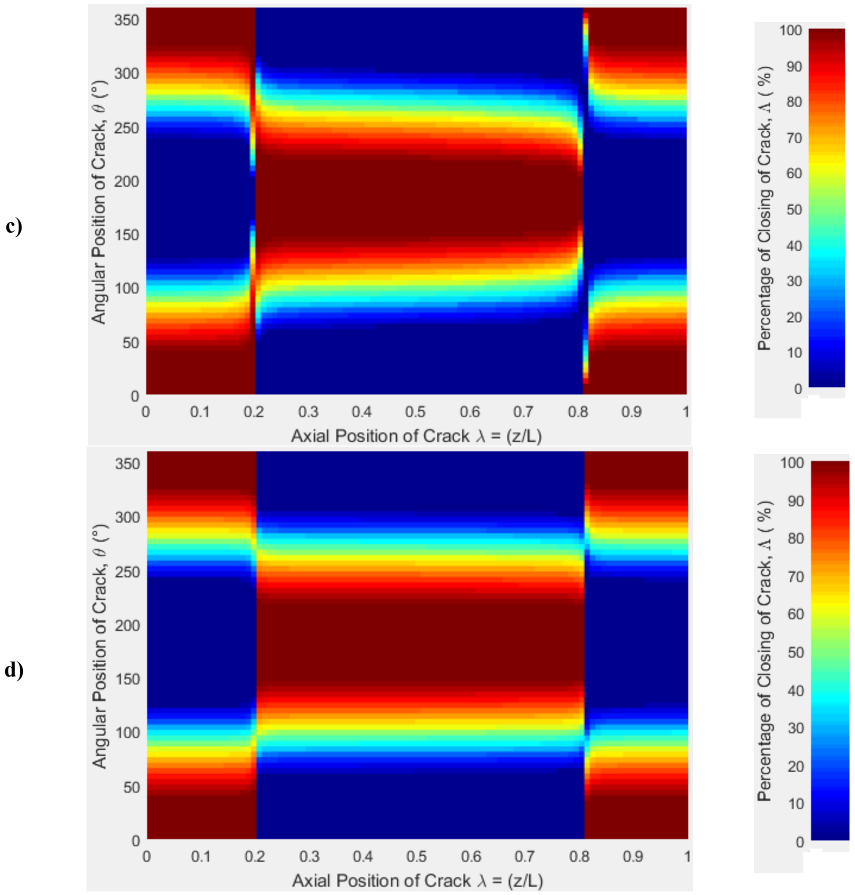
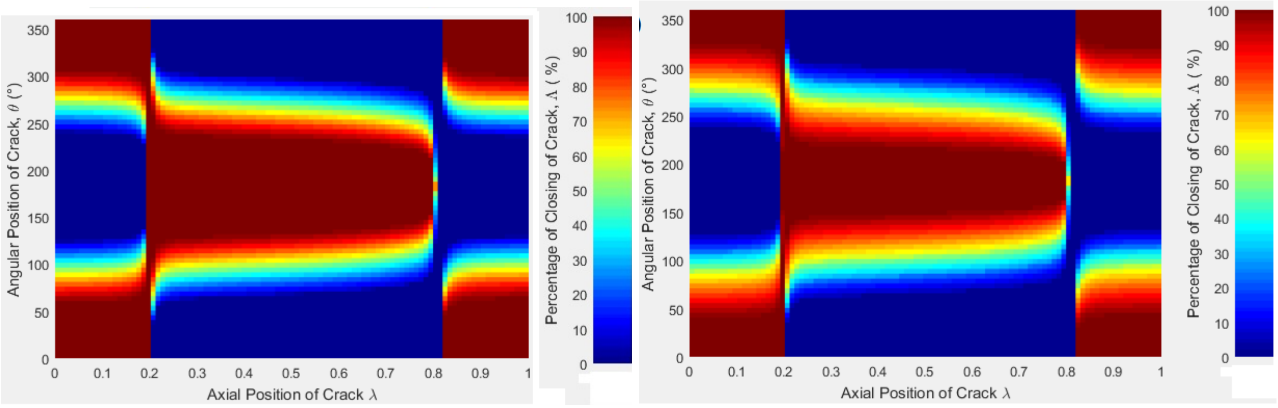
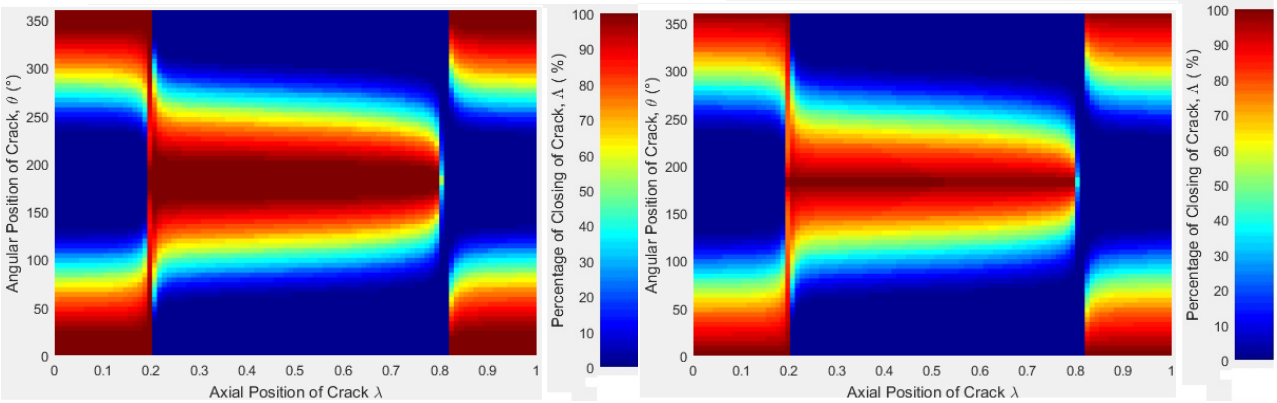


Fig. 7 Statues of the crack in the unbalanced shaft along the shaft location, a) η=5, b) η=10, c) η=20 and d) η=100



(a)

(b)



(c)

(d)

Fig. 8 Statues of the crack of unbalanced shaft along the shaft length for different crack depth ratios: a) μ=0.25, b) μ=0.5, c) μ=0.75 and d) μ=1 where η=10

During a full shaft rotation, the shaft will generally experience two processes, i.e. a stiffening process corresponding to the increasing in percentage of closing and a softening process corresponding to the decreasing in percentage of closing. Based on crack breathing behavior along the shaft length, unbalanced cracked shaft stiffness variation with crack location can be divided into three regions at 0.2 and 0.8. When the crack is located between these two points, it is obvious that the percentage of closing of the crack is lower than from the outside this region, which indicates that the unbalanced shaft is more flexible if crack, located between 0.2 and 0.8 and stiffer if crack, located outside this region.

IV. CONCLUSIONS

In this study, throughout the paper, a large number of simulations have been performed to examine the effects of unbalance force on crack breathing along the shaft length. The results are also compared with those of the balanced shaft. In the unbalanced shaft, crack breathing during shaft rotation is strongly influenced by the unbalance force and thus it behaves differently with varying its location. A crack would remain fully closed at 0.2 and fully open at 0.8, which will never happen in the balanced shaft. Finally, as the unbalance force ratio increase, the breathing behavior of the unbalanced model will gradually approach the breathing behavior of a balanced shaft. These results can be used to study the vibration behavior of the cracked rotor by obtaining the time-varying stiffness matrix.

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