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Effects of a Longitudinal Crack in Overhung Rotor

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Abstract— In this study, a longitudinal crack simulation will be carried out on the shaft using the MSC Nastran/Patran to identify the effect of variations in the depth and length of the crack on the shaft on the stress distribution along the shaft and to determine the dynamic behavior of the rotor shaft overhung system due to cracks. The simulation was carried out with two models, with and without a crack. The first crack position locates between the disk and the bearing, and the second is between the two supports. Based on the simulation test results, the natural frequencies tend to decrease with increasing variations in the depth and length of the crack, especially at first and second natural frequencies. The cracks between the disc and the bearing significantly reduce stiffness than the cracks between the two supports. Furthermore, in the stress analysis, the cracks increase the rotor's maximum stress, which occurs in the area of the ultimate bending moment.

Keywords: overhung rotor, longitudinal crack, natural frequency, and stress analysis.

1. Introduction

Crack is one of many types of defects in the rotor. Types of cracks that often occur in the rotor are transverse crack, slant crack, and longitudinal crack. An enormous amount of research on cracked rotors has been published in the last three decades. Some investigated a simplified rotor with cracks and showed the rotor's characteristics in which the 1x and 2x harmonic components occur in the dynamic responses [1-11]. However, most of them researched only about rotors with transverse crack. Some articles discuss rotor cases with a longitudinal crack, but not as much as in the cases of transverse crack. Lecheb et al. [12] simulated fatigue in the wind turbine rotor that caused a longitudinal crack. They got here six mode shapes at the six lowest natural frequencies. The displacement, strain, and stress increase with crack size increase during crack propagation. Contrary, the six lowest natural frequencies decrease with crack size increase. Patil et al. [13] investigated the longitudinal crack in a rotating shaft using online condition monitoring based on vibration analysis. They found that the crack location and depth influence the vibration amplitude of the system.

Further, Nabian et al. [14] analyzed the dynamic responses of the solid turbo generator shaft with longitudinal crack compared to the circumferential crack. They modeled the rotor as a cantilever rod, in which a longitudinal crack was subjected to torsion. It found that a longitudinal crack in the shaft has only a tiny contribution to its resonance frequency. Meanwhile, the circumferential crack affects the resonance frequencies of the shaft depending on the length and location of the crack. However effect of the longitudinal crack in the rod based on the difference of shaft element stress due to crack location has not been analyzed.

In this paper, a longitudinal crack is modeled in an overhung rotor. The length and depth of cracks are varied. Each crack model is simulated in two different locations on the shaft. Here, the overhung rotor model has analyzed its natural frequencies and the maximum stress of the rotor.

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2. Model of Overhung Rotor

An overhung rotor structure model consists of several parts that form a rotor shaft system. This system consists of several components such as a shaft, disk, two bearings as supports. The shaft has a length of 500 mm and a diameter of 10 mm. The modeling design scheme of the rotor shaft system can be seen in Figure. 1. The material used in this study is homogeneous steel with material properties shown in Table 1. The analysis was carried out with the rotor at rest. Cracks in the mechanical structure are artificial cracks with depth variations from 1 to 4 mm and crack lengths from 6 to 16 mm. In the first case, the crack location is assumed to be between the disk and the bearing. In the second case, between the two supports. For stress analysis, the model is without a disk and is given an external force on the nodal at the disk position.

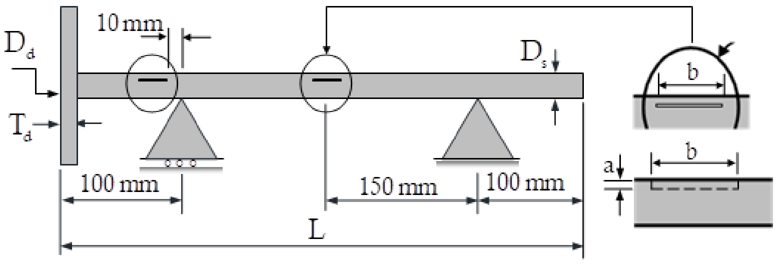

Figure 1. Overhung rotor system with longitudinal crack

Table 1. Properties of the rotor

Properties	Amounts
Length of shaft (L)	500 mm
Diameter of shaft (D_s)	10 mm
Diameter of disk (D_d)	97 mm
Disk thickness (T_d)	20 mm
Material of shaft	Carbon steel
Material of disk	Carbon steel
Mass of disk (m_d)	1.04 kg
Mass of shaft (m_p)	0.31 kg
Density (ρ)	7850 kg/m^3
Young's Modulus (E)	200 GPa
Crack depth (a)	(1, 2, 3, 4) mm
Crack length (b)	(6, 8, 10, 12, 14, 16) mm
Crack width	0.2 mm
Poisson Ratio	0.3

The modeling is designed using the Autodesk Inventor software, and then the data is exported to the MSC Nastran/Patran software, as seen in Figure. 2. The natural frequencies are analyzed using the MSC Nastran/Patran. The natural frequencies are determined regarding the vertical direction U-form mode as first natural frequency, vertical S-form as second natural frequency, and vertical W-form as third natural frequency. Each test is carried out by simulating the rotor shaft system without cracks and then with cracks.

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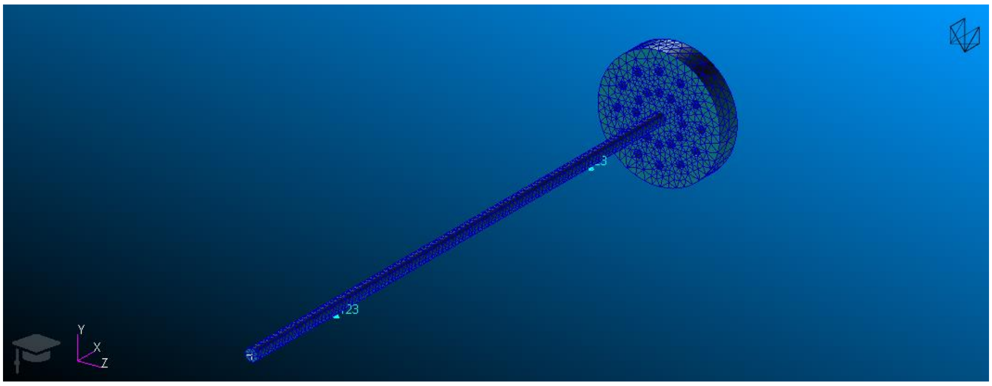

Figure 2. Overhung rotor system model in the Nastran/Patran software

3. Result and Discussion

Ten natural frequencies are obtained based on numerical simulations using MSC Nastran/Patran to the overhung rotor system without cracks. However, what will be analyzed are the three lowest natural frequencies regarding the vertical direction of the U-form as the first natural frequency, the vertical S-form as the second natural frequency, and the vertical W-form as the third natural frequency. The lowest natural frequencies were obtained: 44.7381 Hz, 237.7652 Hz, and 425.8467 Hz.

For the case of the overhung rotor model with a crack position between the disk and the bearing, the three lowest natural frequencies are obtained as listed in Table 1. Then, based on Table. 1, the graphs are plotted as shown in the Figure. 3, 4, and 5. Based on the first natural frequency in Figure 3, it can be seen that the first natural frequency decreases due to cracks on the shaft as the incremental variation of depth and length of cracks. However, it is not very significant. The same thing also occurs at the second natural frequency, as shown in Figure 4. Therefore it shows that longitudinal cracking can reduce the stiffness of the shaft slightly so that the natural frequency also decreases because the natural frequency is directly proportional to the stiffness of the shaft. Further, in the third natural frequency comparison chart in Figure. 5, it shows that the natural frequency tends to be slightly larger and fluctuating than the natural frequency of the rotors without cracks.

Table 2. Natural frequencies of the overhung rotor with the location of the longitudinal crack between disk dan bearing

Natural frequency	Crack Depth [mm]	Crack length [mm]					
		6	8	10	12	14	16
f_1	1	44.3756	44.3749	44.3738	44.3716	44.3711	44.3707
	2	44.3737	44.3720	44.3700	44.3677	44.3641	44.3636
	3	44.3733	44.3707	44.3661	44.3644	44.3625	44.3612
	4	44.3702	44.3693	44.3657	44.3626	44.3589	44.3588
f_2	1	237.7617	237.7546	237.7474	237.7465	237.7423	237.7421
	2	237.7561	237.7447	237.7365	237.7265	237.7218	237.7249
	3	237.7517	237.7415	237.7308	237.7256	237.7164	237.7131
	4	237.7451	237.7380	237.7270	237.7217	237.7120	237.7043

f_3	1	425.9877	425.9003	426.0011	426.1401	425.8413	425.9609
	2	426.0056	425.9662	425.9316	425.8448	425.9693	426.1908
	3	426.2379	425.8480	426.1005	425.9460	426.0574	425.9867
	4	426.0871	425.8623	426.2329	426.2640	426.0956	425.7206

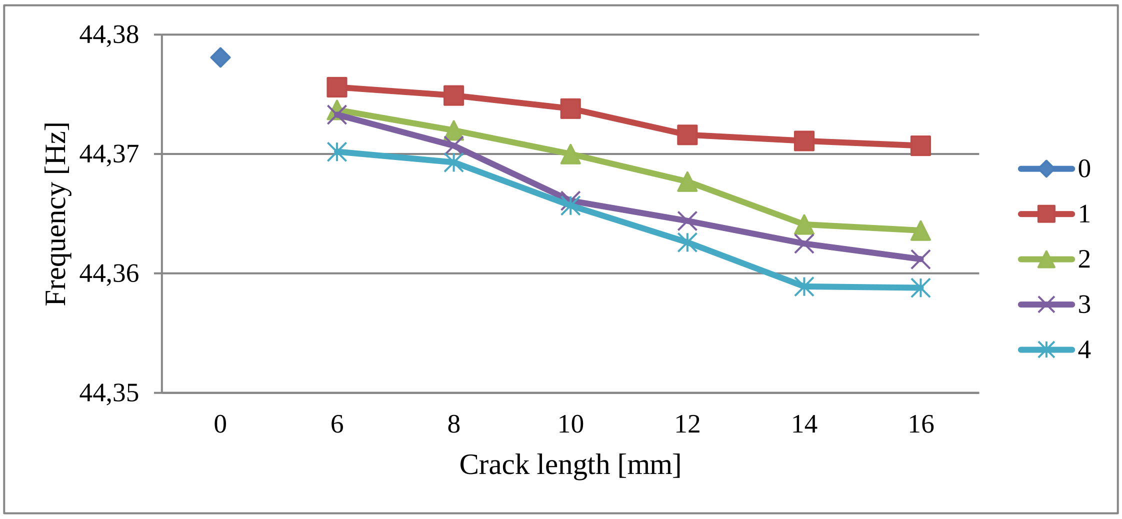

Figure 3. The first natural frequency of the rotor due to crack length for various crack depth with the location of the longitudinal crack between disk dan bearing

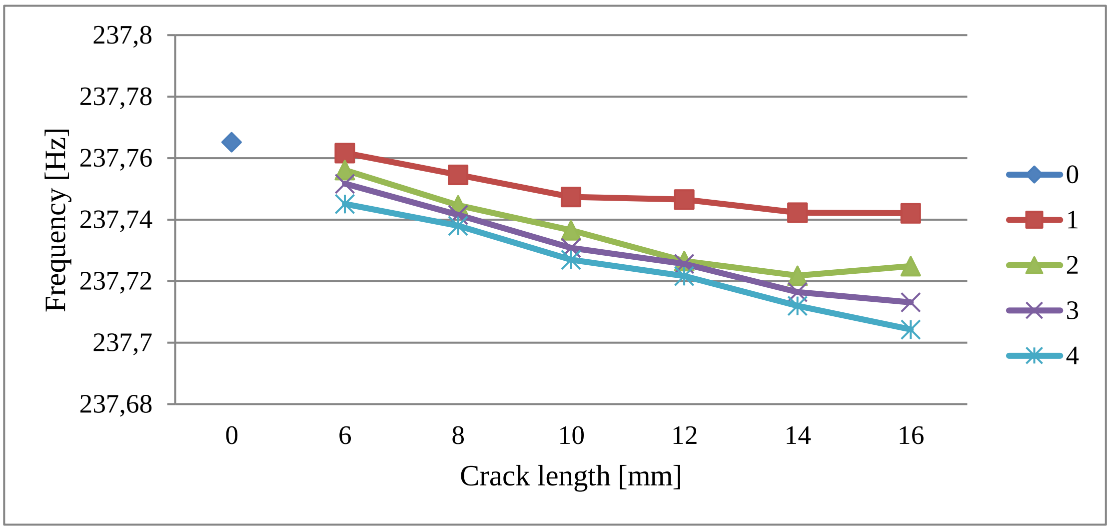

Figure 4. The second natural frequency of the rotor due to crack length for various crack depth with the location of the longitudinal crack between disk dan bearing

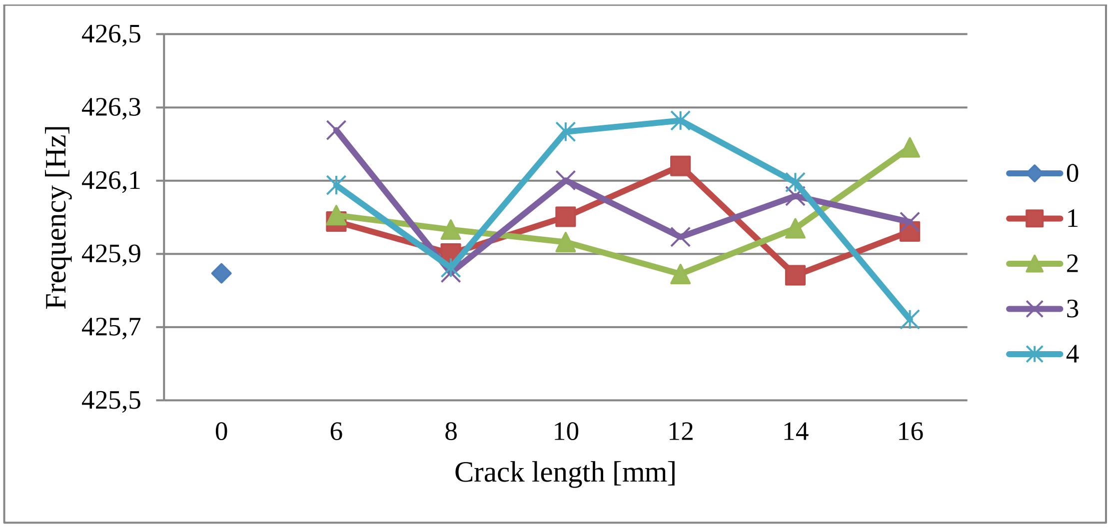

Figure 5. The third natural frequency of the rotor due to crack length for various crack depth with the location of the longitudinal crack between disk dan bearing

Furthermore, for the case of the overhung rotor model with a crack position between the two supports, the three lowest natural frequencies are obtained as listed in Table 3 and plotted in the Figures. 6, 7, and 8. Based on the graph of the first natural frequency comparison in Figure. 6, it can be seen that the first natural frequency also decreased due to cracks in the shaft with increasing variations in depth and length of cracks, although not too significant. The same thing happens at the second natural frequency, as shown in Figure. 7. In the third natural frequency comparison chart in Figure. 8, it shows that the natural frequency tends to be slightly larger and fluctuating than the natural frequency of the rotors without cracks.

Table 3. Natural frequencies of the overhung rotor with the location of the longitudinal crack between two supports

Natural frequency	Crack depth [mm]	Crack length [mm]					
		6	8	10	12	14	16
f_1	1	44.3772	44.3758	44.3755	44.3748	44.3741	44.3736
	2	44.3755	44.3751	44.3750	44.3739	44.3734	44.3724
	3	44.3749	44.3749	44.3745	44.3735	44.3722	44.3693
	4	44.3748	44.3726	44.3711	44.3705	44.3699	44.3687
f_2	1	237.7784	237.7644	237.7597	237.7608	237.7546	237.7404
	2	237.7736	237.7703	237.7739	237.7515	237.7511	237.7342
	3	237.7757	237.7583	237.7685	237.7630	237.7540	237.7320
	4	237.7718	237.7745	237.7514	237.7534	237.7509	237.7324
f_3	1	426.2189	426.1749	426.1195	426.2091	426.0388	426.0764
	2	426.3512	425.9026	426.1884	426.0269	426.0856	426.2131
	3	426.2507	426.0695	426.0361	426.2229	426.3463	426.0900
	4	426.2177	425.9608	425.9954	426.1101	426.2717	426.0642

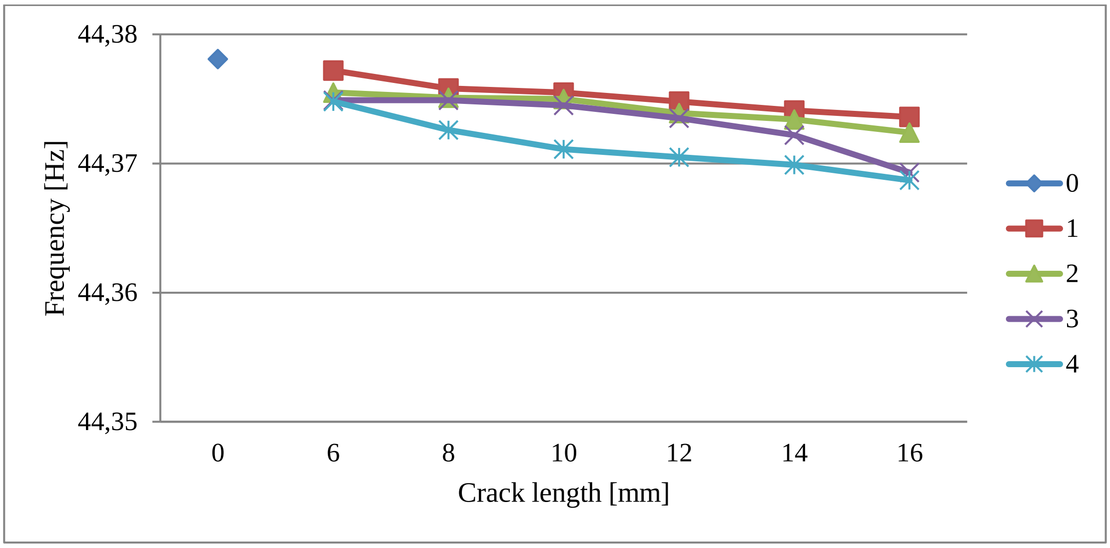

Figure 6. The first natural frequency of the rotor due to crack length for various crack depth with the location of the longitudinal crack between two supports

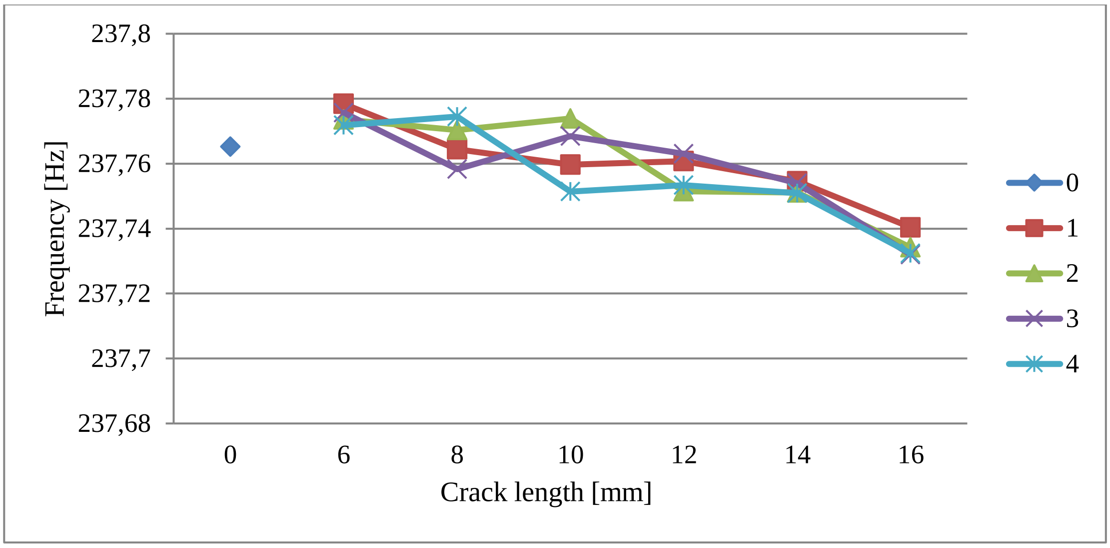

Figure 7. The second natural frequency of the rotor due to crack length for various crack depth with the location of the longitudinal crack between two supports

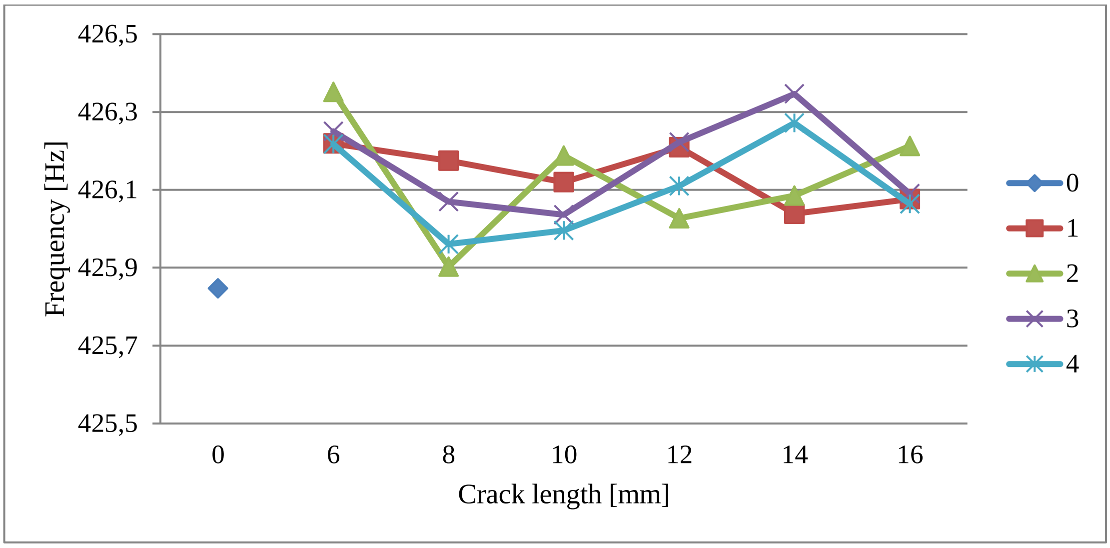

Figure 8. The third natural frequency of the rotor due to crack length for various crack depth with the location of the longitudinal crack between two supports

Furthermore, the stress of the overhung rotor system without cracking is also simulated. The simulation using the MSC Nastran/Patran results in maximum stress of 10.56 MPa. This ultimate stress occurs in the area around the supporting close to the disk. The stress at this location can be calculated analytically, where the bending moment as the primary stress source is also maximum. For the case of the overhung rotor with a crack, especially a crack between disk and bearing, the maximum stress is obtained, as shown in Table 4 and depicted in Figure. 9. The ultimate stress occurs not in the crack but still in the support area, although the location of the crack is close to 10 mm from the support. If analyzed more deeply, it is known that the stress at the crack tip is only around 9.9 to 10.11 MPa or not higher than the maximum stress in Table. 4. However, when compared between the rotor with and without crack, the maximum stress is still slightly higher in the rotor with cracks. This means that longitudinal cracks located between the disk and the support still contribute to the maximum stress in the rotor, although not as much as the contribution of the maximum bending moment.

Tabel 4. The maximum stress of the overhung rotor with a crack between the disk and support

Crack depth [mm]	Crack length [mm]					
	6	8	10	12	14	16
1	10.60	10.60	10.60	10.61	10.61	10.61
2	10.60	10.60	10.59	10.59	10.60	10.60
3	10.57	10.57	10.56	10.58	10.60	10.60
4	10.58	10.57	10.57	10.57	10.57	10.58

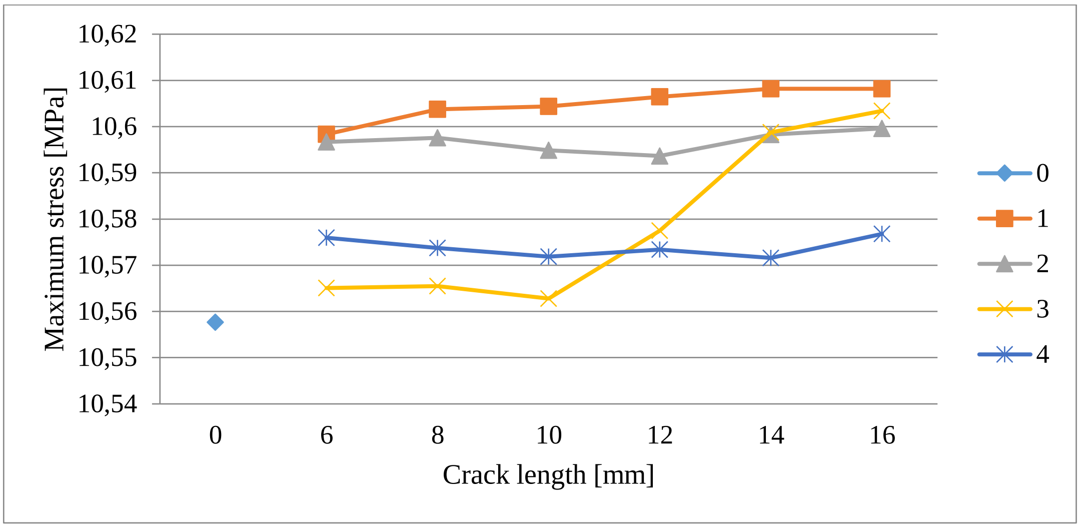

Figure 9. The maximum stress of the overhung rotor with a crack between disk and bearing

For the case of the overhung rotor with a crack, especially a crack between the two supports, the maximum stress is obtained as shown in Table 5 and depicted in Figure. 10. Although the location of the crack is in the middle between the two supports, the maximum stress occurs in the support area. Similar results have been discussed to the rotor without cracks and to the first case of the rotor with cracks. Here, the stress at the crack tip is only in the range of 2.90 to 3.33 MPa or much lower than the maximum stress in Table. 5. However, when comparing the rotor with crack between the disk and bearing and the rotor with crack between the two supports, the maximum stress is higher in the rotor with longitudinal cracking between the two supports. In other words, longitudinal cracks located between the two supports contribute significantly to the ultimate stress in the rotor, especially in the region of maximum bending moment. The possibility of the crack position in the area with a large deflection of the rotor system as the main contributor to the increase in maximum stress is in question.

Tabel 5. The maximum stress of the overhung rotor with a crack between the two supports

Crack depth [mm]	Crack length [mm]					
	6	8	10	12	14	16
1	19.51	13.12	11.77	17.42	15.87	17.90
2	19.92	12.96	11.84	18.43	17.23	17.86
3	20.47	12.43	11.74	15.04	15.96	16.18
4	19.62	12.85	11.77	17.54	16.72	15.94

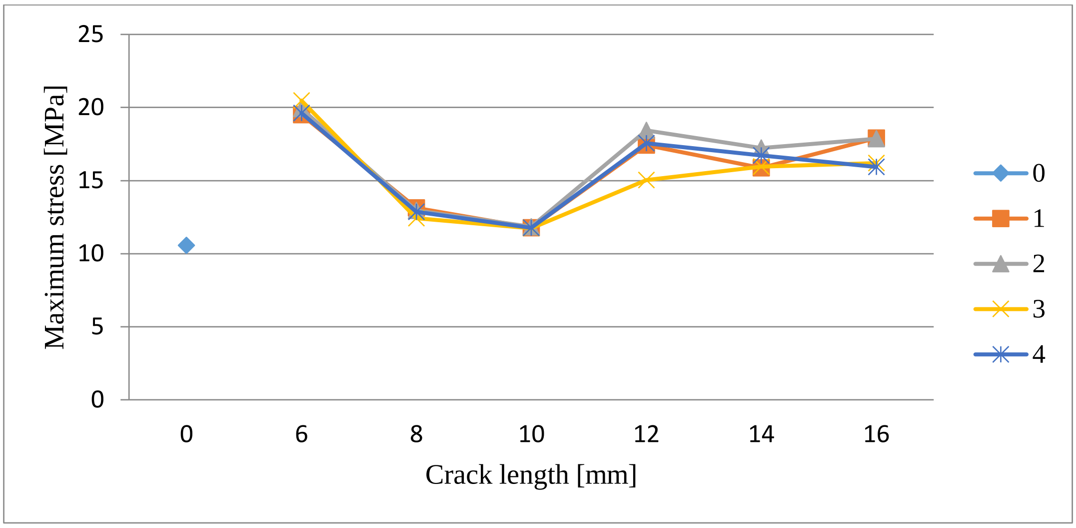

Figure 10. The maximum stress of the overhung rotor with a crack between the two supports

4. Conclusion

Based on the simulation results that have been carried out, the following conclusions can be drawn:

1. Longitudinal cracks cause a decrease in shaft stiffness in which the natural frequencies decrease as well. The value of shaft stiffness decreases with increasing variations in the depth and length of cracks in the shaft.
2. The value of stiffness changes with different crack locations on the shaft. Cracks between the disk and the bearings significantly reduce stiffness than the cracks between the two supports.
3. For variations in crack length, the natural frequency tends to decrease with increasing crack length, especially at the first natural frequency and the second natural frequency, but at the third natural frequency tends to fluctuate.
4. For variations in crack depth, the natural frequency value tends to decrease with increasing crack depth, especially at the first natural frequency and the second natural frequency. Still, the third natural frequency tends to fluctuate.
5. Longitudinal crack can cause stress concentration on the shaft so that the stress that occurs at the crack tip on the shaft increases. However, the ultimate stress occurs in the area with the maximum bending moment, and the longitudinal crack contributes to increasing this maximum stress.

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