Influence of Fatigue Crack Size and Position on the Natural Frequencies of Rotor Blades for Structural Health Monitoring

Farid ASMA and Rachid AZZI

***Abstract*—** Rotating machinery is widely used in vital industries such as aeronautics, energy and nuclear power. Due to the complex loads they are subjected to during operation, their main components, particularly the blades, are often prone to fatigue cracks. This cracking phenomenon is very dangerous as it can lead to blade failure and machine shutdown. In fact, the crack causes local flexibility that alters the overall stiffness of the structure and, consequently, its dynamic behaviour. Studying this change is essential for diagnosing cracks and monitoring the integrity of the structure (SHM). In this study, the effect of fatigue cracks on the natural frequencies of the rotating blade was investigated. The presence of cracks in the rotor blades causes local flexibility and affects the modal characteristics of the structure. The cracks were modelled as open fissures and their definition is based on two parameters: crack size (non-dimensional length l between 0.1 and 0.5) and crack location (non-dimensional position p between 0.1 and 0.9). The rotation speed (between 0 and 5000 minutes) was also considered. The effects on the first three natural frequencies were estimated using a modal analysis under prior constraints using Ansys software, which allows the significant effect of centrifugal force on blade stiffness to be taken into account. The study demonstrates that the decrease in the natural frequencies of the blade resulting from the crack is directly related to the size and location of the crack, making it a reliable indicator for fault detection in SHM applications.

***Index Terms*—** Blade Rotor, Fatigue Crack, Natural Frequencies, Ansys.

I. INTRODUCTION

Rotating machinery are omnipresent in the aircraft industry, energy, nuclear etc. During their operation, they are loading in deferent directions, thus their principal components such as the shaft and the blades led to fatigue cracks [1, 2]. Blades cracking phenomenon is very frequent and can lead to the breaking of the blade and the dysfunction of the machine [3]. Generally, a crack introduces a change into the rigidity of the blade and consequently into its dynamic behavior. The vibrations of cracked rotating blades receive a growing interest on behalf of researchers and operating staffs due to their practical importance. In principle, the dynamic characteristics of a cracked structure are different from those of the healthy structure due to the change of rigidity caused by the crack. This difference in the dynamic characteristics will be useful for the detection of the crack [4]. A crack in an element of structure causes the reduction of its rigidity and by consequence the reduction of these natural frequencies and a change in the mode shapes of vibration. Several researchers studied the relationship between the crack characteristics, the length, the position, and the vibration characteristics of the element [5]. In case of the components of a rotating machinery such as blades, the consideration of the rotation effect on the vibration characteristics is very significant. The blades of turbine, windmill… etc., rotate while in operation and the rotating speed is constant for many operations. The dynamic characteristics of the rotating elastic bodies are different from their dynamic characteristics in the nonrotating state. The difference is come from the centrifugal force, which causes to change in the stiffness of the body, this difference is called the "apparent stiffness" [6]. The study of the dynamics of cracked blades is a delicate problem, which requires an appropriate modeling for the crack as much as for the blade. The analysis of the studies undertaken for the modeling of the cracked blades shows that there are two models [6-8]:

- Open crack model.
- Breathing crack model.

The first model of open crack supposes that the crack is open and it remains opened during the vibration, the model of breathing crack takes into account the mechanism of opening and closing of the crack and the contact between the two surfaces of the crack.

In this study, transverse cracks of various lengths are inserted in the model into several places along the length of the blade. The crack is defined by its non-dimensional length (l) (ratio between the length (a) of the crack and the width (b) of the blade) and by its non-dimensional position (p) (ratio between the position (x) of the crack and the length of the blade (L)). During the analysis, the non-dimensional crack length is varied from 0.1 to 0.5 with an increment of 0.1 and the non-dimensional position is varied from 0.1 to 0.9 with an increment of 0.1. The rotating speed of the rotor varied from 0 min^{-1} to 5000 min^{-1} with an increment of 1000 min^{-1}. To simplify the analysis, it is supposed that the crack is open and remains opened during the vibration. The structure of the blade whose mechanical properties are illustrated on Table 1 is fixed to a

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rotor of radius (R) at root. By performing an analysis using ANSYS software, the first three natural frequencies of un-cracked and cracked blades are calculated. However, the blade is subjected to the rotation effect during its operation and the rotating motion significantly change the modal parameters of the blade. To account for that change, a pre-stress modal analysis is performed by doing a static analysis before the modal analysis so that all the stresses and displacements, which are created by the centrifugal force, are included into the modal analysis [9].

In order to compare the frequencies of the cracked and un-cracked blades, we consider the percentage change in natural frequencies defined as follow

$$C_i\% = \frac{F_i uncracked - F_i cracked}{F_i uncracked} * 100 \qquad (1)$$

Where i defines the ith -frequency of the system.

The principal goal of this analysis is to study the relationship between the characteristics of the crack, length, position, and the modal parameters of the blade in the states of rotating and non-rotating blades. This relation will be useful for the definition of an online crack detection system.

II. Modelisation of the Blade Rotor

The model of the cracked blade rotor was designed using SolidWorks software as illustrated on Fig. 1. The geometrical characteristics of the blade rotor are illustrated in Table I.

TABLE I: Geometric and material properties of the blade

Parameters	Value
Young's modulus (E)	2.1×10^{11}N/m^2
Poisson's ratio (γ)	0.3
Density (ρ)	7850 Kg/m^3
Length of the blade (L)	200 mm
Width of the blade (b)	50 mm
Maximum thickness of the blade located at root (emax)	3 mm
Minimal thickness of the blade located at free end (emin)	2 mm
Diameter of the rotor (d=2r)	400 mm

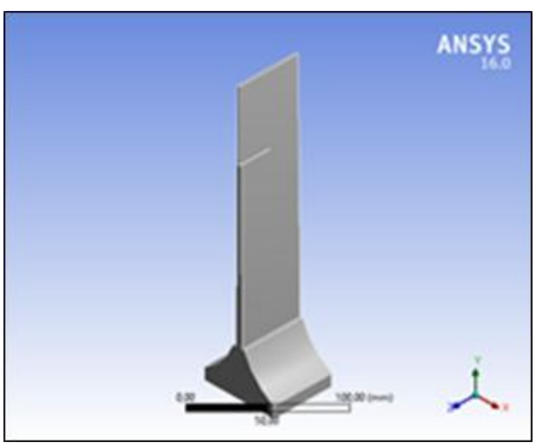

Fig. 1. 3D design of the cracked blade.

The model of the blade was imported in ANSYS WORKBENCH for modal analysis. The blade is discretized in tetrahedral finite element with a mesh refinement near the crack, the number of elements is equal to 8298 for the un-cracked blade, Fig. 2. For all the crack cases in this study, the blade's finite element meshes are designed approximately with a same number of nodes and elements.

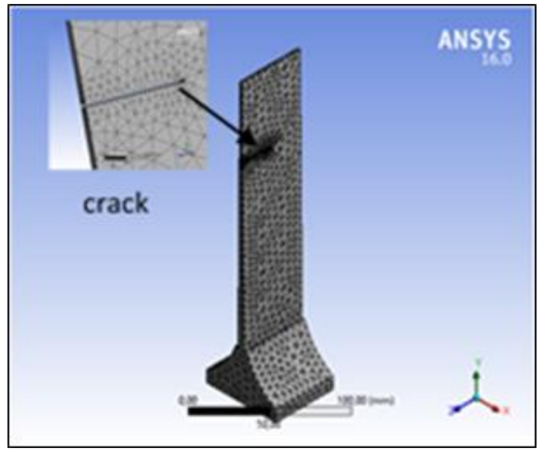

Fig. 2. Finite element model of the cracked blade.

III. Modal Analysis of Non-Rotating Blade

The structure of the blade is constrained at its base as it is attached to rigid rotor disc. By using the ANSYS software, the first three natural frequencies were calculated for each model of the blade. The natural frequencies of the cracked blades are compared with those of the un-cracked blade, and the influences of the crack parameters on the natural frequencies are estimated and analyzed in the following paragraphs.

A. *Influence of the Crack Length on Natural Frequencies*

The effect of the crack length on the first three natural frequencies is illustrated in Fig.(3).

It is seen that as the non-dimensional crack length increases, the percentage reduction in the natural frequencies increases considerably for the different crack positions. For the cracks which are close to the end of the blade (p=0.9), it is seen that they do not have influence on the first natural frequency of the blade. On the other hand, they have an influence on the second and the third natural frequencies and their effect increase with the increase of the crack length.

For the lower length crack (l=0.1), the percentage reduction in the natural frequencies is weak. According to these three graphs, the crack length affects considerably the natural frequencies of the blade, and this influence depends on the crack position. For cracks located near the tip of the blade, the percentage reduction is significant when the crack length becomes significant. It is visible that the effect of the crack parameters strongly depends on the mode shape of the blade.

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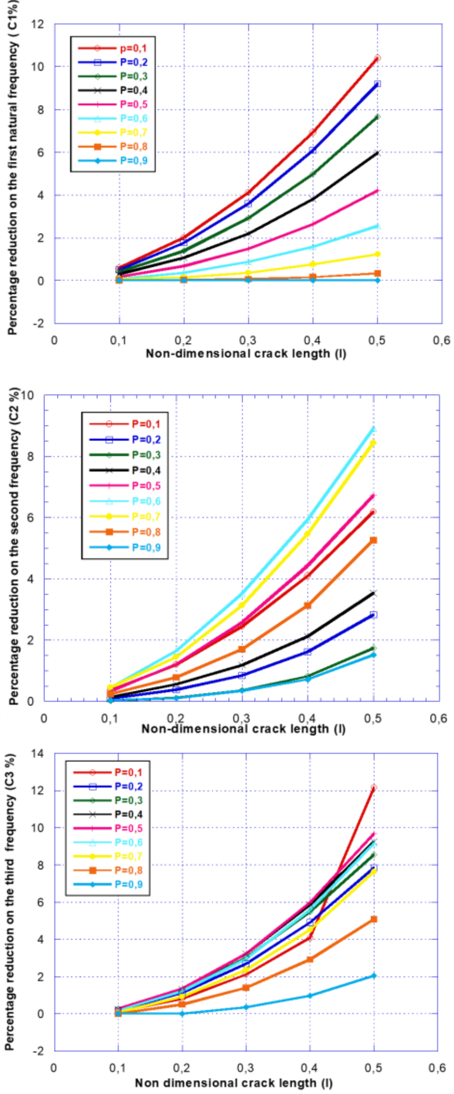

Fig. 3. Percentage reduction of the first three natural frequencies to crack length for different crack positions.

B. *Influence of the Crack Position on Natural Frequencies*

Fig. (4), illustrates the percentage reduction of the natural frequencies of the blade in terms of crack positions for different crack lengths. It is seen that the percentage reduction of the first natural frequency decreases as the crack position moves away from the root of the embedded blade. The percentage reduction (C1%) is null for the case of the cracks which are close to the free end of the blade (P=0.9), because at the end of the blade the moment is null.

For a particular crack position, the percentage reduction increases with the increase on the crack length. The percentage reduction of the second natural frequency is significant with some positions of the crack (p=0.1) and (p=0.6), and less significant in other positions. This difference in the effect of the crack position is due to the crack position compared to the positions of node and belly of second mode shape of blade. The cracks, which are near the blade tip, have an effect on the second frequency when their lengths are significant. The percentage reduction (C3%) is significant for more parts of the crack positions.

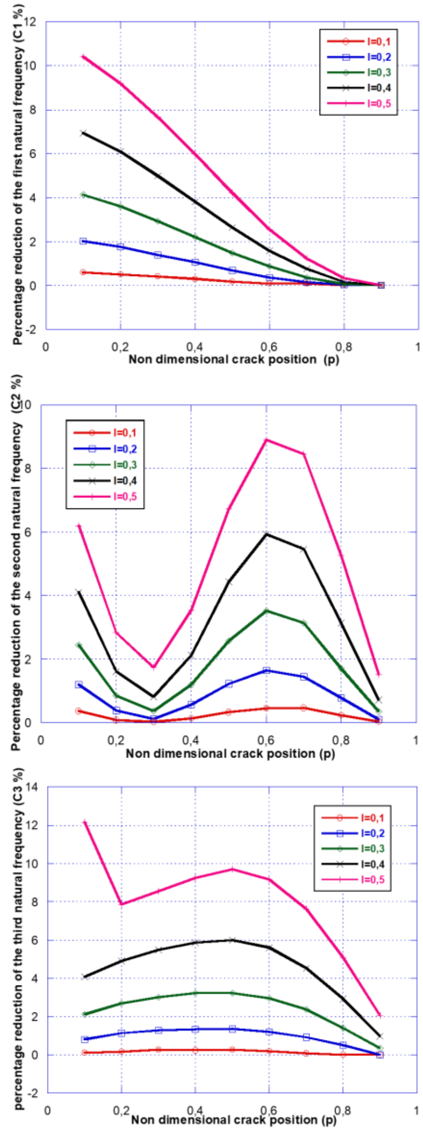

Fig. 4. Percentage reduction of the first three natural frequencies to crack position for different crack lengths.

IV. MODAL ANALYSIS OF ROTATING BLADE

Ansys software is used to calculate the first three natural frequencies of each model of the blade. The following figure illustrates the natural frequencies of the un-cracked blade for different rotating speeds. As we seen on the Fig. (5), with the increase of rotating speed, the natural frequencies of the blade also increase; this increase is due to the increase in the rigidity of the blade

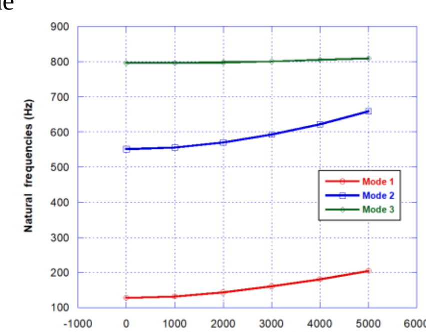

Fig. 1. Natural frequencies in terms of rotating speed

A. Influence of the Rotating Speed

Fig. (6) shows the percentage reduction of the first natural frequency in terms of rotating speed for different crack lengths for particular crack positions p=0.1 and p=0.8.

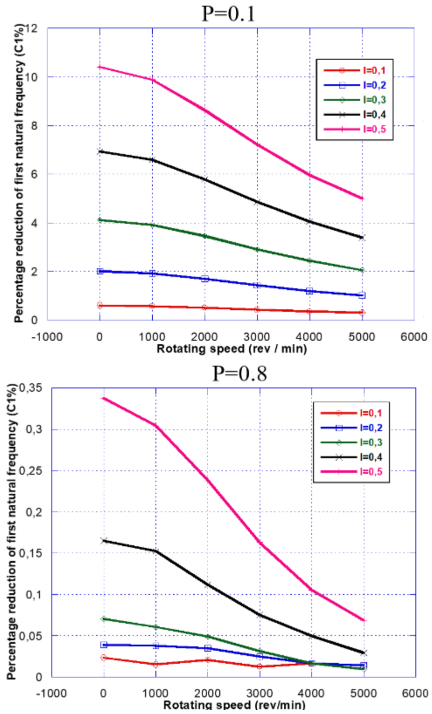

Fig. 2. Percentage reduction of the first natural frequency to rotating speed for different length cracks, p=0.1, p=0.8

It is seen that, for a defined crack, the percentage reduction (C1%) decreases in proportion as the rotating speed increases. This reduction is due to the centrifugal force, which is proportional to the square of the rotating speed, which in its turn increase the rigidity of the blade and compensate the crack effect.

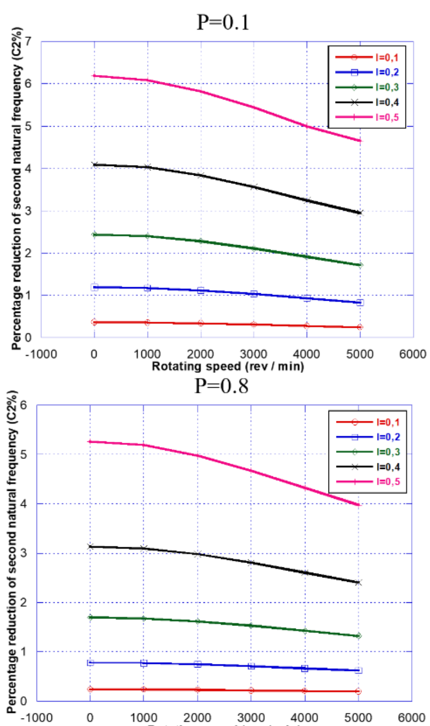

Fig. 7. Magnetization as a function of applied field

Fig. (7) shows the percentage reduction of the second natural frequency in terms of rotating speed for the various crack lengths and for particular crack positions. It is seen that the percentage reduction (C2%) decreases by increasing the rotating speed, and the reduction in C2% is lower significant compared to that of the C1%.

Fig. (8) shows the percentage reduction of the third natural frequency in terms of rotating speed of the blade for various crack lengths and at particular crack positions (p=0.1) et (p=0.8). It is seen that the percentage C3% increases with the increase of the rotating speed. The third vibration mode of torsion of the blade is less affected by the effect of the blade's rigidity, which is due to the rotating speed and which reduce the flexibility caused by the fatigue crack.

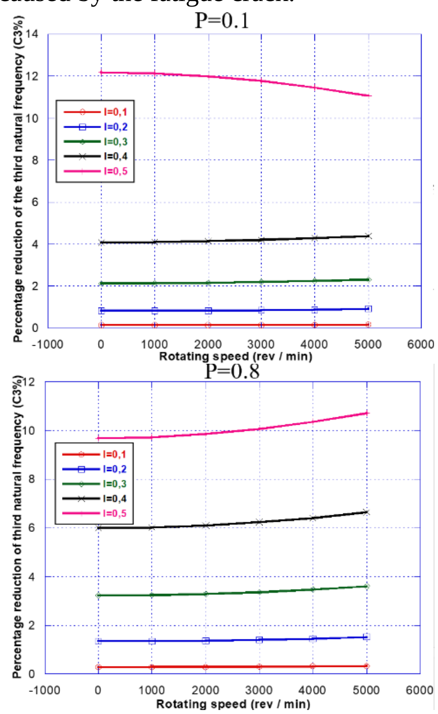

Fig. 3. Percentage reduction of the third natural frequency to rotating speed for different crack length, p=0.1, 0.8.

V. Conclusion

In this study, the effect of crack characteristics, position and length, as well as the rotor rotating speed on the dynamic characteristics of a blade rotor such as the natural frequencies and the modes shapes were analyzed. The percentage reduction of the natural frequencies increases in a significant way as the crack length increases, this is valid for the various crack positions and also for the three vibration modes. For a particular crack length, the percentage reduction is a function of the crack position and the vibration mode. The percentage reduction of the first natural frequency decreases as the crack position moves away from the base of the blade. The cracks located near the nodes of second mode shape affect less the second natural frequency. The rotating speed has a significant effect on the modal parameters of the cracked blade, with the increase of rotating speed the percentage reduction of the first natural frequency as well as the percentage reduction of the second natural frequency decreases. The influence of crack on the first two frequencies decreases with the increase of rotating speed. The percentage reduction of the third natural frequency increases with the increase of rotating speed, then the effect of the crack is higher than that of the rotating speed.

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