Numerical investigation of cracked rotor

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Abstract. The aim of this paper is investigating the cracked Jeffcott with an offset disk rotor system. The finite element method (FEM) used in ANSYS gives an attractive approach for modeling the rotor dynamic system. The effect of changing speeds has been analyzed on the dynamic parameters of journal bearings (stiffness and damping) and then on Sommerfeld number. The relation of the dynamic bending stress with the static stress of rotor with cracks (dynamic load factor (DLF)) and with the ratio of depth crack to radius rotor has been established. The results have been obtained numerically by using ANSYS. The results show when crack’s depths increase the DLF increases and reach to maximum when a/R = 0.8.

1. Introduction
For the study of vibration behavior of rotating structures like, motors, engines, disk drive, turbines and fans, the researchers developed the characteristic of inertia effect which could be analyzed for improvement of the design and simultaneously decreases the failure cases. The inertia effect in the gyroscopic moment is one of the important terms. The gyroscopic moment is generated by the precession motion of the rotor while it rotates [1].
The ability to recognize the crack at early stages of growth is imperative for reducing maintenance cost and time. Early crack detection makes the operator think for repair with no need of prematurely take the machine for an extended period of operation [2].
The cracked rotor-bearing system investigated analytically using MATLAB to get the relation between oil film stiffness, dampers and rotor spin speed for short journal. Finding the compliance matrix coefficients for a cracked shaft with a rotational motion leads to find the stiffness matrix of cracked element [3-6].
In this paper, the DLF has been calculated to the offset Jeffcott rotor with crack by dividing the dynamic maximum bending stress on the static stress by numerical method. The aim of a standard rotor dynamics study and design checking is to help engineers to describe the dynamic design characteristics but the study of some rotary equipment [7-12]. A general method has been used for performing the standard lateral analysis of vibration by using finite element analysis (FEA) with selected SOLID187 in the ANSYS [13].

2. Modeling and design data input by ANSYS
The element which has been used for an uncracked and cracked model for $L_1\neq L_2$ model is 3-dimensions beam element SOLID187 with the unbalance of 0.5 gr.mm. The analysis has been done for
harmonic analysis getting the first mode, response for uncracked and cracked models. The shapes of the elements SOLID187 which are used in the analysis are shown in figure 1. The three-dimension discretization of the rotor is shown in figure 2 and figure 3. Table 1 shows the dimension of the selected model and the properties of the shaft’s material (AISI4140).

Figure 1. Shapes of the elements SOLID187.

Figure 2. Isometric view discretization of solid187 element for $L_1 \neq L_2$ model.

Figure 3. Shaft of rotor with the crack in the depth of (a) $a=5\text{mm}$; (b) $a=10\text{ mm}$; (c) $a=15\text{ mm}$. 
Table 1. Dimensions of the model studied and shaft material AISI4140 properties.

| Description                              | Dimensions               |
|------------------------------------------|--------------------------|
| Total shaft length                       | 0.654 m                  |
| Shaft diameter                           | 0.048 m                  |
| Disk diameter                            | 0.34 m                   |
| Distances between disk and bearings      | L1 = 0.24m, L2 = 0.414m   |
| Crack depths                             | 0.005, 0.01, 0.015, 0.020 m |
| Distances between the left side of disk  | 0.01 m                   |
| and crack                                |                          |
| Disk thickness                           | 0.02 m                   |
| Total rotor mass                         | 23.25 kg                 |
| Young Modulus (\(E\))                   | 2.05× 1011 N/m²          |
| Poisson's Ratio (\(\nu\))               | 0.29                     |
| Density (\(\rho\))                      | 7850 Kg/m³               |

3. Result and discussion

3.1. Bending stress of cracked rotor

The bending stress has been calculated numerically by two methods using ANSYS. For the numerical method, the three dimensions beam element type Solid187 has been taken [13]. For the shaft of the rotor, the elements Solid187 is represented and the crack region represented by subtracting the crack volume from shaft volume with refining mesh.

After applying the boundary conditions and setting the rotation speed, analyzing started to find the stresses bending stress, shear stress, and Von-Mises stress. However, the important feature is bending stress which affects on the shaft that causes vertical deflection.

The distribution of bending stresses has been found by drawing the contour for each case of crack (uncracked, 0.2\(R\), 0.4\(R\), 0.6\(R\) and 0.8\(R\)) depths as shown in figure 4.

**Figure 4.** Numerical bending stress distribution in cracked region contour of various crack depths (a) top view uncracked rotor; (b) top view cracked rotor with depth crack \(a=5\) mm; (c) side view cracked rotor with depth crack \(a=5\) mm.
3.2. Dynamic load factor DLF of Cracked Rotor

The DLF has been found by dividing the dynamic maximum bending stress on the static stress by numerical method. The bending stress DLF increases when the cracks depths ratios increase as shown in figure 5. The results in table 2 have been listed and compared with the response displacement DLF by numerical method from [14]. The percentage of error has been found for DLF, which has found from numerical solution to the bending stress and response displacement, the results were in good agreement with a maximum percentage of error 3.85 %. It can be shown the stress DLF is higher than the response DLF for various crack depths.

![Figure 5. Dynamic load factor (DLF) versus crack depths ratio of a cracked rotor.](image)

| Ratio depth a/R | Static stress N/m² | Dynamic bending stress N/m² | DLF from Stress ratio | DLF from displacement ratio [14] | The error of DLF from stress and displacement ratios |
|----------------|--------------------|-----------------------------|----------------------|----------------------------------|---------------------------------------------------|
| 0              | 3.605E+6           | 2.922E+6                    | 0.8105               | 0.780                            | 3.76 %                                            |
| 0.2            | 3.832E+6           | 3.129E+6                    | 0.8165               | 0.785                            | 3.85 %                                            |
| 0.4            | 4.789E+6           | 4.022E+6                    | 0.8398               | 0.813                            | 3.19 %                                            |
| 0.6            | 4.903E+6           | 4.713E+6                    | 0.9612               | 0.935                            | 2.72 %                                            |
| 0.8            | 5.6531E+6          | 5.602E+6                    | 0.9909               | 0.963                            | 2.81 %                                            |

4. Conclusion

The dynamic load factor (DLF) is one of the main engineering ideas which is in a simple manner of the ratio of maximum dynamic bending stress to the static stress. The static stress is produced by steady force with the same value as the peak magnitude of the acting force.

DLF could be extended to bending stress ratio or response displacement ratio, as a principle to engineering judgment in the early stages of a design, is regarded as an important value [15].

In this paper, the cracked Jeffcott with an offset disk rotor system has been considered. The dynamic behavior of the rotor with the help of numerical modeling of a Jeffcott rotor with a crack while the depths of crack changes have been investigated. The DLF has been found by FEM. The stress ratio DLF increases when the cracks depths ratios increase.

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