24th ABCM International Congress of Mechanical Engineering
December 3-8, 2017, Curitiba, PR, Brazil

COBEM-2017-0564
VIBRATIONAL ANALYSIS OF CRACKED HOOKS

Emilio Cordoba Janssen
Eduardo Farinazzo Gama
Universidade Positivo de Curitiba
Emilio9245@yahoo.com.br

Marcus Vinícius Manfrin de Oliveira Filho
Universidade Positivo de Curitiba
Marcus.oliveira.filho@gmail.com

Abstract. *It is a well-known fact that the presence of cracks modifies the dynamic responses of structures. It is also known that the use of hooks is one of the preferred methods for lifting and handling loads, and that several failures and accidents involving crack propagation in such equipment have been reported. Although predictive and prognostic maintenances of hooks are desirable for industrial applications, the study of vibrational behavior of cracked hooks is still incipient. In the present work, a three-dimensional model of a hook was computationally constructed using the finite element method. In this model, cracks with different depths and positions were inserted into the higher stress concentration site. The different simulated scenarios allowed studying the influence of damage on the natural frequencies of hooks and vibrating mode shapes. It was observed that some vibrational modes are more sensitive to damage than others: the fourth natural frequency and the mode shape were the most affected, followed by the fifth and sixth ones. Based on the results of the present study, a crack identification method based on natural frequencies and mode shape shifts detected in damaged hooks can be developed.*

Keywords: *Modal analysis, mode shape, hook, natural frequency, crack.*

1. INTRODUCTION

The need for handling and lifting loads in construction sites, industries, and ports is increasingly demanding. Equipments used in them are provided with lifting hooks which, in most cases, completely support the load and the equipment as a whole. Thus, they must be in full operating condition, i.e., with no signs of wear or structural damage. The incorrect use of such equipment can lead to serious accidents involving not only the equipment but also the safety of workers.

The emergence of cracks in structures is related to several factors, ranging from fatigue of the component due to high cycles of loading and unloading to the exposure of that structure to overload. In recent years, several methods of non-destructive analysis have been developed, but there is still no method applicable to all structures, since each of them has its own advantages and disadvantages. One of the most recent, non-destructive methods is the modal analysis of structures with which it is possible to detect the presence of cracks and analyze the changes that the crack causes in the mechanical properties of the structure, such as changes in its stiffness and area. With this, the vibrational properties of the system will also be modified, thus changing its natural frequencies and vibration modes.

Traditionally, one of the main failure regions of the hooks is located in their inner radius, where the emergence of cracking is common. Figure 1 shows an Asm example of hook failure.

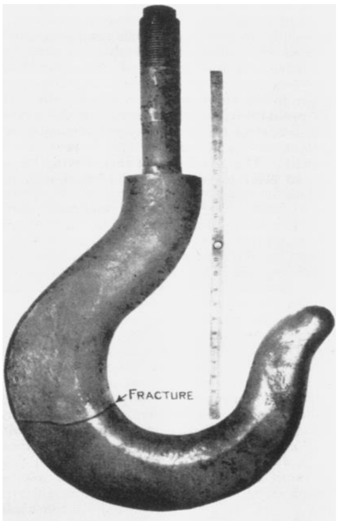

Figure 1. Real hook with a crack in the highest stress region.

An extensive study in the literature on damaged structures was carried out by (Richardson, 1980) in order to verify all the technology available for detecting cracks. All that study focused on the structures present in nuclear power plants. Another study, carried out at the same time by (Cawley and Adams, 1979), showed that analyzes using the finite element method can be used to determine the location and size of the defect imposed on the structure, and just one dynamic analysis suffices for each type of structure.

(Shen and Chu, 1992) and (Rezaee and Fekrmandi, 2012) demonstrated the dynamics of the truss beams model, in which the crack opens and closes according to vibrating modes, a phenomenon known as ‘breathing crack’. (Chati, *et al.*, 1997) addressed the analysis of the nonlinearity present in beams with cracks with the modal analysis method and the use of finite elements. To determine the natural frequencies of the system, the idea of bilinear frequency was used, which is obtained by computing the frequencies associated to each linear part of the system. To carry out this analysis, it is necessary to model two different configurations of the structure with the open and closed crack. (Owolabi, *et al.*, 2003), (Priyadarshini, 2013), (Agarwalla and Parhi, 2013), (Nahvi and Jabbari, 2005), (Kim and Stubbs, 2003), and (Sinha, *et al.*, 2002) performed experimental analyzes of beams with cracks aiming at detecting, quantifying, and determining the position of the cracks by verifying the variation of the natural amplitudes and frequencies of the system, since, for each position and depth scenario, unique results are found. (Rizos, *et al.*, 1990) analyzed the method for determining the existence and position of transverse cracks on the surface of rectangular beams, in which the modal characteristics of the beam were analyzed. As the existence of cracks modifies the local flexibility of the structure, this method ends up being very effective for determining the position of cracks in one-dimensional structures. (Adams, *et al.*, 1978) addressed the method for non-destructive assessment of structures integrity for one-dimensional systems. Vibration measurements performed in a region of the structure can be used together with a theoretical model; experimental results on various structures (prismatic bars, camshaft, etc.) demonstrate that the relationship between predicted and actual damage sites is quite narrow.

Despite the technological interest in structure analysis, and the fact that hooks have problems with cracks and ruptures in the maximum stress region, no article was found in literature presenting a study of cracks in this type of mechanical structure. Thus, the present study aims at analyzing the vibrational behavior of a hook using the finite element method, based on two main scenarios: hooks with and without cracks.

The ‘with crack’ scenario was subdivided into 20 scenarios aiming at analyzing the vibrational variations that the hook presents when exposed to different positions and depths of crack. With the analysis of the modal results of each scenario, it is possible to develop a method to verify and monitor structures that may present defects, thus avoiding possible accidents.

2. METHODOLOGY

In order to implement the project, an analysis of the types of hooks available in the market was carried out. In that analysis, the most common types of hooks were identified, regarding different geometries, sizes, and applications. The three-dimensional model of the hook was obtained from the CAD platform, commonly used by hook manufacturers.

After the modeling process, the component was imported into the commercial software Ansys 17.2, where the mechanical properties, mesh characteristics, element sizes, and the contour conditions of the problem were applied. Having built the computational model, it was possible to calculate the natural frequencies of the hook and to analyze different scenarios of the structure using the finite element method.

2.1 Modeling the hook without crack

The hook used in the analysis is shown in Figure 2, where it is also possible to observe its dimensions in millimeters.

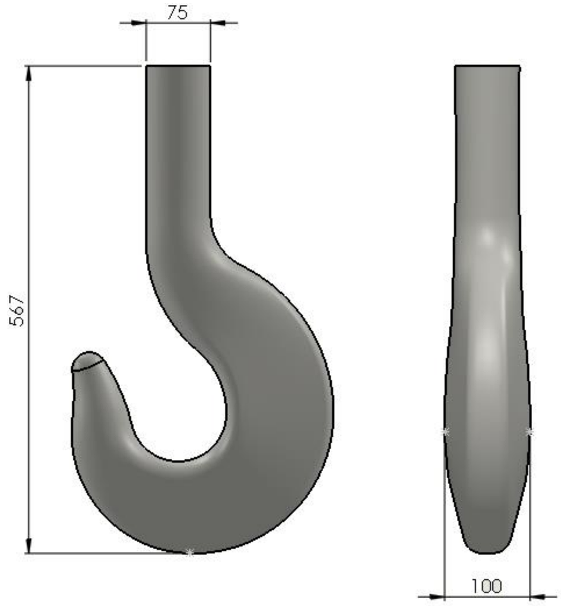

Figure 2. Hook without crack.

After having defined the geometry, the mechanical properties were added. The material considered in the analysis was carbon steel, with a Poisson coefficient of 0.3, density of 7850kg / m³, and elasticity modulus of 200 GPa.

2.2 Modeling the hook with crack

The cracked hook has basically the same geometry and mechanical properties of hook without crack, showing just a small discontinuity in the region of the inner ray, as shown in Figure 3.

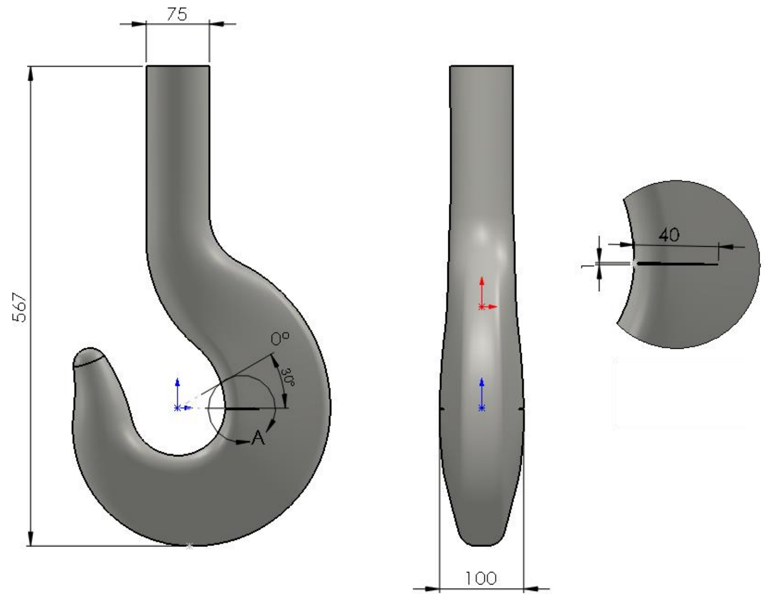

Figure 3. Hook with crack.

The crack was positioned from 10 to 40° of the reference axis, adopting 2mm of thickness and 5 to 40mm of depth, as shown in Table 1. With this amount of variations in position and depth, it was possible to prospect results of different vibrational behaviors of the hook.

Table 1. Scenarios of cracks applied to the hook.

Scenarios	Angle of the crack(°)	Width of the crack (mm)	Depth of the crack (mm)
1	10	2	40
2	10	2	30
3	10	2	20
4	10	2	10
5	10	2	5
6	20	2	40
7	20	2	30
8	20	2	20
9	20	2	10
10	20	2	5
11	30	2	40
12	30	2	30
13	30	2	20
14	30	2	10
15	30	2	5
16	40	2	40
17	40	2	30
18	40	2	20
19	40	2	10
20	40	2	5

Twenty different scenarios were performed for the cracked model, varying the depth and position of the crack. The position was performed at 4 different points, each position variation with 5 depth variations.

(2)

2.3 Modeling with finite elements

The model of the part was discretized with a finite element mesh using the SOLID187 element. This element is commonly applied and suitable for geometries with uneven and complex surfaces, as indicated in the help tool, ANSYS Help, prepared by the software manufacturer. The SOLID187 element, shown in Figure 4, has 10 nodes and three degrees of freedom for each node, and is used in both integral and cracked hook models.

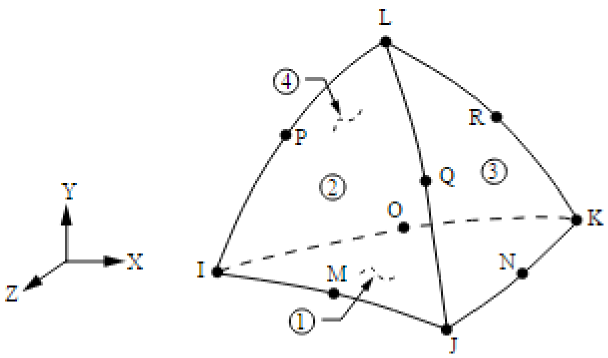

Figure 4. Mesh element SOLID187.

A mesh sensitivity analysis was performed to verify the size of the element that yielded a better result and quite a low computational time. The results obtained showed that mesh refinement in the crack region with mesh elements smaller than 3mm does not vary the accuracy of the results, only adds more elements, thus increasing the computational time of the model. Figures 5, 6, and 7 show the variations obtained in the results of the first six natural frequencies of the part: Figure 5 shows the first and second frequencies, Figure 6 shows the third and fourth frequencies, and Figure 7 the fifth and sixth natural frequencies. It can be observed that the smaller the mesh, the more refined the results.

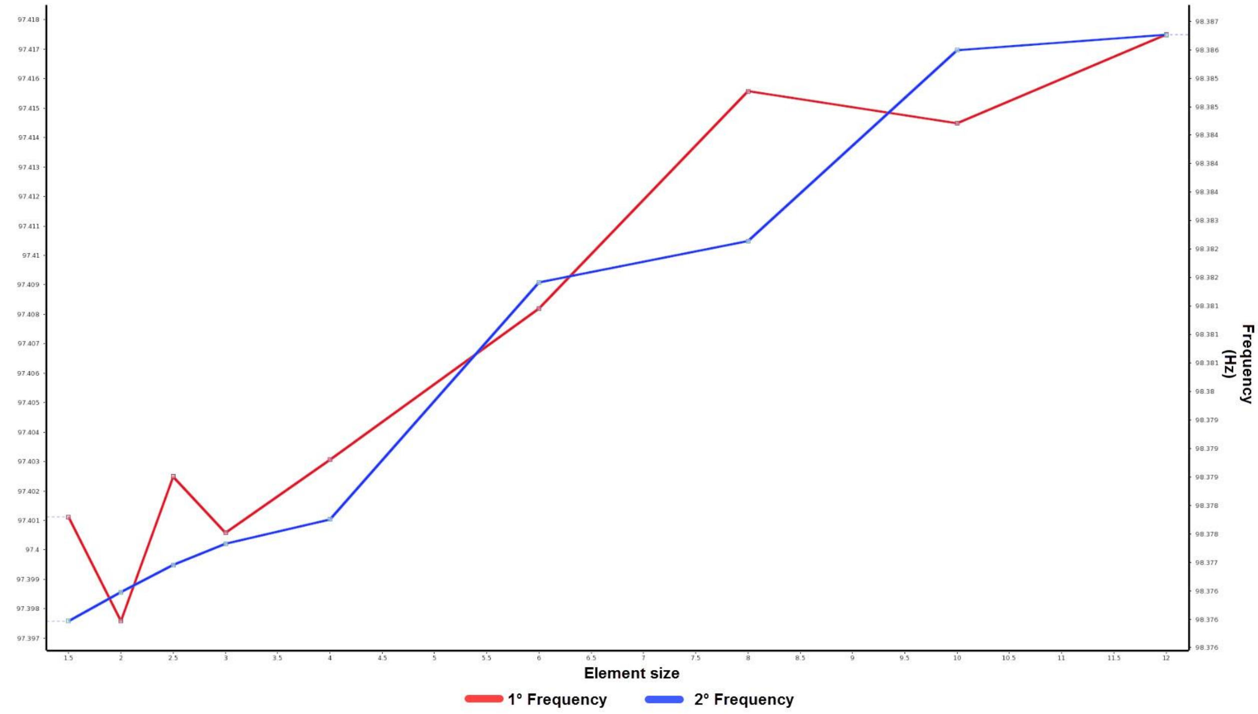

Figure 5. Variations of frequencies 1 and 2.

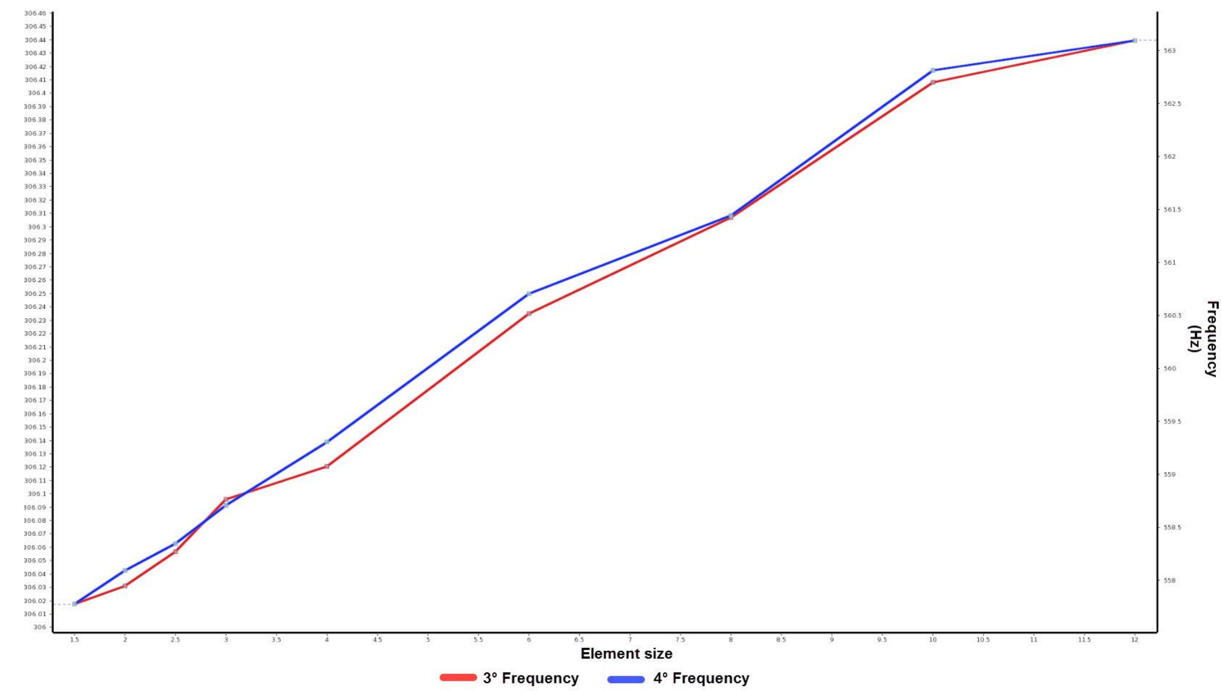

Figure 6. Variations of frequencies 3 and 4.

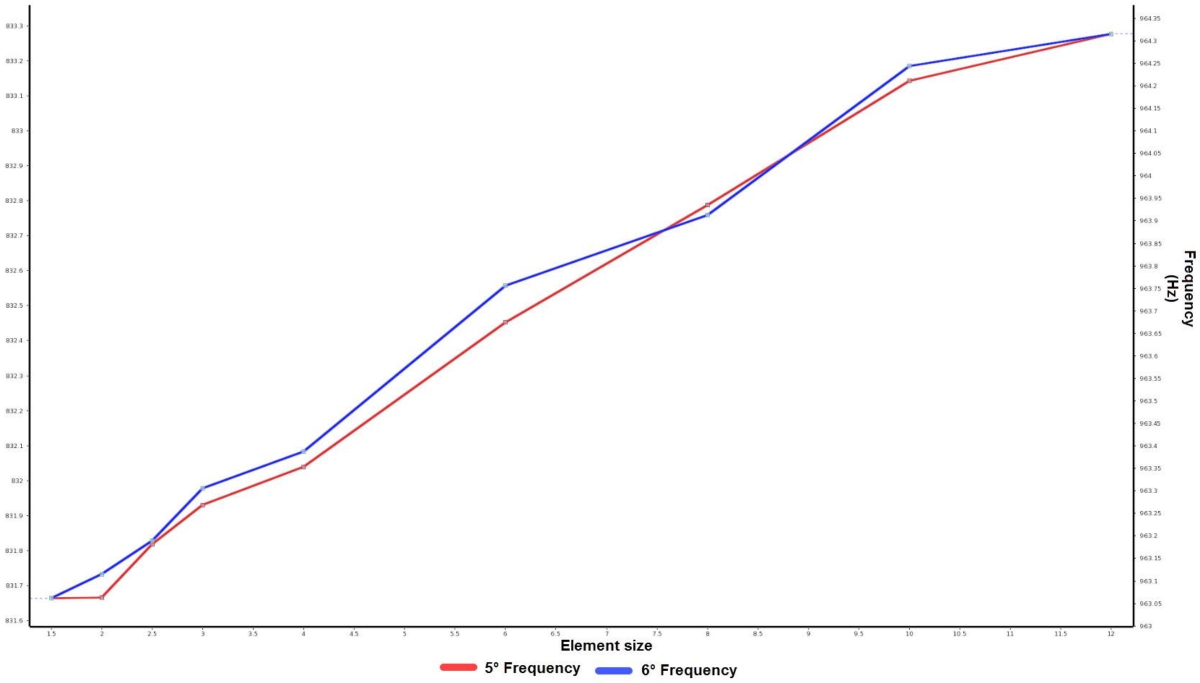

Figure 7. Variations of frequencies 5 and 6.

Figure 8 shows the relationship of mesh elements created for each element size used in the crack refining, so one can observe that elements smaller than 3mm increase considerably the total number of elements and, consequently, the computational time of the analysis.

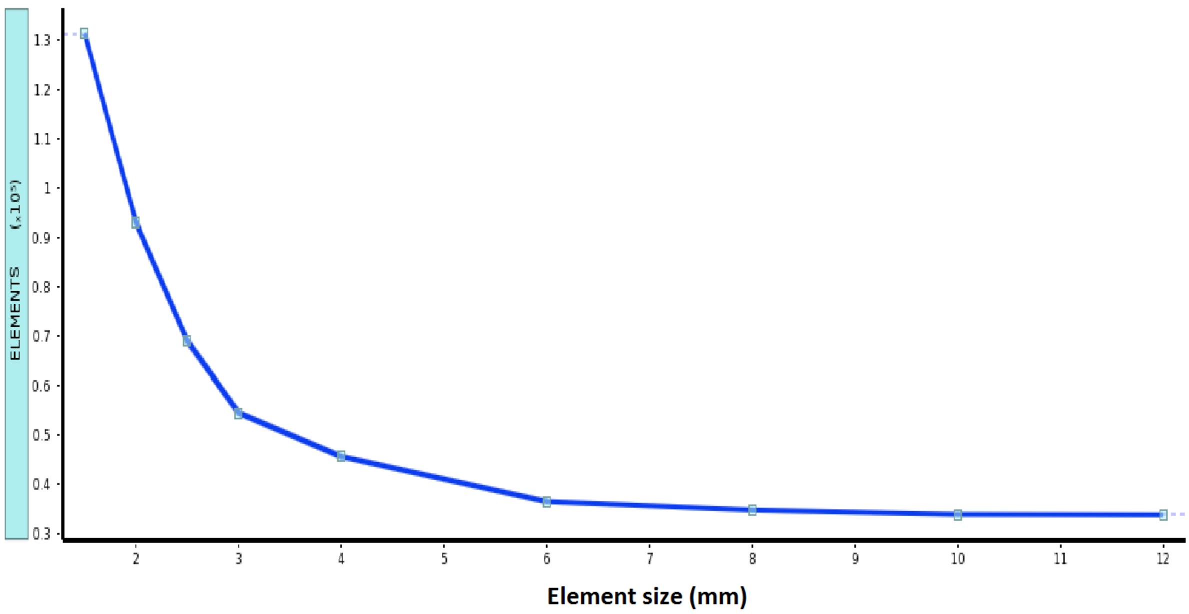

Figure 8. Mesh elements.

With the mesh sensitivity results, a final mesh was selected, as shown in Figure 9. Figure 9 A shows the final mesh adopted for the first scenario with the presence of the crack, and Figure 9 B shows the final mesh adopted for the hook without crack.

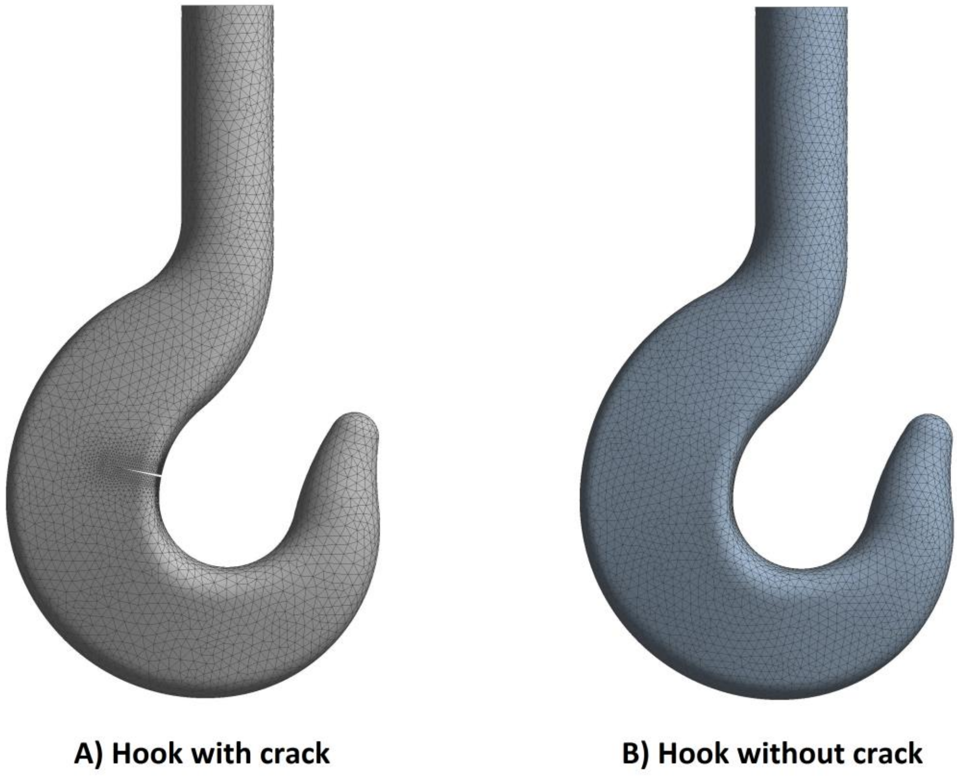

Figure 9. Final mesh.

The contour conditions used for the analysis are intended to simulate the working conditions of the part. For the present study, the crimping of the upper face of the hook was performed, restricting rotations and displacements in the 3 axes. Figure 10 shows the fixed region.

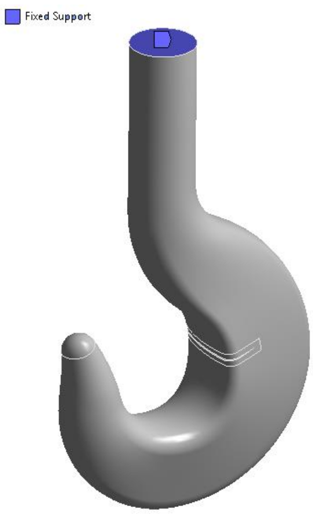

Figure 10. Contour conditions.

3. RESULT AND DISCUSSION

The results of the crack analysis without the presence of the crack were obtained with the finite element method. The first six natural frequencies can be seen in Table 2. One can observe that the first two frequencies have very close results, but they are associated with different modes of vibration.

Table 2. Natural frequency.

Scenarios	Natural frequency (Hz)
1	97.750
2	98.488
3	313.020
4	707.480
5	871.500
6	1018.300

The first six vibration modes for the hook with crack were analyzed, not all of them are strongly influenced by the presence of the crack. Figure 11 shows the first six vibration modes of the hook with crack. One can observe that the first three modes are the least affected by the presence of crack in that region.

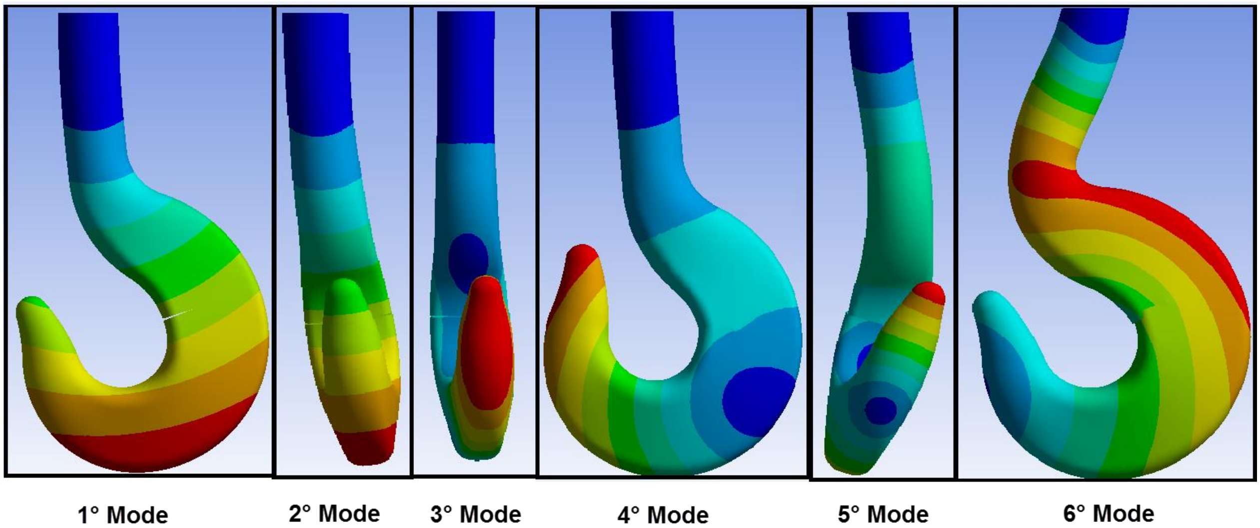

Figure 11. Vibration modes.

The results of the six natural frequencies for each scenario are shown in Figure 12. One can see that the fourth natural frequency is most affected by breathing crack, followed by the fifth and sixth ones. On the other hand, the first, second, and third natural frequencies and vibrational modes are not so sensitive to this type of crack in that region. The greater the crack, the lower the stiffness of the structure and, consequently, the lower the natural frequency.

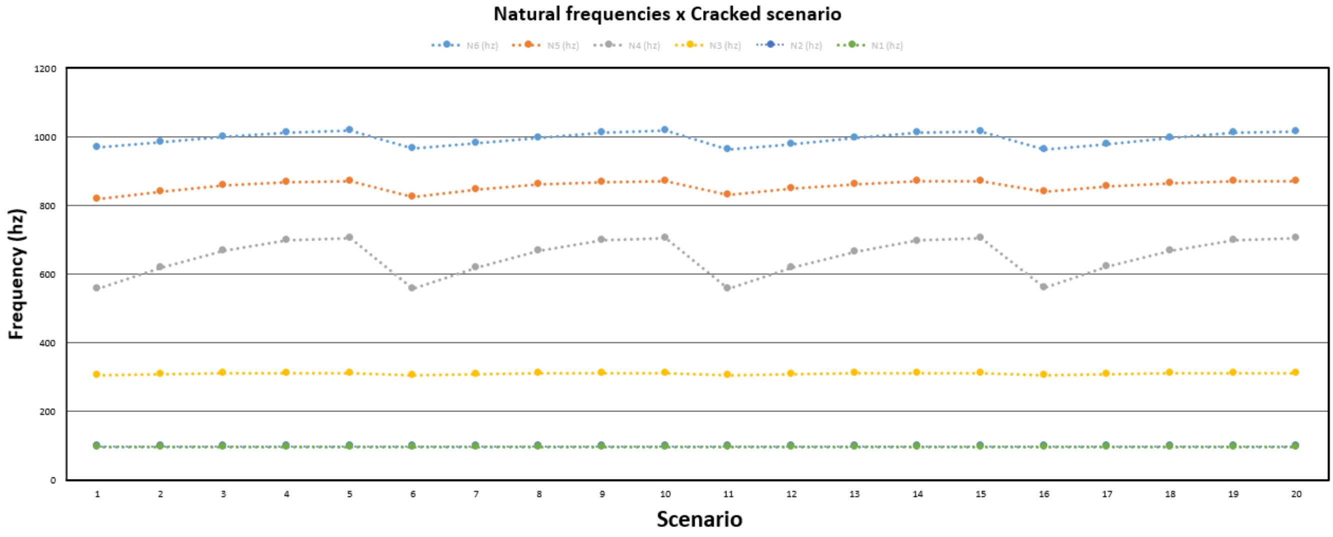

Figure 12. Result of natural frequencies.

The numerical results presented in graphic form in Figure 12 can be verified in Table 3, which shows the relationship of the geometric configuration of the crack with the first six frequencies obtained by the model.

Table 3. Scenario of frequencies found.

Scenarios	Angle of the crack (°)	Depth of the crack (mm)	Frequency (Hz)					
			1	2	3	4	5	6
1	10	40	97.2338	98.1605	306.0782	558.8270	818.8991	968.5121
2	10	30	97.4863	98.3260	309.3552	619.3452	841.6969	984.0594
3	10	20	97.6490	98.4264	311.4638	667.2584	858.8521	1000.2941
4	10	10	97.7391	98.4858	312.6360	697.8639	869.1928	1013.6457
5	10	5	97.7555	98.4914	312.9345	705.3871	871.2413	1017.2797
6	20	40	97.3127	98.2764	306.0173	557.7503	824.8545	965.1811
7	20	30	97.5283	98.3884	309.3363	618.7768	845.2601	981.2661
8	20	20	97.6671	98.4523	311.4490	666.7973	860.3522	998.4593
9	20	10	97.7398	98.4884	312.6340	697.6798	869.3972	1013.0160
10	20	5	97.7546	98.4950	312.9316	705.3258	871.2476	1017.1535
11	30	40	97.3891	98.3646	306.0548	558.5540	831.7798	963.0512
12	30	30	97.5706	98.4366	309.3112	618.5646	849.2102	979.2878
13	30	20	97.6854	98.4757	311.4300	666.4209	862.0419	997.1061
14	30	10	97.7446	98.4919	312.6270	697.3467	869.6946	1012.4001
15	30	5	97.7560	98.4956	312.9302	705.1704	871.2772	1016.9598
16	40	40	97.4684	98.4463	306.1395	561.6687	840.4238	961.9645
17	40	30	97.6106	98.4773	309.3357	620.6386	854.2460	978.4648
18	40	20	97.7024	98.4927	311.4362	667.2834	864.2520	996.5852
19	40	10	97.7459	98.4976	312.6324	697.5023	870.1263	1012.2450
20	40	5	97.7566	98.4962	312.9332	705.2091	871.3567	1016.9133

4. CONCLUSION

It is well known that cracks cause changes in the dynamic responses of structures. Although, along history, several faults have been reported in hooks, the study of their vibrational behavior is incipient. The aim of the present work was to analyze the variation of natural frequencies and vibration modes of hooks according to different crack sizes and locations, simulated through a three-dimensional computational model created with the finite element method.

The results of the simulations make clear the variation of the vibrational behavior of the hooks when their stiffness is affected by the presence of cracks; the change in vibration modes and natural frequency is proportional to the magnitude of the damage: the deeper the crack, the greater the difference in the value of natural frequencies. For the analyzed hook, and with the boundary conditions adopted, the fourth mode of vibration presented a greater sensitivity to the localized damage, followed by the fifth and sixth modes, respectively.

Based on the results obtained, it is possible to develop a method to identify cracks in hooks, that is, to determine the position and depth of existing cracks through the analysis of vibrational data acquired on those structures.

5. REFERENCES

Adams, R.D., Cawley, P., Pye, C.J. and Stone, B.J., 1978. “A vibration technique for non-destructively assessing the integrity of structures”. In *Journal Mechanical Engineering Science*.

Agarwalla, D.K. and Parhi, D.R., 2013. “Effect of crack on modal parameters of a cantilever beam subjected to vibration”. In Procedia Engineering, Vol. 51, Pages 665-669.

Asm international, 2004. “Brittle fracture of a crane hook”. 1 April 2017. <http://products.asminternational.org/fach/data/fullDisplay.do?database=faco&record=1681&trim=false>.

Chati, M., Rand, R. and Mukherjee, S., 1997. “Modal analysis of a cracked beam”. In *Journal of Sound and Vibration*, 207(2), 249-270.

Cawley, P. and Adams, R.D., 1979. “The location of defects in structures from measurements of natural frequencies”. In *Journal of Strain Analysis*, 14 (2).

Kim, J.T. and Stubbs, N., 2003. “Crack detection in beam-type structures using frequency data”. In *Journal of Sound and Vibration*, Vol. 259, Pages 145-160.

Navi, H. and Jabbari, M., 2005. “Crack detection in beams using experimental modal data and finite element model”. In *International Journal of Mechanical Sciences*, Vol. 47, Pages 1477-1497.

Owalabi, G.M., Swamidas, A.S.J. and Seshadri, R., 2003. “Crack detection in beams using changes in frequencies and amplitudes of frequency response functions, In *Journal of Sound and Vibration 265*, Pages 1-22.

Priyadarshini, A., 2013. “Identification of cracks in beams using vibration analysis”. *Master of technology in structural engineering – Civil Engineering*. National Institute of Technology Rourkela.

Rezaee, M. and Fekrmandi, H., 2012. “A theoretical and experimental investigation on free vibration behavior of a cantilever beam with a breathing crack”. In *Shock and Vibration 19,* Pages 175-186.

Richardson, M.H., 1980. “Detection of damage in structures from changes in their dynamic (modal) properties”. A Survey, US, *Nuclear Regulatory Commission*, Washington, DC.

Rizos, P.F., Aspragathos, N. and Dimarogonas, A. D., 1990. “Identification of crack location and magnitude in cantilever beam from the vibration modes”. In *Journal of Sound and Vibration 138(3)*, Pages 381-388.

Shen, M.H.H and Chu, Y.C., 1992. “Vibrations of beams with a fatigue crack”. In *Computers and structures 45*, Pages 79-93.

Sinha, J.K.,Friswell, M.I. and Edwards, S., 2002.” Simplified models for the location of cracks in beam structures using measured vibration data”. In *Journal of Sound and Vibration 251,* Pages 13-38.

6. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.