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Experimental Analysis of Cracked Turbine Rotor Shaft using Vibration Measurements

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ABSTRACT: The gas turbine rotors are subjected to different types and directions of loading like axial, bending, shear and thermal loading. This loading is changed periodically during the operation which can lead to crack initiation in the rotor shaft. When these cracks propagate to the extreme limit, it will lead to sudden failure of the shaft rotor. Crack existence can be detected by observing the vibration parameters of the rotor, the vibration parameters is changed when the shaft is cracked. The most observable change in these parameters is the natural frequency and the response of vibration. In this study, the vibration of gas turbine rotor is studied with the existence of cracks and without them. The rotor was modelled experimentally. A test rig was built to model the real rotor. During the experiments, the rotor speed range was variated from zero to 10000 rpm. Two crack depths of 0.2 and 0.4 of the shaft radius were modeled in addition to the uncracked shaft. The behavior of the results of the vibration parameters was compared with other previous research and was closely similar. When the rotor was intact, the critical speed is (7900) RPM and the acceleration response is (10.291) m/s2. When a crack is fabricated deeply (0.2R) the critical speed decreases to (7750) RPM and the acceleration response increases to (11.5043) m/s2. When the crack depth increases to (0.4R), the critical speed was less (7500 RPM), and the acceleration response increased more to (12.4429) m/s2.

KEYWORDS: Shaft Vibration, Crack Shaft, Turbine Rotor Shaft, Vibration Turbine Shaft, Vibration Measurement Rotor Shaft.

INTRODUCTION

The researches about the presence of crack in rotor shafts were began at 1954. The crack risk lies that not possible to be detected during the work of rotor by the Nondestructive testing methods. In order to get an assessment about the expected risk; the rotor is monitored by the vibration parameters. When there is a crack, the parameters will be changed, and the depth, position and angle of the crack can be detected from the vibration data. There was study of the effect for axial loads and gyroscopic effect on the rotor, it was concluded that the effect shear strain and axial load can be represented by the rotor element, [1,2].

When the crack was generated, an imbalance will be formed in the distribution of the masses for the rotor, a matrix of stiffness of the cracked shaft was provided from [3]. The case of open and closed crack is formed because of the weight of the shaft, and the excitation is generated from the circulation of rotor, Penny et.al [4] documented the methods of early detection of the crack. Drape et.al [5] showed that the stiffness value of the rotor in the crack area is the lowest value when it is fully open, where the angle of the crack position is (180) degrees. Al Darajy [6] found the relationship between the speed of rotation, the depth of the crack and its location with normal frequency. The maximum value of natural frequency was determined by Thomas et.al [7], where it was at the speed of rotation (80-120%) of the critical speed. The parameters of stiffness and damping must be found to solve the equation of motion, then the value of the response will be found to the system. In general, the crack defect in each structure, plate or beam, leads to reduce the stiffness of the structure, then, decreases the natural frequency and increases the structure response and other mechanical behavior, [8-14].

Chauvin [15] used the Jeffcott type rotor, and the parameters of the two bearings were equal because of similarity. Sinou [16] presented that when the crack depth is increased, the system instability was also increased because the vibration parameters were affected by changes in rotor stiffness. Todorovic, et.al [17] observed that the critical speed decreases and the response increases with increament of crack depth, and this is a good indication of the presence of a crack when monitoring the rotor. José M. Machorro-López, et al, proved

that the crack represents (2%) of the causes of vibration when compared with misalignment and mass imbalance, most of the frequencies produced by the crack are (1x), [18]. Chasalevris showed that the greatest stress and deflection occured at the site where the greatest moment, so the location of the crack was chosen in the same place, [19].

Sinou [20], studied the transient case for open crack in rotating system, vibration parameters were found in the first third of critical velocity, and this is a good indication of the presence of crack in the rotor. The stability of the dynamic rotor system decreases with the presence of a crack or two crack in the rotor. Untaroiu [21] studied two issues , the first was open crack and the second was breathing crack, it was concluded that instability is increases with increased number of cracks. Murthy, et.al [22], solved the equation of motion of a rotary system containing crack, it was concluded that the nonlinear vibration of the system effects on fractional order damping.

Ramezanpour, et.al [23] studied the oblique crack in the Jeffcott rotor, and the relationship between the angle of crack and deformation displacement was investigated, it was found that the vibration parameters in the transverse crack are lower than the parameters in the full open crack. Ferjoui investigated [24] transverse crack in the rotor carried by a journal bearing. It was assumed that the bearing from the short type to get away from the complexity of the solution, and proved that increasing the depth of the crack affected on the centralization of the journal bearing and reduced the stability. Al-Shammari [12] investigated the free vibration characteristics in a cracked sandwich plate. It is found that the fundamental natural frequency is decreased with the increment of crack length and the maximum value is obtained when the crack is at an angle of 45o. The objective of this work is to model a turbine rotor shaft experimentally. It was represented by a disk and shaft, and the crack site was confirmed to be the in the same position where it is expected on the real rotor. The model was tested using a constructed test rig so the vibrational characteristics will be used to clarify the crack effects. The behavior of the vibrational orbit path will be studied as a result of a presence of right crack with several lengths and depths.

EXPERIMENTAL WORK

The test apparatus aims to simulate the dynamics and vibration of the gas turbine rotor, which is manufactured by the US company GE and generates a capacity of 123.5 MW. The rig shown in Fig.1 was designed and manufactured in to model similar conditions of that in the real rotor gas power station. The shaft and the disk were designed and configured with a reduction ratio of 1/10 to the original dimensions of the rotor, adjusting none equal length of both ends of the shaft outside the disk i.e. ($L_1 \neq L_2$). The rotor is supported by two journal bearings at both ends. These bearings and the lubrication system were also designed and manufactured to present conditions similar to the real conditions too. There are two measuring devices that are fitted to the test rig; these are an accelerometer and rotational speed reader.

Figure 1. layout of the TEST RIG

An air system has been added to the lubrication system as shown in Fig.2 and Fig.3 the purpose of this system is to compress air to the oil which reaches the bearings at constant pressure, thus the oscillation pressure was

eliminated when using the pump, so the results will be more accurate.

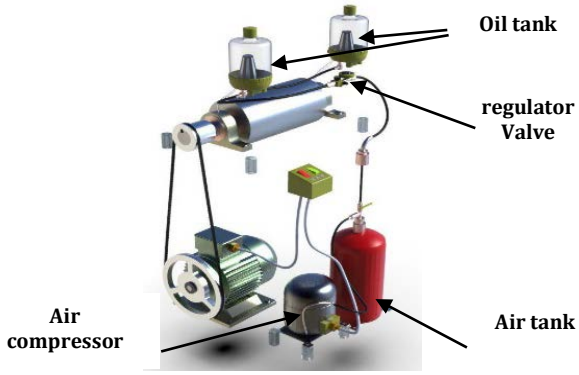

Figure 2. The air and liberation systems of rotor.

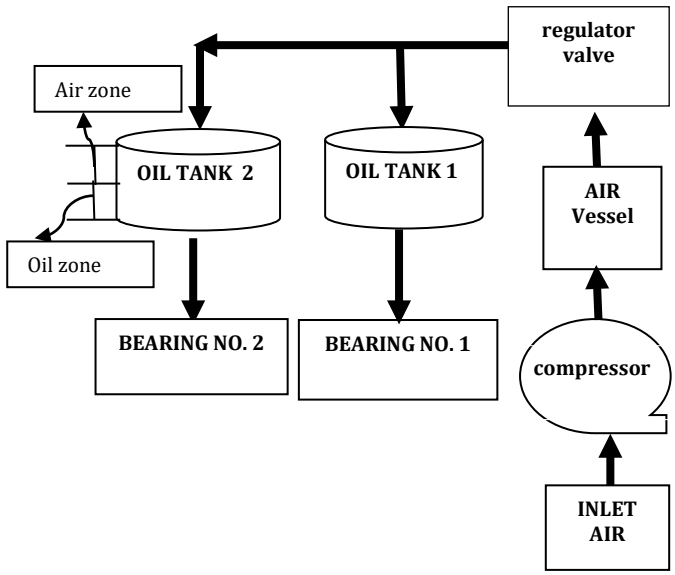

Figure 3. layout of the lubrication system.

A single crack was fabricated and at depth (0.2R) and (0.4R) as shown in Fig.4, the critical speed was measured by accelerometer of type (352C68) installed on the bearings cover as shown in Fig.5, [25-27]. The critical velocity of the uncrack shaft was in experimental analysis (7900) RPM. Then, since the experimental results obtained were acceptable , [28-36], then it can be used only to gain the dynamic behavior for shaft structures, but, to increase the dependably of the experimental results; the numerical techniques can be utilized for the comparison process. [37-42].

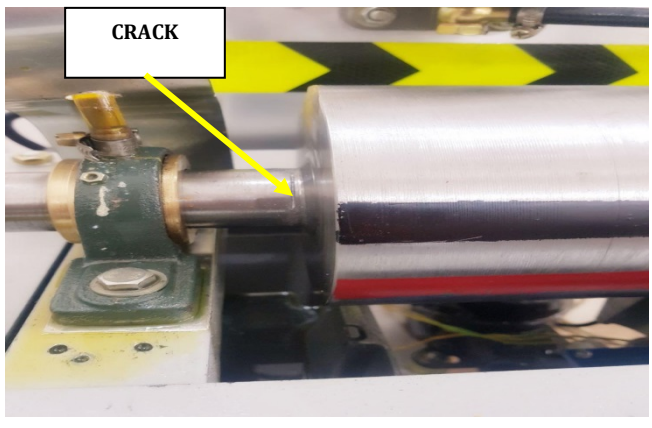

Figure 4. the location of the 0.2R crack depth.

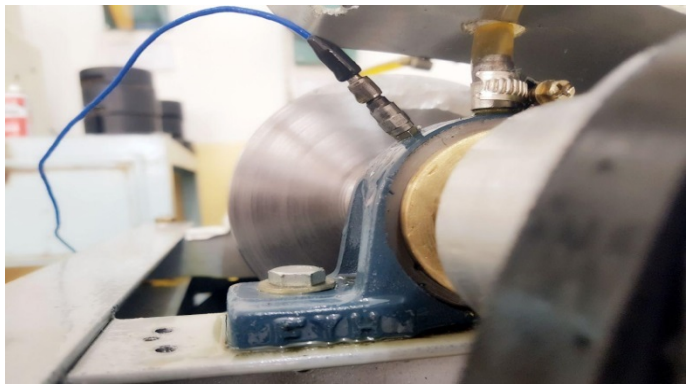

Figure 5. Mounting of the accelerometer

In addition; many of numerical techniques can be used to calculate the dynamic behavior of the shaft structures, since the numerical technique was a very important technique; it can be utilized to calculate various mechanical behavior results and compare them with the other results calculated by experimental or analytical techniques, [43-55], with a good agreement, [56-67]. Where, a different methods used the application the numerical technique which the finite element method is one of them, [68-84], and other method.

RESULTS AND DISCUSSION

The vibration wave is formed as a result of the unbalance in the rotary shaft. The unbalance is increased when the crack is formed on the surface of the shaft due to the decrease in stiffness in the crack site, where the crack is always formed on the surface because periodic stresses are concentrated at it. So a crack was created on the surface and near the disk because the greatest moment is beside it.

The results of experimental analysis were determined by measuring the critical velocity of proper and cracking rotor, where a single crack was made with two depths (0.2R, 0.4R). Vibration wave compounds, represented by frequency and response, were analyzed. The frequency is the result of the imbalance of the shaft and is transmitted from the rotor to the bearing cover and received by the accelerometer. But the response will not the true value of the crack site because the location of the accelerometer at the bearing. Even so, it will give an indication of the critical speed, because the critical speed is at greatest response of the rotor dynamic system.

It was observed in Table.1 that the critical speed was decreased and the response increased with increasing of crack depth, this is due to a decrease in stiffness due to the reduction of cross-sectional area when cracking.

Table 1. The Critical speeds values to several depths of single crack.

Crack Depth tests	Critical speed in experimental work
Uncrack test	7900
0.2R test	7750
0.4R test	7500

The behavior of the curves in the phenomenon in Figure 6 was compared with the analytical results of the research [6]. It was noted that the behavior of the curves is similar, where if the depth of the crack increased, the critical speed decreases with increase in the response. The reason is to increase the flexibility in the vertical direction and thus increase the capacity of movement of rotor. Figure 7 shows the behavior of the curves in the ref. [6] with increasing crack depth.

Increased response leads to increase the dynamic repeated forces a result of increased the unbalanced of distributed masses, and this threatens the safety of the equipment.

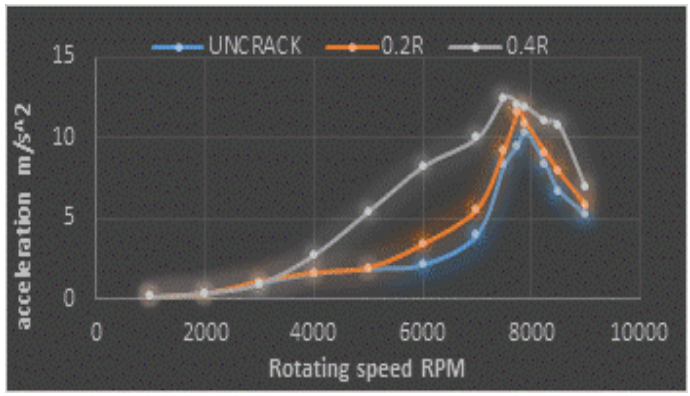

Figure 6. the acceleration behavior with different depths.

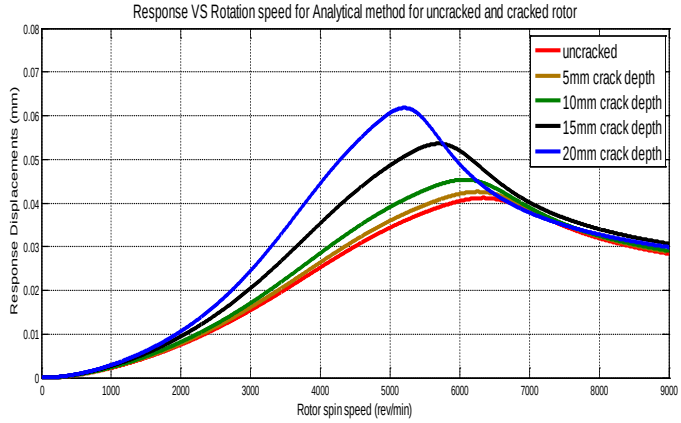

Figure 7. Analytical Response versus rotation speed for single cracked

CONCLUSIONS

The change in vibration parameters is a good indicator of a certain defect in the rotor, and one of the reasons for this change is the presence of crack. The following conclusions were drawn from this study

1. When the crack occurs, the critical velocity of the rotor in which the greatest response occurs will be reduced, the increased response due to presence of crack accelerates its growth because of the increased acceleration of the movement of the rotor and thus increase the dynamic forces affecting on the rotor in the crack site.

2. When the crack depth is increased to (0.8R), then it will expect sudden failure at any time with high growth speed for crack. When the area of the cross section decreases, the moment of inertia increases, and this increases the stress concentration in the crack tip zone.

3. It has been concluded that when the depth of the crack is increased, the orbit size of whirl will be increased also, and this will decrease the stability in the dynamic rotor system, this leads to increased the crack growth speed.

4. In the experimental work when the shaft was not cracked, it is observed that the speed of rotation is very close to the frequency resulting from the vibration, so it is possible to consider the wave from type (1X).

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