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The numerical characterization of the gas turbine blade with static stress analysis applying finite element method

La caracterización numérica del álabe de la turbina de gas con el análisis de esfuerzos aplicando el método de los elementos finitos

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Abstract

The lifespan of a blade is reduced due to the operating environment and high mechanical and thermal stresses, where typically two or more factors act simultaneously. The most common degradation mechanisms are: contamination, blade pitting, opening of the gap between rotor and stator, and erosion of the leading and trailing edge of the gas turbine blade. Degradation is mainly caused by scale, corrosion, hot corrosion, oxidation, erosion, abrasion, particle melting and mechanical degradation. The research that has been carried out in turbine blades are based on visual observations, optical microscopy, scanning electron microscopy, fractography analysis, metallography, structural analysis and hardness tests. This work proposes a methodology to carry out numerical analysis of the nozzle blade of a gas turbine. The investigation will perform a scan to obtain a 3D model using reverse engineering. Reverse engineering technology can be used to assist in the manufacture of replacement parts when the original parts inventory is depleted. The numerical analysis with the point mesh of the nozzle blade and static stress modeling in ANSYS were made. The main objective of this work is to know the maximum and minimum values at which a turbine blade is operating and located the area of the gas turbine blade is more prone to failure due to different wear mechanisms and to the stresses that the blades are subjected during the operation of the gas turbine.

Blades, Gas turbine, ANSYS, Static modeling

Resumen

La vida útil de un álabe se reduce debido al entorno de funcionamiento y a las elevadas tensiones mecánicas y térmicas, donde suelen actuar dos o más factores simultáneamente. Los mecanismos de degradación más comunes son: la contaminación, las picaduras en los álabes, la apertura del claro entre el rotor y el estator, y la erosión del borde de ataque y de salida del álabe de turbina de la turbina de gas. La degradación se debe principalmente a las sales, la corrosión, la corrosión en caliente, la oxidación, la erosión, la abrasión, la fusión de partículas y la degradación mecánica. Las investigaciones que se han llevado a cabo en los álabes de turbina se basan en observaciones visuales, microscopía óptica, microscopía electrónica de barrido, análisis de fractografía, metalografía, análisis estructural y ensayos de dureza. Este trabajo propone una metodología para realizar el análisis numérico del álabe de la tobera de una turbina de gas. La investigación realizará un escaneo para obtener un modelo 3D mediante ingeniería inversa. La tecnología de ingeniería inversa puede utilizarse para ayudar a la fabricación de piezas de repuesto cuando se agota el inventario de piezas originales. Se realizó el análisis numérico con la malla de puntos del álabe de la tobera y el modelado de la tensión estática en ANSYS. El objetivo principal de este trabajo es conocer los valores máximos y mínimos a los que opera un álabe de turbina y localizar la zona del álabe de turbina de gas más propensa a fallar debido a los diferentes mecanismos de desgaste y a las tensiones a las que están sometidos los álabes durante el funcionamiento de la turbina de gas.

Álabes, Turbina de gas, ANSYS, Modelado estático

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Introduction

Gas turbines play an important role in fields such as aviation and power generation. The main function of blades in gas turbines is to use or extract energy from a fluid stream to change the speed and pressure of the fluid flow. In the absence of design data, the reverse engineering process can be considered an important tool for modeling. The reverse engineering process involves detecting the geometry of the blade, creating a geometric model from the detected data, and passing this model to an appropriate CAD / CAM system for fabrication. (Gopinat, 2014)

Turbine blades are subject to complex conditions of temperature, stress, oxidation and hot corrosion (Giampaolo, 2016). The extreme service environment often results in premature failure of the turbine blades, when the turbine inlet gas temperature exceeds the service temperature limit, the turbine blades are subjected to overheating; this could lead to rapid microstructural degradation and even brittle fracture. (Xiaotong, 2016) Gas turbine efficiency in oil & gas applications has improved more than 40%, currently, leading OEM manufacturers and researchers are working on gas turbine optimization design to constantly improve efficiency and reduce cost of gas turbines maintenance (Jun Su, 2019).

To further increase the thermodynamic efficiency of advanced gas turbines, higher gas inlet temperatures are required. An increase in the gas inlet temperature causes an increase in thermal stresses throughout the engine, especially in the turbine blades and therefore drastically reduces its useful life. Experimental research of turbine blade materials under real operating conditions are very demanding Figure 1 shows seventh stage compressor blade; thermal and mechanical analysis must be performed based on the finite element method (O Kaussa, 2019).

Figure 1 Rotor blades of axial compressor.
Note. Adapted from Turbine Compressor Disc, Villagrán-Villegas Luz Yazmin, 2017

Turbine blades are subject to stresses because of high temperatures, high centrifugal forces, and thermal cycling; these stresses accelerate the growth of defects that may be present in the material; this is the base of the demand for materials that can withstand high temperatures without losing their resistance to centrifugal forces, vibrations, thermal cycles, oxidation or corrosion.

The improvement in creep and rupture strength properties was constant from the late 1940s to the early 1970s, since 1960, the reliance on sophisticated cooling techniques for turbine blades and nozzles has increased. The increase in the turbine inlet temperature was possible thanks to new air-cooling schemes and the incorporation of complex ceramic core bodies used in the production of hollow and cast parts, Figure 2 shows two elaborated compressor blades of a chromium superalloy and a power turbine blade with red coloration due to the exposure of the ceramic coating to high temperatures in the first power stage.

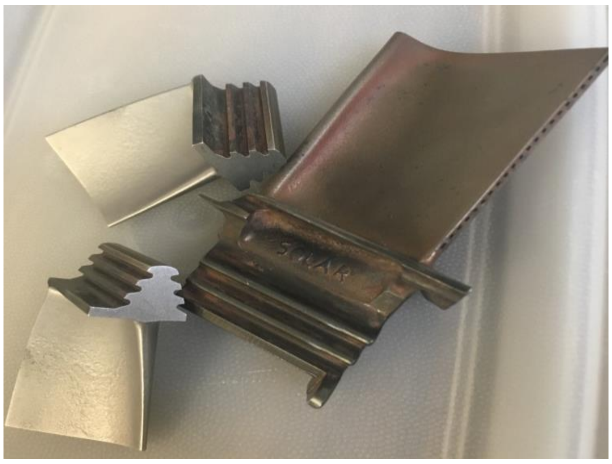

Figure 2 Two rotor blades of an axial compressor and a power turbine blade
Note. Adapted from Turbine Compressor Disc, Villagrán-Villegas Luz Yazmin, 2017

Protective coatings used on turbine blades were developed to serve as physical barriers between the aggressive environment and the substrate. (Jaroslav,2010)

In addition, Thermal Barrier Coatings are used as a cover material, delay creep degradation and reduce the severity of thermal gradients; no coating has been found that can fully survive the aggressive turbine environment. The durability of thermal barrier coatings is limited by degradation of adhesion by environmental interactions rather than mechanical stress. (Miller, 2010)

The most serious degradation modes are as follows: oxidation of high temperature, hot corrosion, damage due to thermal and thermomechanical fatigue, mechanical damage from erosion and creep degradation during overheating.

Solar Turbines' Centauro 40 gas turbine operates in the active Bellota-Jujo complex located in the city of Comalcalco, 30 km from Villahermosa, Tabasco, the fields are in the municipalities of Comalcalco, Paraíso, Jalpa de Méndez, Nacajuca, Cunduacán, Cárdenas and Huimanguillo.

The area represents the greatest oil wealth in southeastern Mexico, due to the quality of its hydrocarbon and because of the giant fields that have been discovered there. (Córdova, 2011) The Centauro 40 turbine has the following normal operating conditions, shown in Figure 3: Inlet temperature, inlet air pressure, sensing of 5 temperatures of the third power turbine stage (T5), alarms and compressor efficiency (NGP) and in power turbine (NPT). (Padilla, 2021)


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Solar Turbines   RESUMEN DE OPERACION        Pantalla 004
            NGP   95.9 %    NPT   84.8 %          ALARMA
TERMOCOPLES PG                 SENSORES DE GAS PG
T1           95.0 °F    Entrada Cabina        -0.4 %LEL
T5 TC 1      1418 °F     Salida Cabina        -1.1 %LEL
T5 TC 2      1437 °F       OPERACION DE LA MAQUINA
T5 TC 3      1314 °F                NORMAL
T5 TC 4      1394 °F        F1  NORMAL  PRUEBA  F2
T5 TC 5      1410 °F       PRODUCTOR DE GASES
T5 TC 6      1425 °F        DP Ent Aire         5.2 inH20
T5 Promd     1400 °F        DP Filt Entr        3.3 inH20
Act T5's        6           PCD               107.5 psig
Baterias     27.3 Vdc   Com Alabes Var        100.0 %
Junta Fria  119.0 °F    Cmd Abrir Valv Sang      ABRIR
                        Cmd Cerrar Valv Sang     CERRAR
                          pag 1 de 5     F7  Pag Sig
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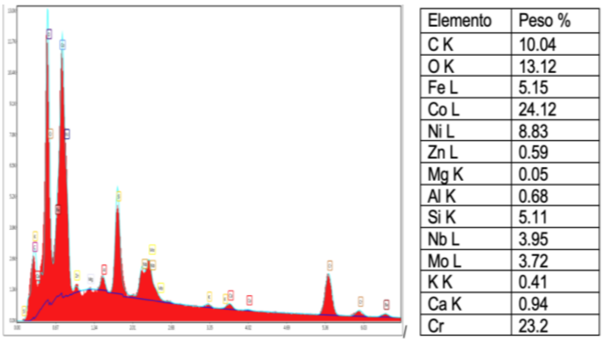
Figure 3 C40 Gas Turbine Operation Summary
Note. Adapted from Blade Wear Analysis of TG C40, Villagran-Villegas Luz Yazmin, 2017

Fabrication materials for centaur 40 gas power turbine blades

The following figure shows a graph that contains the elements that make up the Centaur 40 gas turbine blade as well as their percentage that each element occupies, made from a chemical analysis, in a scanning electron microscope.



Elemento	Peso %
C K	10.04
O K	13.12
Fe L	5.15
Co L	24.12
Ni L	8.83
Zn L	0.59
Mg K	0.05
Al K	0.68
Si K	5.11
Nb L	3.95
Mo L	3.72
K K	0.41
Ca K	0.94
Cr	23.2

Figure 4 Chemical elements of the C40 gas turbine compressor blade
Note. Adapted from TG Blade Wear Analysis, Villagran-Villegas Luz Yazmin, 2017, ***b***

Methodology

The methodology of the numerical analysis will be developed in five stages (Figure 5), which are the following:

1) First stage: Know the operating conditions of the gas turbine.

2) Second stage: Obtaining the samples to be analyzed (power turbine blades).

3) Third stage: Acquire the model in a point cloud from the original model. (reverse engineering).

4) Fourth stage: Numerical analysis and simulation in static state supported by engineering software (ANSYS).

5) Fifth stage: Research conclusions.

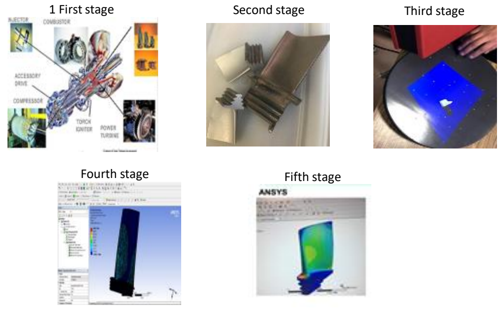


Figure 5 Methodology of numerical analysis.
Note. Adapted from Study on the damage caused by wear in the blades of a gas turbine compressor *(Villagrán-Villegas Luz Yazmin, 2017)*

A. Determination of operating conditions.

Figure 6 Blade sample after its operation in the Northeast Region, in the Cantarell asset, Nohoch Alfa Oil Platform

The sample in Figure 6 was in operation in the Northeast Region, in the Cantarell asset, Nohoch Alfa Oil Platform. The air enters the gas turbine at room temperature of 15 ° C (at the sea level) and increases its temperature when compressed, reaching 1,800 ° C, after passing through the combustion chambers. The Centaur 40 turbine is made up of 11 stages. In the axial type of compressor, the pressure ratio is 10.3: 1 and the air flow input is 18.7 kg / sec (41.3 lb / sec). The variable vanes begin to open when the Pcd (pressure compressor discharge) reaches approximately 32 psi (gauge) and fully open when the Pcd reaches approximately 76.5 psi (gauge).

Table 1 shows the information provided by the manufacturer and Table 2 the sample data.

Condition	Value
Compressor discharge pressure (PCD)	107.5 psi (lb/in^2)
Average temperature of thermocouple T5	1400 °F
Gas Producer Speed **NGP.**	95.9 %
Power Turbine Speed) **NPT.**	84.8 %

Table 1 Turbine C40 data

Sample	Material	Stage	Weight
Blade	Superalloy	1	42.37 g

Table 2 Power turbine blade data

B. Obtaining samples.

The ATOS ScanBox (Figure 7) is a 3D optical measurement equipment that was developed by GOM for efficient quality control in the production and manufacturing process; it is an optical 3D coordinate measuring system.

Figure 7 ATOS ScanBox

ATOS sensors provide full-field 3D coordinates for each individual measurement of up to 16 million independent measurement points and are captured within 1 to 2 seconds. The measurement data is characterized by a very detailed reproduction and therefore also allows the measurement of very small components (38mm).

ATOS captures the entire surface geometry of an object accurately in a dense point cloud or polygon mesh; that enable detailed, high-resolution scans, rapid data collection, advanced inspection functionality, and comprehensive dimensional analysis. GOM Inspect is software for 3D measurement data analysis. GOM software is used in product development, quality control, and production. The generated model is a polygonal mesh that can be smoothed, thinned and refined, likewise, from the initial model, the holes in the mesh can be filled, allowing curvatures to be extracted. The mesh is processed using algorithms based on curvatures and tolerances. The software provides the user with a view prior to each processing step and generates the calculation of an average mesh.

Once the scanner assembly and calibration process has been carried out, it is time for the digitization of the part that we want to evaluate in this particular case it is the blade of a gas turbine.

The scanner works in an optimal way when the piece is white, since there is a difference in tones, in addition to eliminating the reflection in the metallic pieces, which makes the sensor perfectly detect the details, thus achieving a model. STL similar to the original part.

If the piece to be scanned is not white, there is a procedure, which consists of applying a zinc oxide coating that manages to change the original color and at the same time eliminates the excess shine that a metallic piece can get. to be reflected, thus guaranteeing optimal performance by the scanner.

Our sample to be scanned (blade) will require the application of a zinc oxide coating due to its color tone (Figure 8).

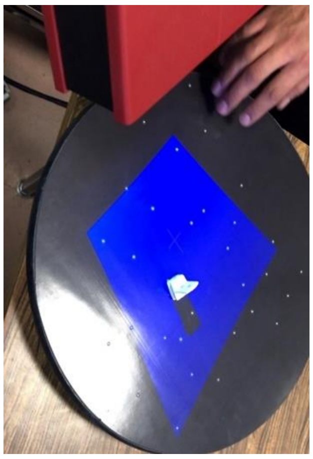


Figure 8 Zinc oxide coated blade.

Note. Adapted from Study on the damage caused by wear in the blades of a gas turbine compressor, Villagrán-Villegas Luz Yazmin, 2017.

C. 3D model

The piece to be scanned must be completely dry after applying the zinc oxide coating, to start the digitization process; For this, sample holder clips and stickers are used that will serve as reference points when closing our piece after scanning. (Figure 9)

Figure 9 Blade with reference points

Note. Adapted from Study on the damage caused by wear in the blades of a gas turbine compressor, Villagrán-Villegas Luz Yazmin, 2017.

The piece is placed on a rotating base full of reference points that will help us to obtain digitization. Once the light bombardment process has started by the scanner, the part cannot be moved from its original position. As soon as the software detects that the part and all the reference points are in the correct position, the equipment will begin to scan and obtain the first parts of the point cloud (Figure 10) represented with the parts in red.

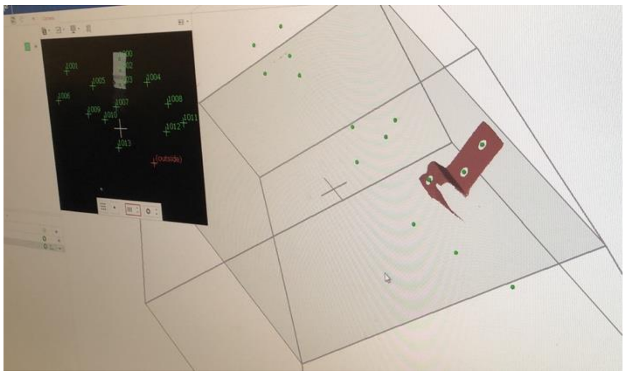


Figure 10 Power turbine blade point cloud

At the end of the necessary scans, the two measurement series will be joined using the reference points to obtain a single point cloud that combines the two measurement series, which shows us a form very similar to the real one. The process of scanning a part is a very exact process. Reverse engineering is used since a design is obtained from a product. Without a doubt, the point cloud obtained through the ATOS & GOM scanner closely matches the actual design of the piece. Once the entire process has been carried out, the .STL file is obtained, which offers us endless possibilities, either by solidifying the model to be able to simulate it in some engineering software or by transforming it to another format readable by a 3D printer to finally print it.

D. Numerical analysis.

To overcome the difficulty of solving real continuous problems, engineers and mathematicians have been proposing, over the years, various methods of discretization. The application of these methods makes it necessary to carry out some approximation, in such a way that it can be expected that it approaches, as closely as desired, the true continuous solution as the number of discrete variables increases. (Cuevas,2017)

The unique way of approaching discrete type problems leads us to the definition of the finite element method as an approximation procedure for continuous problems, in such a way that:

a) The continuum is divided into a finite number of parts (elements), whose behavior is specified by a finite number of parameters.

b) The solution of the complete system as an assembly of the elements follows precisely the same rules that apply to discrete type problems.

The Finite Element Method uses the discretization hypothesis, which is based on the following:

- The continuum is divided by means of imaginary lines or surfaces into a series of contiguous and disjoint regions of simple and normalized geometric shapes, called finite elements.

- Finite elements are joined together at a finite number of points, called nodes.

- The displacements of the nodes are the basic unknowns of the blade structure and this determine the deformed configuration of the structure.

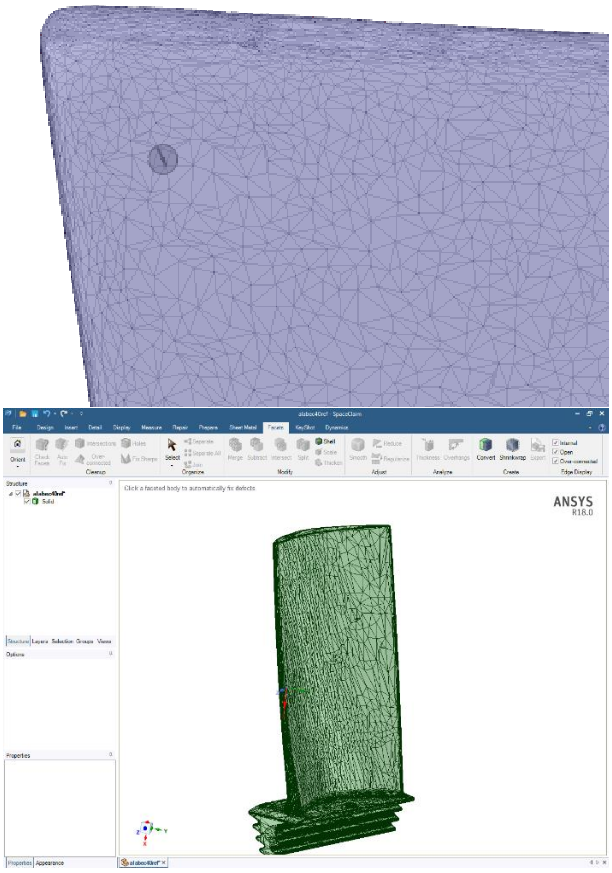
- The displacement of any point is uniquely determined by the displacement of nodes of the element to which the point belongs and interpolation functions are defined for each element that allow the calculation of the value of any interior displacement by interpolating the nodal displacements.

- The interpolation function and the nodal displacement defined the state of strains inside element.

- For each element, there is a system of forces concentrated in the nodes, which balance the tension in the element contour and the external forces acting on it.

- The solution function of the problem is approximated independently in each element. The solution function is approximate within each element, relying on a finite (and small) number of parameters, which are the values of said function in the nodes that make up the element and sometimes its derivatives. (Celigüeta, 2019)

Due to the characteristics of the scanned blade geometry, our .STL file has a total of 688,076 facets (Figure 11). If you zoom in on any region, you can see a large number of facets into which our point cloud is divided.



Click a faceted body to automatically fix defects

Figure 11 Power turbine blade mesh with 688,076 facets

Results

The values of the variables used in the stationary stress analysis (type: Von Mises) in the blade are: (Figure 12).

Material: Base Superalloy Cr (Losertová, 2014)

Module of Young 0.211 Gpa (Losertová, 2014)

Density: 8.35 x 10 3 kg/m3 (Losertová, 2014)

Relation of Poisson: 0.325 (Losertová, 2014)

Fluid stress: 0°-15 ° (Solar, 2007)

Air pressure: 110 psi (Solar, 2007)

Maximum stress: 158.31 Mpa (Solar, 2007)

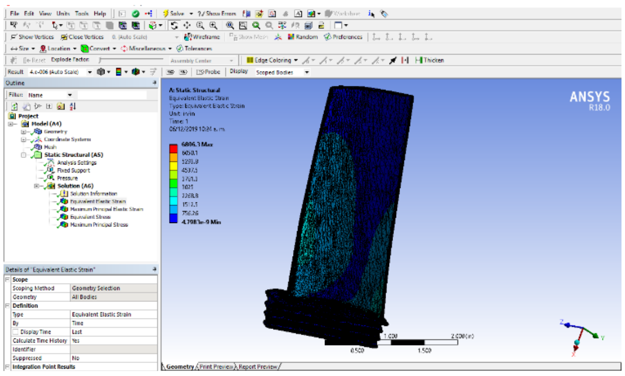


Figure 12 1st stage power turbine blade

Conclusions

The simulation of a gas turbine blade from the power turbine area was achieved.

In the project, 3D models of the blade were obtained, through the ATOS & GOM optical scanner (tool provided by the National Polytechnic Institute), of which a dotted mesh with 688,076 facets was recorded.

With the SpaceClaim software, the solidification of the model obtained was obtained.

Finally, a static analysis was carried out with the help of the ANSYS Workbench R18.0 software, where the characteristics of which the blade material is made were added, as well as the application of a mesh (Figure 13).

The work concluded with a Finite Element Analysis, with a pressure of 107.5 psi distributed in the intrados of the blade, obtaining a maximum Von Mises effort of 1.873e5 (psi) and a minimum of 1.321e-7 (psi) with a total of 367,381 nodes and 217,272 elements.

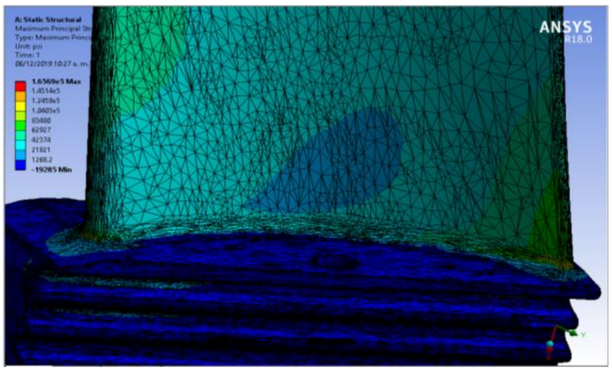


Figure 13 Finite element analysis in the power turbine blade

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