Journal-Mathematical and Quantitative Methods 9[15]1-14: e1915114
Article

Microcrack evaluation using modal analysis under two loading conditions on rotodynamic shafts

Evaluación de microfisuras usando análisis modal bajo dos condiciones de carga en ejes rotodinámicos

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Classification:

Area: Engineering
Field: Engineering
Discipline: Mechanical Engineering
Subdiscipline: Vibration and acoustics

https://doi.org/10.35429/JMQM.2025.9.15.1.1.14
History of the article:
Received: October 30, 2025
Accepted: December 30, 2025

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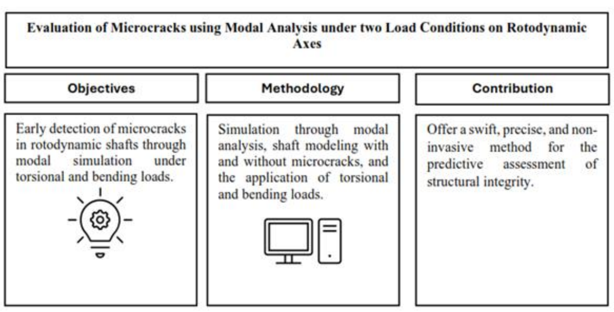
Abstract

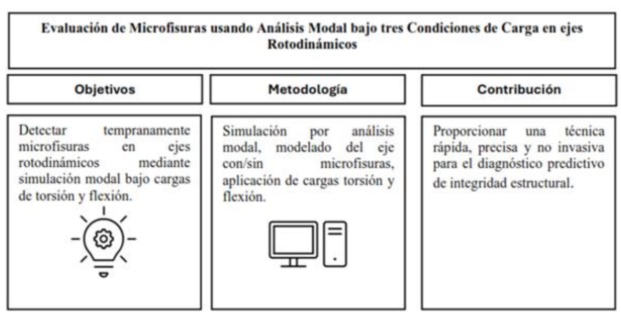
Microcracks in a component are characterized as minor imperfections that manifest in specific materials, particularly those integral to critical structures. Their diminutive size renders detection exceedingly challenging, presenting a substantial obstacle for analysts of structural systems. These microcracks frequently signify the onset of a more extensive degradation process, so they early identification is crucial. Otherwise, the mechanical integrity of the equipment could be put at risk. Currently, standard practice entails subjecting components to laboratory tests, which, although informative, are not invariably nondestructive. Considering this, the adoption of simulations based on modal analysis and the monitoring of stiffness variations under controlled loads is gaining traction, with the objective of shortening evaluation times and safeguarding the component's integrity during diagnosis.



Microcrack, Modal analysis, Rigidity

Resumen

Las microfisuras en un componente se definen como pequeñas imperfecciones que aparecen en ciertos materiales, sobre todo en los que forman parte de estructuras críticas. Debido a su reducido tamaño, localizarlas resulta sumamente complicado, lo que plantea un reto significativo para quienes analizan sistemas estructurales. Estas microfisuras a menudo marcan el comienzo de un proceso de degradación más amplio, por lo que identificarlas a tiempo es vital; de lo contrario, el rendimiento mecánico de la pieza puede verse comprometido. Actualmente, la práctica habitual pasa por someter los elementos a ensayos de laboratorio, protocolos que, si bien informativos, no siempre son no destructivos. Ante este panorama, surge el aprovechamiento de simulaciones basadas en análisis modal y en el monitoreo de variaciones de rigidez bajo cargas controladas, con el fin de acortar los plazos de evaluación y proteger la integridad del componente durante el diagnóstico.



Microfisura, Análisis modal, Rigidez

Area: Promotion of frontier research and basic science in all fields of knowledge

Citation: Romero-Sotelo, Francisco Javier, Rodríguez-Blanco, Marco Antonio, Pérez-Montejo, Salatiel and Álvarez-Arellano, Juan Antonio. [2025]. Microcrack evaluation using modal analysis under two loading conditions on rotodynamic shafts. Journal-Mathematical and Quantitative Methods. 9[15]1-14: e1915114.

Introduction

Timely detection of microcracks in rotor-driven shafts represents one of the most significant challenges in contemporary mechanical engineering. These components, integral to turbines, generators, and combustion engines, endure substantial dynamic forces and fluctuating operating conditions that promote the emergence of nearly imperceptible cracks. Despite their minuscule size, these defects can precipitate severe fractures if not promptly recognized, as they disrupt local rigidity, alter natural frequencies, and compromise the structural integrity of the machine. Consequently, this leads to failures that impact safety, diminish availability, and escalate maintenance expenses[Jorge et al., 2024].

Up until now, ultrasound, magnetic particle examination, or destructive metallography has been used in labs to examine these breaks. These approaches are helpful, but they require extensive periods of downtime and equipment handling, and they aren't always completely non-destructive. Also, they have big problems when trying to find faults that are less than a millimeter long. In a world where Industry 4.0 and predictive maintenance strategies are common, there is a strong need for fast, reliable, and mostly virtual ways to check the condition of an axis both during the design phase and throughout its operational lifespan. This will reduce the need for invasive physical testing. [Sinou & Lees, 2007].

Finite element analysis [FEA] serves as an invaluable technique for this purpose. By determining the natural frequencies, damping ratios, and modal shapes of the structure, it becomes possible to identify significant alterations induced by the emergence of microdefects. These discrepancies are accentuated under torsional and flexural loads, as the applied torque creates stress concentrations at the crack edges, thereby modifying the overall vibrational response. The integration of modal simulation with a comprehensive analysis of equivalent stiffness provides a robust theoretical and computational framework that correlates frequency reduction with localized stiffness degradation, establishing a foundation for quantitative damage assessment [Garcia, 2017].

This study simulates a cylindrical specimen per ASTM E8, featuring a flaw smaller than 1 mm [microcrack], and conducts modal analysis in ANSYS© Workbench for both intact and compromised conditions. The method allows for the measurement of displacements for the first bending and torsion modes, calculates the stiffness loss in the affected area, and sets warning levels that can be used in online monitoring systems. The proposed method adds value during both the design phase [confirmation of tolerances and fatigue life through simulation] and the operational phase [asset monitoring via vibration sensors] by providing quick, repeatable results that don't require direct intervention on the equipment [Garcia, 2017].

In conclusion, the methodology outlined here addresses the growing need for non-destructive methods based on simulation models that reduce downtime, improve maintenance, and enhance the reliability of critical rotating systems. These results show that modal analysis and stiffness studies work well together to locate microcracks and fully assess the structural integrity of rotary shafts.

The evaluation of microcracks under diverse loading situations by modal analysis has become a significant area of research due to its ability to detect subtle changes in the system's dynamic features. This procedure makes it easier to find cracks before they get big enough to put the shaft's structural integrity at risk [Rodríguez Bravo et al., 2022].

Literature review

Within the bibliographic review, different authors have carried out studies and experiments to determine the phenomenon or explain the behavior of a crack in an axis or rotodynamic mechanical element, in the first Dilena & Morassi [2002] they examined, using analytical models and experimental tests, the variations in the vibration modes of thin beams subjected to resonance. The results showed that the presence of a crack significantly alters the location of the nodes in these vibrational modes, possibly resulting in the displacement of the nodes allowing the location of the damage to be determined.

Expensive tools and large data sets are required to assess damage via the vibrations of iron marks.

ISSN: 2531-2979
RENIECYT: 1702902

Most of the time, the uncertainties tied to models are ignored, affecting their accuracy. Alegria Gómez et al. [2024] suggests an innovative computational methodology using optimized genetic algorithms tailored to sparse and incomplete data sets. Unlike previous approaches, this model accounts for the uncertainty pertaining to shape and mass. The use of only three flexional vibration modes eliminates the need for higher modes' information. The methodology has been experimentally validated on an iron frame structure and provides proof of efficacy in the presence of multiple and illustrative damage conditions. The methodology achieved 100% success in damage identification and 80% in the estimation of severity. This indicates an outstanding level of performance, particularly for the low cost of the procedure in comparison to alternative approaches.

Nahvi & Jabbari [2005] demonstrate in their work that, by integrating experimental measurements of natural frequencies and mode shapes [Kushwaha & Patel, 2023] with an analytical model, it is possible to locate and estimate the depth of a crack in a cantilever beam: the comparison between measured frequencies and normalized frequency contours, followed by a minimization algorithm, allows to quickly and accurately identify the damaged element.

Kisa & Gurel [2006] propose a hybrid approach that combines the finite element method with component mode synthesis to modally analyze circular beams exhibiting multiple open and fixed cracks. The process fragments the beam into segments over the cracked areas and assembles them using flexibility matrices derived from fracture mechanics. This allows obtaining, in reasonable computational times and for any boundary conditions, the natural frequencies as the modal shapes of the beam vary systematically according to the position and depth of the damage. Viola et al. [2001]presented a finite element design for Timoshenko beams with open cracks and showed that, by including variations in stiffness and mass in the model and comparing the results with modal test measurements, it is possible to locate the crack with high precision and assess its severity from the recorded changes in the frequencies and modes of the structure.

Rastogi & Kumar [2009]review 40 years of studies on fatigue cracks in rotors defects that can lead to serious failures and critically assess the main strategies employed. They summarize: [1] advanced analytical and Lagrangian models that capture cyclic hardness variation due to crack "breathing"; [2] numerical techniques based on finite elements and modal synthesis that analyze many cracks at low computational cost; [3] physical testing and inversion algorithms, including AI approaches, to locate and measure damage; and [4] time-frequency signal analysis that finds sub-synchronous nonlinear components. The conclusion highlights challenges in validating in-service data, modeling growing cracks, and coupling bearing effects, to achieve more robust diagnostics in today's rotors.

Czajkowski et al. [2017] presented a Jeffcott model of a flexible, non-spinning rotor, which consists of a weightless shaft with a transverse crack near the disk and supports the system on ball bearings. With this arrangement, they numerically studied how breath-like opening in the crack modifies stiffness and thus natural frequencies. As the angular position of the rotor changes, each mode splits into two nearby peaks that only manifest themselves on damaged shafts; therefore, the systematic appearance of these modes duplicate peaks becomes an early and reliable sign for detecting cracks before the rotor goes into service.

According to the research, they agree that cracks significantly alter the modal properties of beams and rotors natural frequencies, vibration modes and nodes and that, by studying these variations through analytical models, finite elements, mode synthesis, or experimental tests, it is possible to locate the crack and assess its severity with good precision. In this sense, nodal displacement, peak frequency splitting, and the comparison of measured modal data with calibrated models emerge as early and reliable indicators of damage in rotodynamic elements.

Fundamentals of Modal Analysis

Modal analysis serves as a fundamental tool for identifying microcracks in rotating machinery. This method makes it easier to find the structure's inherent frequencies, damping coefficients, and mode shapes, as shown in figure 1. It is a strong and helpful way to describe dynamic behavior, notably in vibration research.

ISSN: 2531-2979
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It is often called structural modal analysis. In essence, it is a computational method based on a mathematical model of certain parts of the structure, focusing on how they vibrate.

Box 1

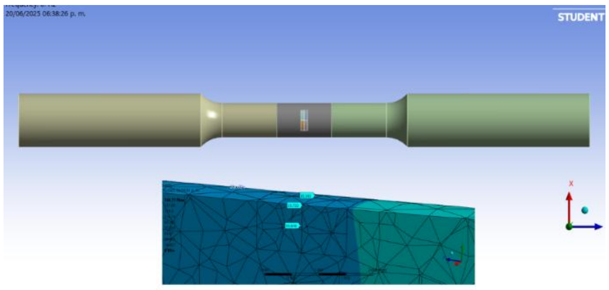

Figure 1
Modal analysis in software to assess vibrations resulting from loads or defects
Source: Own elaboration

In the classical framework of linear modal analysis, the structure is regarded as an ideal elastic system where mass *M*, damping *C*, and stiffen *K* are considered constant over time. This assumption facilitates the formulation and resolution of the problem without the need for physical testing, enabling the direct extraction of vibration modes and their natural frequencies, which act as indicators of the structure's integrity. By disregarding real loads, such as shear stresses, temperature gradients, or elastic supports, the model offers an intrinsic dynamic representation of the element, serving as a benchmark for comparison with any subsequent state.

However, the emergence of microcracks undermines the assumption that the material always maintains rigidity. Each crack introduces a localized flexibility [$\Delta K_{cracked}$] that alters the effective stiffness, resulting in the following relationship:

$$K_{cracked} = K_{intact} - \Delta K_{fissure} \qquad [1]$$

As the shaft rotates, the crack functions as a diaphragm, opening under tension and closing under compression.

This phenomenon "breathes" leading to a periodic modulation of stiffness, which results in additional harmonics at submultiples of the rotational frequency and slight shifts in the natural frequencies.

Finite element analysis facilitates the integration of contact conditions at the crack edges and the superposition of realistic loads—such as torsion, combined bending, and thermal gradients. Parametric sweeps correlate the amplitude of modal displacements with the size, orientation, and depth of the crack, thereby establishing numerical thresholds for predictive maintenance. Consequently, an abstract linear model serves as a baseline against which the nonlinear effects induced by microdefects are measured, simulated, and ultimately detected while the machine remains operational.

In summary, the integration of linear modal analysis with sophisticated simulations that incorporate "breathing" microcracks a term that will be elucidated later provides a robust framework that enables: [1] the definition of the normal vibration pattern of the shaft, [2] the measurement of stiffness loss resulting from early damage, and [3] the prediction of crack progression, specifically those smaller than one millimeter, based on spectral changes before they impact the operation of critical rotodynamic machines.

Fissure Breathing Phenomenon

Crack breathing is a critical phenomenon for comprehending the behavior of structurally compromised rotodynamic shafts, specifically cracked shafts [Hossain & Wu, 2018]. This term refers to the process whereby a crack in the shaft periodically opens and closes as the component rotates. As the shaft turns, alternating forces, often resulting from bending, generate cyclic tensile and compressive stress in the damaged area. During the tensile phase, the crack opens, leading to a significant loss of load-bearing capacity in the cracked section and a reduction in its local stiffness. Conversely, when subjected to compression, the crack faces make contact, the crack closes, and stiffness is partially restored [Wang et al., 2021].

This continuous cycle of opening and closing causes a periodic modulation of the stiffness of the shaft. This rhythmic variation acts as a parametric forcing in the rotating system, which translates into vibratory components at characteristic frequencies. Specifically, the effect of the breathing fissure is usually reflected as an obvious peak in the vibration spectrum at twice the rotational speed, i.e. at 2x.

ISSN: 2531-2979
RENIECYT: 1702902

In addition, spectral analysis can reveal harmonics at multiples of the rotational frequency and even subharmonic responses, all resulting from the internal modulation of the material's stiffness.

Therefore, the damaged shaft not only responds to the forced excitation at the rotational frequency, but also generates extra frequencies caused by the periodic change in its rigidity.

As a result, a shaft that exhibits a crack not only vibrates at the frequency of forced rotation, but also shows additional components generated by cyclical changes in its rigidity. Phenomena such as the prominent 2X peak and other lateral modulations then act as characteristic indicators of breakage and are key to diagnosing failures in rotating machinery. To understand these vibrations, it is necessary to face their nonlinear nature and consider the intermittent contact between the faces of the crack and the distribution of stresses in its vicinity.

As effective stiffness changes with angular position, some analytical approaches simplify it and model it with a well-determined periodic function, for example, a sine wave that repeats throughout an entire revolution. However, to reproduce the real behavior it is preferable to resort to non-linear numerical simulations that handle the phenomenon more faithfully. These advanced models, usually implemented with finite elements, include contacts that allow the opening and closing of the crack to be simulated in an explicit and realistic way at each turn [Liu et al., 2023].

A finite element model defines a surface-to-surface interaction with hard contact in the normal direction, preventing crack faces from overlapping while preventing tensile stresses from being transmitted when the crack is open.

In this manner, the model effectively captures the abrupt decrease in stiffness during crack opening and the immediate restoration of that stiffness upon closure, thereby replicating the cyclical hardness pattern observed in experimental tests. While the nonlinear formulation incorporating three-dimensional contact is regarded as the most dependable for simulating the effects of a breathing crack, its implementation necessitates extensive computation times, which constrains its practical application in industrial designs.

Therefore, the presence of a breathing crack gives the rotor [El-Mongy & Younes, 2018] a complex and non-linear dynamic behavior, with fluctuating stiffness over time; Hence, their inclusion in models is essential to understand the response of damaged rotating axes and to develop robust tools for diagnosing and detecting faults in rotating machinery[Varney & Green, 2012].

Most important modules of a modal analysis

The dynamic analysis of a structural model, in addition to comprehensively studying the transient response of that model to various external excitations, also provides invaluable information about how currently designed models respond to periodic perturbations, depending on the frequency of such perturbations[Rodríguez Bravo et al., 2022].

This information is extremely useful and practical in the design stage, as it allows structures to be optimized and possible failures to be foreseen. The evaluations are carried out within a Modal Analysis, which includes four specific resources to judge the structures accurately. These are:

1. Modal analysis, which provides an initial overview of the system's natural vibration modes [Bertero et al., 2022].

2. ARM Analysis, this procedure is superior to the classic Modal when working with large or complicated elements and calculation time is limited. It provides a detailed list of frequencies and mode shapes in the chosen band, which speeds up the design.

3. Torsion Mode analysis, which investigates how the structure rotates under torsional loads.

4. Modal visual analysis. This approach It uses the structure's torsion mode to show the deformations and behavioral states that can arise under excitations, thus providing fundamental data for design and optimization. These methods are essential to ensuring that buildings not only meet safety requirements but are also efficient and durable over the long term.

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Methodology

The procedure for identifying and studying microfractures using modal simulations performed in ANSYS© software begins with the creation of a three-dimensional model that defines the geometry, material properties, and a fine mesh that highlights the critical areas of the rotodynamic axis. Next, it is shown how the modal analysis was performed according to the ASTM E8 standard, determining vibrational frequencies and dynamic modes, and special attention is given to the modes that concentrate stress in susceptible regions, to then impose torsional loads of figure 2, which replicate the real conditions of the fieldwork and evaluate the stress and strain distributions.

Box 2

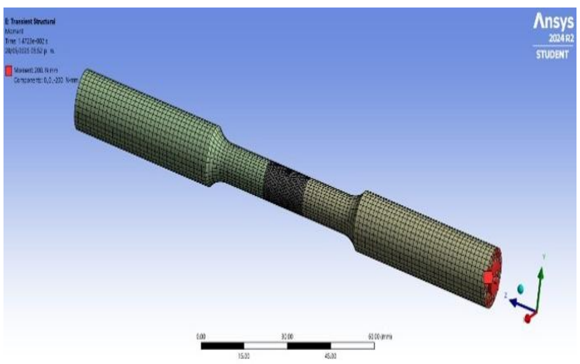

Figure 2
Definition of boundary conditions for simulation
Source: Own elaboration

Modal analysis is a fundamental technique in structural and mechanical engineering that allows characterizing the dynamic behavior of systems and structures by determining their intrinsic vibratory properties. This methodology combines solid theoretical principles with advanced experimental techniques to obtain critical modal parameters such as natural frequencies, damping factors and modal shapes, allowing them to predict their response to dynamic excitations and optimize their design to avoid resonance problems [Sinou & Lees, 2005].

Microcrack Simulation Modeling

A test specimen was designed to comply with the ASTM E8 standard for torsion tests [in simulation and future work in experimentation], in this stage will be the simulation stages, using computer-aided design software, where the first model is free of microcrack defects.

The model is a 9 mm diameter cylinder around application of the microcrack, considering an ASTM A36 steel, and appropriate boundary conditions were defined as shown in figure 3.

Box 3

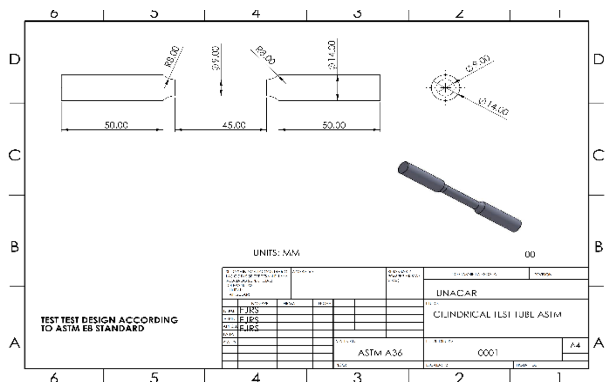

Figure 3
Shaft modeled according to ASTM E8 Standard for Vibration Testing
Source: Own elaboration

Microcracks were then incorporated into the second model to simulate potential initiation and propagation sites of microcracks and essentially determine whether microcracks smaller than 1 mm are affected by the proposed models. A modal analysis was performed to evaluate the effects of these microcracks on the natural frequencies and mode shapes of the system, which helps to detect changes in the dynamic response of the system, figure 4.

Box 4

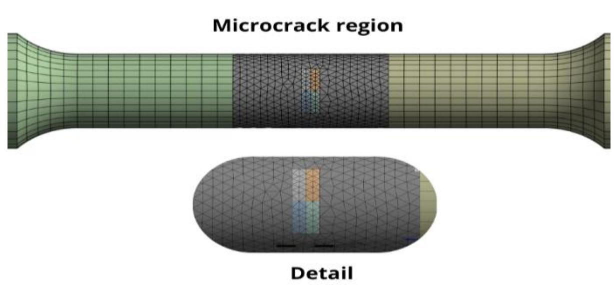

Figure 4
Modeled Shaft with Microcracks for Modal Analysis
Source: Own elaboration

Microcrack Simulation in Modal Analysis

Microcrack simulation in modal analysis using ANSYS© software allows for the study of how cracks, even small ones, affect the dynamic properties of a structure, including its vibration modes and natural frequencies.

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Changes in vibrational modes, displacements, and stress levels can be examined with damage models in certain regions due to the presence of microcracks. This approach is especially useful for estimating the influence of defects on the stability of a structure with respect to vibratory movements, thus aiding in the assessment of the risk of sudden and unpredictable failures and improving maintenance strategies [Gomez Peral & Fabra Rodriguez, 2022].

Experimental theoretical and technical principles are included in modal analysis. Theoretical modal analysis is based on a physical model of a dynamical system containing elements such as mass, stiffness, and damping, which are given through differential equations [Rufino-Arteaga & García-Pérez, 2025]. For a physical model to be more plausible as well, it must possess such properties in terms of their spatial distributions, and for this reason they are called matrices of mass, stiffness, and damping that are introduced into a system of differential equations of motion, as shown in Equation 2[Sadeghi, 2021]:

$$[M]\{\ddot{x}(t)\} + [C]\{\dot{x}|(t)\} + [K]\{x|(t)\} = F(t) \qquad [2]$$

M, C, K : Mass matrix, damping and stiffness, respectively.
$\ddot{x}$ $[t]$, $\dot{x}$ $[t]$, x[t]: Vectors acceleration, velocity and displacement, respectively.
F[t]: Vector force.

The modal analysis applied in the simulation offered a deeper and more detailed perspective on the natural frequencies, damping values and modal shapes that characterize the structure of the object in question. This high-level analytical technique facilitated the modification and improvement of the object's design, thus mitigating its vulnerability to different forces that arise during its use. Additionally, specific behaviors were detected that could be optimized to ensure a more efficient and safe operation of the research work in a structured way according to the scheme.

When performing modal analysis using the finite element method, it is crucial to have a model that accurately represents the geometry and other features of the system. The prudent choice of element size and type ensures that the modal shapes of the model accurately represent the natural vibrations of the system.

Specifically, elements must precisely construct the component's geometry to detect natural frequencies and insightfully and reliably characterize the associated bending and torsional modes. This allowed us a clearer understanding of the vibrational tendencies of the system as seen in Table 1.

Box 5

Table 1

Modal Vibration Modes

Frequency Mode	Without fissure [Hz]	With fissure [Hz]
Mode 1 Flex x	246.3	303.3
Mode 2 Flexion y	246.3	303.3
Mode 3 Combined Flexion	1742.9	1994.6
Mode 4 lengthways	1742.9	1994.7
Mode 5 Twist	3265.8	3466.6
Mode 6 Oscillating	4721.7	5216.9

Source: Own elaboration

It is shown in Table 1 that there are some changes in the frequencies obtained when there is microcracks in Mode 1 and 2 that are similar since they only change bending direction and give as data that there is the presence of a microcrack which by simple analysis gave us more information to determine the changes in material stiffness.

Initial calculations reveal six fundamental vibration modes, although the spectrum can be extended by combining multiple physical phenomena. Each new mode reflects variations in the material's stiffness and results in a slight shift in self-frequency, an effect that can be amplified by geometric changes, loss of mass, or the application of specific loads.

The appearance of a microfissure is a paradigmatic case that immediately alters these frequencies. Figure 5 shows the first mode in bending around the x-axis: panel 5-a illustrates the state of the material without cracking, while panel 5-b exhibits the vibrational response once the crack has been introduced, the natural frequency values are 246.3 Hz without cracking and 303.3 Hz with the presence of the microcrack resulting in a stiffness change of 18% of its frequency.

ISSN: 2531-2979
RENIECYT: 1702902

Romero-Sotelo, Francisco Javier, Rodríguez-Blanco, Marco Antonio, Pérez-Montejo, Salatiel and Álvarez-Arellano, Juan Antonio. [2025]. Microcrack evaluation using modal analysis under two loading conditions on rotodynamic shafts. Journal-Mathematical and Quantitative Methods. 9[15]1-14: e1915114.
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In Mode 2 of bending in y-axis the values obtained in figures are shown, 6a-b, where in a without crack and b with microcrack giving as results without crack a natural frequency of 246.3 Hz without a crack and 303.3 Hz with the presence of the microcrack, resulting in a stiffness change of 18% of its frequency.

Box 6

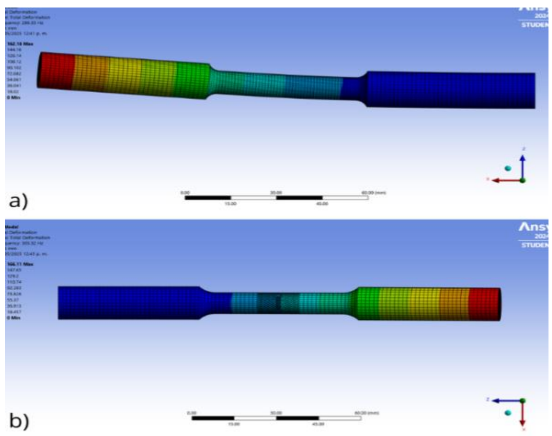

Figure 5
Vibration mode 1, in X-axis bending: [a] Without microcrack; [b] With microcrack

Source: Own elaboration

Box 7

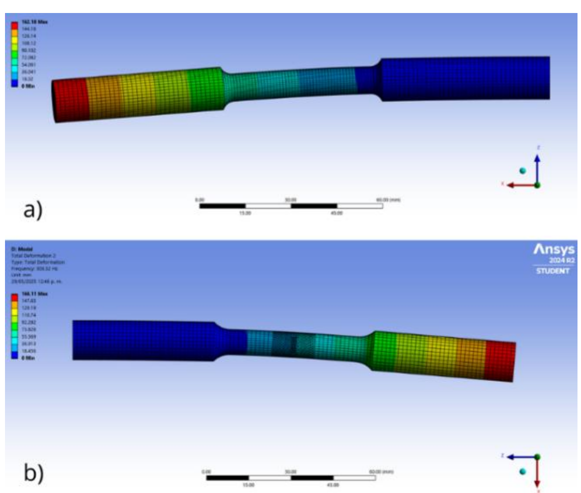

Figure 6
Vibration mode 2 in bending Y-axis: [a] Without microcrack; [b] With microcrack

Source: Own elaboration

In Mode 3, the values obtained in figure 7 are shown, under the conditions without microcrack in figure 7-a, and with microcrack in figure 7-b.

Box 8

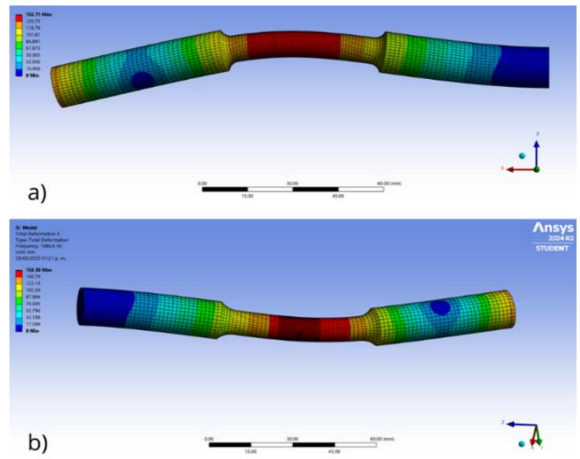

Figure 7
Vibration mode 3 in combined bending: [a] Without microcrack; [b] With microcrack

Source: Own elaboration

In Mode 5, which is the torsion mode, it is shown in figure 8, in conditions without microcrack in figure 8-a, and with microcrack in figure 8-b, resulting in a frequency of 3265.8 Hz without a crack and with a crack 3466.6 Hz with a difference of 8%.

Box 9

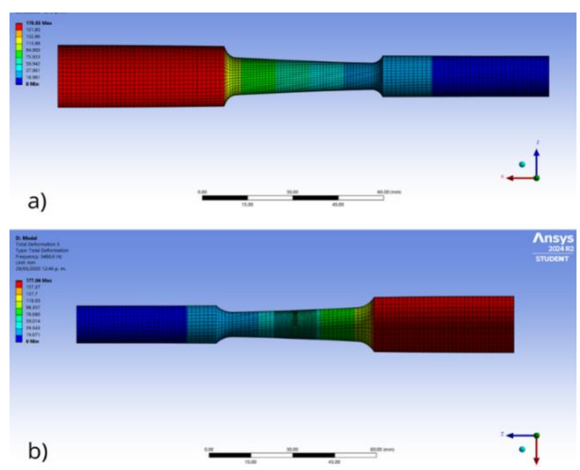

Figure 8
Torsional vibration mode 5: [a] Without microcrack; [b] With microcrack

Source: Own elaboration

Finally, figure 9 shows the chaotic Mode 6 that combines several conditions to determine the natural frequency of the material and the modeled axis, in which the conditions without microcrack figure 9-a and with microcrack figure 9-b are shown, giving as results frequencies without microcrack of 4721.7 Hz and with crack of 5216.9 Hz with a difference of 9.5 %.

ISSN: 2531-2979
RENIECYT: 1702902

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Box 10

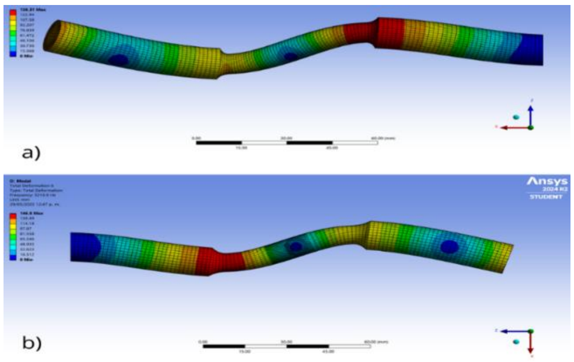

Figure 9

Vibration mode 6 in oscillating condition: [a] Without microcrack; b] With microcrack

Source: Own elaboration

Shaft stiffness analysis by simulation

The stiffness of the material is crucial for the analysis of the microcrack created in the proposed model and from where the results obtained will be evaluated in the conclusions and discussion section that will validate the proposed simulation results. In figure 10-a, the stiffness in the healthy axis or without microcrack created for its study is analyzed. figure 10-b shows the change in stiffness obtained by the modal analysis technique.

Box 11

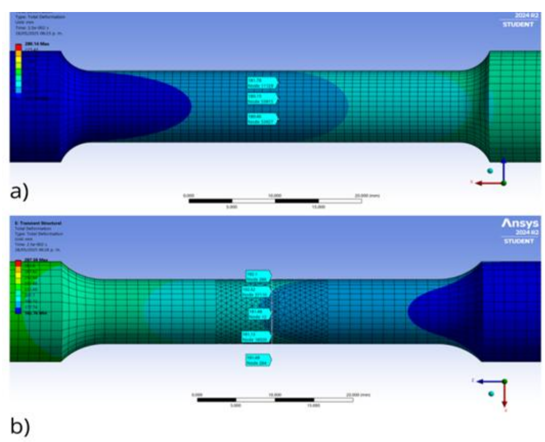

Figure 10

Stiffness Analysis: [a] Shaft without microcrack [b] Shaft with microcrack

Source: Own elaboration

The appearance of a microcrack in a material causes a gradual decline in some of its mechanical properties, including stiffness. Stiffness is defined as the resistance that a body offers against deformation due to a prescribed load and is directly related to the structural integrity of the material. The creation of a microcrack causes discontinuity that modifies stress distributions and decreases the ability of a material to withstand elastic deformations.

$$K_i = \frac{F_i}{\delta_i} \quad [3]$$

Ki: Rigidity
Fi: Applied Load
δ_i:Calculated deformation

There are different ways to analyze stiffness, depending on the type of load that is applied, such as axial, bending or torsional load, being the torsional one that will be analyzed to compare with those obtained in the general stiffness considering the deformations of the material in the simulation.

The torsional stiffness of a straight bar of uniform cross-section is defined as the ratio of the torque applied at one end to the angle of torque applied to that end, when the other end of the bar is held at rest, according to the following equation:

$$K_i = \frac{FM_x}{\theta_x} = \frac{GJ}{L} \quad [4]$$

G: Transverse elastic modulus
J: Torsional moment of inertia
L: Bar Length

Isotropic linear elastic materials obey the relationship between the transverse modulus of elasticity, Poisson's coefficient and Young's modulus.

$$G = E/2[1 + V] \quad [5]$$

E: Elastic Module
V: Poisson coefficient

The flexural stiffness of a straight bar is defined as the relationship between the bending moment applied at one of its ends and the angle of rotation experienced by that end when it undergoes deformation, considering that the bar is embedded at the opposite end.

In the case of straight bars with a uniform cross-section, two stiffness coefficients can be identified, which depend on the direction in which the bending moment is applied, whether it is aligned with a main direction of inertia or with a different one. This property of stiffness is

ISSN: 2531-2979
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determined in Equations 6 and 7 [Wang et al., 2021]:

$$K_{flex,y} = 4EI_y/L^3 \quad [6]$$

$$K_{flex,z} = 4EI_x/L^3 \quad [7]$$

Iy, Iz: These are the second moments of cross-sectional area
E: Elastic Module
L=Bar Length

Results

According to Table 1, it is observed in the first instance that the frequencies determined in the modal analysis change in the first case there is no microcrack present [healthy], while in the second case there is a slightly small change, but it is related to the size of the proposed microcrack [with loads].

The stiffness change calculations were performed and will be analyzed in a section of the results, as well as the analysis of the results obtained from the modal calculation.

Results of the shaft stiffness change analysis

In figure 11 the stiffness analysis was performed according to the condition of equations 2 and 3, and from there the change in values was calculated to determine the behavior of the axis due to the type of load considered in the analysis.

The same figure shows how the stiffness of the material changes under conditions under the presence of the microcrack within the shaft, resulting in maximum values of 1.1374 N/mm to a minimum value of 1.0896 N/mm, while in the model with microcrack there is a stiffness of a maximum value of 1.0593 N/mm and minimum values of 1.0388 N/mm. resulting in a change in the stiffness of the section where the microcrack occurs, changes in stiffness of 6.87 % in the high peaks and a reduction of 4.66 % in the low peaks and validating the proposal for the generation of microcracks that allows us to determine the microcrack conditions in different mechanical elements and facilitate experimental work, in this project, a second stage is intended that considers the experimental part that will allow a better understanding of how a microcrack behaves in modal analysis and in this case how the rigidity of the material changes.

Box 12

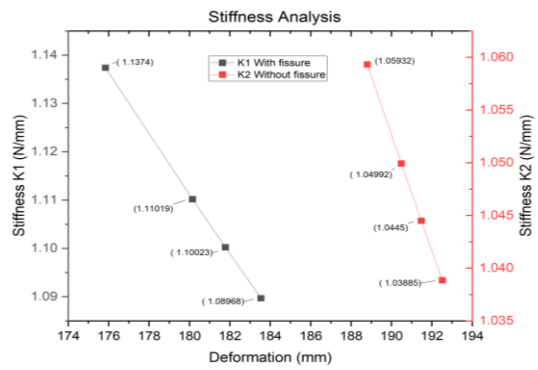

Figure 11
Stiffness analysis under torsional loading conditions on the shaft
Source: Own elaboration

Axis modal analysis results

In the most relevant phase of the study, the system's natural frequencies were determined using a modal analysis performed under loading conditions [torsion and bending], both without microcracks and with microcracks present in a specific section. The modal response was compared in both scenarios, and vibrations were recorded along the principal axes x and y. The first condition, under torsion, is presented in figures 12 and 13. From these data, a clear correlation could be established between the vibration amplitude, expressed in millimeters, and the frequencies measured in Hz.

Figure 12 shows the analysis on the x-axis under torsion conditions, where values of 4.09×10^{-6} mm of amplitude were obtained at a frequency of 200 Hz to 5.25×10^{-7} mm in the presence of a microcrack, with several peaks that allow us to relate these results with the presence of the microcrack while when there is no microcrack the only amplitude that occurs is 1.19×10^{-7} mm. at a frequency of 3400 Hz.

Box 13

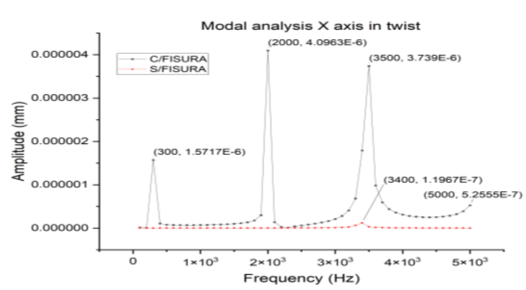

Figure 12
Modal analysis on the X axis, under defined loading conditions.
Source: Own elaboration

ISSN: 2531-2979
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Amplitude evaluation can be approached under various conditions; in this article, we use displacements resulting from torsion and bending. However, it is also possible to consider the change in amplitude caused by variations in stress, shaft speed, and other factors, both in the material without microcracks as well as in the presence of a microcrack, which will be the subject of another future work. The results presented in figure 13 show the measurements obtained on the y-axis; without a microcrack, the amplitude reaches 1.1148 mm at 3,500 Hz; however, with a microcrack, the value drops to 0.3072 mm, which clearly indicates the influence of the defect, showing an amplitude difference in the presence of a microcrack and without it of 66% with respect to the highest peaks. Thus, demonstrating a response to the presence of a microcrack.

Box 14

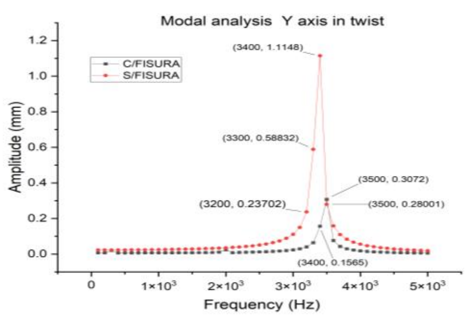

Figure 13
Modal analysis on the X axis, under bending conditions
Source: Own elaboration

The second analysis condition was that of bending along the axis, considering the same characteristics as the tests with torsional loading, determining the amplitudes and frequencies in conditions with and without the presence of microcracks.

In figure 14, the values obtained from the modal analysis of the flexural x-axis were graphed, where maximum amplitude values of 19.59 mm are obtained at a frequency of 300Hz and a value less than 2.95 mm at a frequency of 2000 Hz without fissure present, since microcracks are included, maximum values of 16.94 mm are presented at a frequency of 1300 Hz and a minimum of 1.94 mm amplitude at a frequency of 3000 Hz, showing an amplitude difference in the presence of microcrack and without it of 13.5 % with respect to the highest peaks, and a difference of 34.2 % in the low peaks. Thus, demonstrating a response to the presence of a microfissure.

Box 15

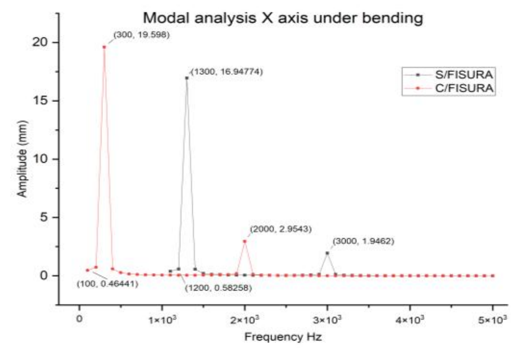

Figure 14
Modal analysis on the X axis, under bending conditions

Source: Own elaboration

In the last bending analysis, shown in figure 15, maximum values without crack of 5.17 mm amplitude are found at a frequency of 300 Hz and a minimum of 0.97 mm amplitude at a frequency of 200 Hz, with crack the values are 19.59 mm amplitude with a frequency of 300 Hz and a lowest of 2.95 mm at a frequency of 200 Hz, having a difference of 13.3 % in the high peaks, and a difference of 34.2 % in the low peaks, concluding the obtaining of values that visibly allow us to conclude that there is the presence of a microcrack.

Box 16

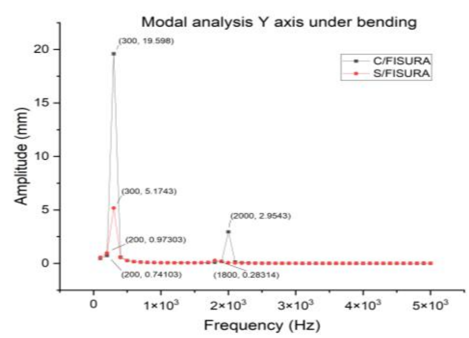

Figure 15
Modal analysis on the Y axis, under bending conditions
Source: Own elaboration

Conclusions

This study explores methodologies to identify and diagnose microcracks in components focused on rotodynamic machines, carrying out a detailed analysis through modal simulations using the ANSYS© software, with particular attention to torsional conditions and stiffness change.

ISSN: 2531-2979
RENIECYT: 1702902

The findings of this work show the existence of a microcrack in a material that leads to a decrease in its rigidity compared to a homogeneous material, resulting in the discontinuity introduced by the microfracture, which facilitates the deformation of the material before the application of loads.

These results offer the possibility of extracting new features, which, under certain considerations, have a practical dimension and are highly relevant for addressing the problem of microfracture detection and understanding structural integrity in complex systems. It was revealed that the reduction in stiffness is not an independent phenomenon, but a quantifiable parameter directly related to the microcrack, as well as to its size, orientation, density, and the intrinsic properties of the material. This relationship is manifested in how the material's deformation capacity is altered by external loads, establishing a direct link with the dimensions of the microcracks and the characteristics of the material in question.

Based on these findings, future studies should focus on experimentally confirming the stiffness-frequency relationships in full-dimensional rotodynamic shafts under their realistic operating conditions. Ultra-sensitive vibration monitoring, coupled with classification algorithms, can improve the boundary thresholds established in this work by considering environmental factors such as temperature, lubrication conditions, and the changing morphology of growing cracks. Furthermore, unexplored aspects of respiratory crack contact dynamics that incorporate thermomechanical processes in finite element models could uncover additional useful frequency separation patterns for early warning diagnostics. Such multidisciplinary approaches would strengthen the theoretical basis for microcrack detection while simultaneously accelerating its implementation in proactive maintenance frameworks for critical industrial assets.

Declarations

Conflict of interest

The authors declare no interest conflict. They have no known competing financial interests or personal relationships that could have appeared to influence the article reported in this article.

Author contribution

Conceptualization, R-S,F.J. and R-B,M.A.; methodology, R-S,F.J.; software, R-S,F.J.; validation, M.A.R.-B and P-M,S.; formal analysis, P-M,S; investigation, R-S,F.J.; resources, R-S,F.J.; data curation, P-M,S.; writing—original draft preparation, P-M,S.; writing—review and editing, P-M,S.; visualization, R-B,M.A.; supervision, P-M,S.; project administration, R-B,M.A.; funding acquisition, R-S,F.J. All authors have read and agreed to the published version of the manuscript.

Availability of data and materials

There is the institutional support of the Universidad Autónoma del Carmen to use the necessary equipment for simulation with specialized software and experimentation in vibration equipment, as well as the Doctorate in Engineering Sciences of the Faculty of Engineering as part of the Doctoral training of the main author.

Funding

It receives funding from the Faculty of Engineering of UNACAR and the thesis director of this project.

Acknowledgements

The authors deeply appreciate the financial support provided by both the Secretaria de Ciencia, Humanidades, Tecnología e Innovación SECIHTI and the Universidad Autónoma del Carmen UNACAR. According to the catalog Marvid, this work belongs to the Engineering area, Mechanical Engineering Discipline, Vibration and Acoustics subdiscipline of Engineering Area VII.

Abbreviations

FEA	Finite element analysis
ASTM	American Society for Testing and Materials

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Background

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ISSN: 2531-2979
RENIECYT: 1702902