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PREDICTION OF ROTOR THERMAL BOW USING 3D FINITE ELEMENT MODEL

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Abstract: *The rotor system of the gas turbine is cooled after shutdown by heat transfer through natural convection and radiation. This is a typical engineering problem that often arises in practice in a variety of applications. Typically, in power engineering, this phenomenon has long been known and is solved by slow start-up and shutdown of the rotor system. In the field of aircraft engines, the problem is more severe as the operating conditions and temperatures are variable depending on the selected flight mode or drop in the case of engine shutdown. At the same time, engine aftercooling is very difficult, given the geometry and equipment. This paper deals with the application of a developed FEM tool for the prediction of rotor thermal bow induced by temperature differences between the upper and lower side of the rotor. The paper describes the mathematical model of the FEM tool and the calculation of the rotor deflection on the selected geometry.*

Keywords: Rotor Thermal Bow, Natural Convection, Gas Turbine Engine, 3D FEM.

1. Introduction

The operating temperature of parts, trend/health monitoring and components control system has a significant impact on their reliability and service life in all areas of industry. It may even have a greater impact on the aviation industry in which it can impact on flight safety. Temperatures of aircraft engines, in this case turboprop engine, and their adjacent components are affected not only by mechanisms and processes in the engine (compressor, combustion chamber, turbine), but also by other devices located in the nacelle that extract the heat from the engine and its components. The prediction of the Rotor Bow due to non-homogeneous temperature field of the turbine engine is discussed in the paper. The problem of heat transfer during engine cooling due to natural convection and radiation has been described and presented in earlier papers Pařez et al. (2022a, 2021). The results of the temperature field distribution during engine cooling were further used in the development of the 1D FEM solver by Pařez et al. (2022b), however, was not sufficient for a comprehensive analysis of the rotor system. For this purpose, a 2D FEM solver was developed by Pařez et al. (2022c). However, basing on a 2D solver does not correspond to the real 3D geometry and the required physical principles. For this purpose, it was necessary to develop a complete 3D FEM solver where the temperature field distribution and strain fully correspond to the real condition.

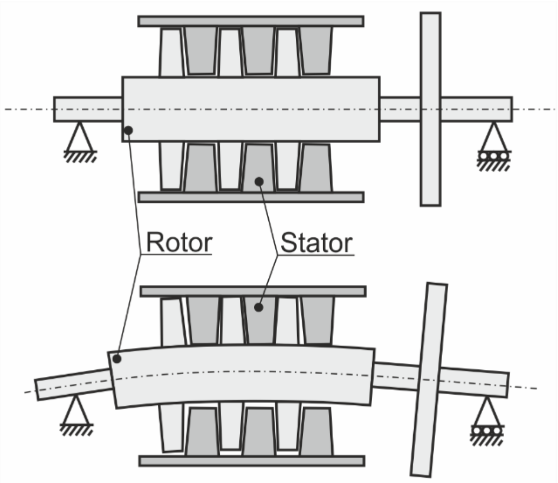

Fig. 1: Effect of Rotor Thermal Bow.

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Research aimed at understanding the onset of thermal bow in turbomachinery was carried out by Deepthikumar et al. (2014). Yuan et al. (2009) used computational fluid dynamics (CFD) to model the onset of thermal bow due to convective flow of hot air inside the compressor shaft. Using CFD, Yuan et al. (2009) predicted the temperature difference at different axial locations along the rotor length over a range of "dwell times" after engine shutdown. Marinescu and Ehrsam (2012) performed a similar analysis on a working KA26-1 steam turbine. They found that the cooling time of a large steam turbine can be on the order of 100 hours. The complexity of the geometry of their model meant that the transient 3D CFD model converged only with time steps on the order of 0.01 milliseconds.

Due to the obvious computational complexity, they were forced to work with the simulation in 2D and then modify the results to account for 3D effects. Their model, which was fully validated by temperature measurements from a real engine, was able to capture the physics of natural convective cooling of a particular engine. It was also used by Marinescu and Ehrsam (2012) to perform a sensitivity analysis to various operational and environmental influences. Research by Pennacchi and Vania (2004) at the University of Milan focused on comparing the effectiveness of model-based diagnostic techniques that can be used to identify the presence of thermal sag in generators. The numerical determination of the dependence of the temperature distribution on rotor vibration stability supported by experimental measurements was also studied at the University of Florence by Penara et al. (2015). Although some information is available in the literature for aeronautical applications. The presence of this phenomenon on aircraft gas turbines is marginally discussed in the Deepthikumar et al. (2014) articles and is known to occur in both military transport helicopters and fighter jets. More recently, Smith and Neely (2013) have begun to address the issue of rotor system thermal bow, presenting a numerical model with an initial study on an aircraft engine compressor. The numerical model was also studied in relation to rotor dynamics and vibration.

2. Mathematical method

The Finite Element Method (FEM) solver is based on a set of scripts in Matlab. The control script sequentially executes the partial parts of the calculation. First, input information about the geometry of the computational mesh, material and physical properties and boundary conditions of temperatures and nodes support are retrieved. From these, the computational mesh is created. Finally, a calculation range is selected from the temperature distribution, structural calculation or dynamic properties.

First, the computational nodes network is generated by discretizing the rotational component according to the required numbers of nodes along the circumference and radial element layers. In this network, the computation region is determined according to the boundaries of the rotor system and points at the boundary's edge are added. This simply structured network is advantageous for the calculation of trapezoidal elements. These elements are made up of five sets of 4 points for the front, back and middle planes in a counter clockwise direction and are created by a for cycle for all considered points satisfying the conditions of the calculation area. In Fig. 2, an element consisted from the computational nodes is shown. Table 1. show element nodes notation.

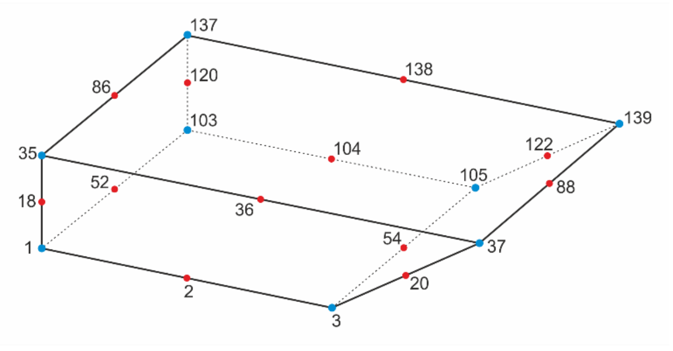

Fig. 2: Mesh element composition from nodes and their notation in Tab. 1.

Tab. 1: Temperatures in the groups of nodes and type of support in bearing

El. num	Front plane	Back plane	Front plane	Back plane	Middle plane
1	[1 3 37 35]	[103 105 139 137]	[2 20 36 18]	[104 122 138 120]	[52 54 88 86]
2	[3 5 39 37]	[105 107 141 139]	[4 24 38 20]	[106 124 140 122]	[54 56 90 88]

The actual calculation of the temperature field and deformations is based on the first step of the calculation of the temperature field by constructing a heat conduction matrix of the sub-elements, which are then assembled into a matrix of the whole geometry and boundary conditions added. By finding the solution of this matrix, the temperature distribution for each node of the mesh is obtained. Once the temperature field distribution is determined, a stiffness matrix of the entire geometry consisting of the sub-elements is similarly constructed. The displacement of each node of the computational network is found by finding the solution of this matrix. The whole calculation is solved by a linear calculation.

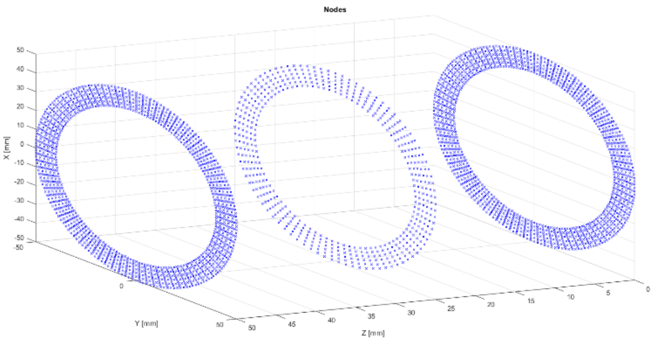

Fig. 3: Nodes mesh model.

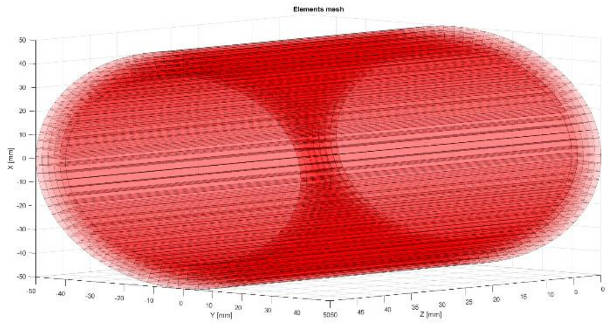

Fig. 4: Mesh element composition from nodes and their notation.

2.1. Computational model

The computational model of the rotor system is simplified into an annular cylindrical geometry. The 3D mesh consists of 445 elements equally spaced on inner radius. The number of radial layers of elements is given by 5 layers and 2 planes specifies the number of axial planes. The rotor system support corresponds to two-bearing supports, where one bearing is fixed and not allowing radial displacement. The second bearing allows the influence of axial displacement to compensate for thermal displacement. The rotor material considered was conventional steel with known properties. The temperature field distribution is chosen to consider the previously performed measurements of the temperature field in the double annulus under engine cooling conditions after shutdown. The temperature field distribution is prescribed for the edge nodes and its significant values is 600 [degC] for upper side and 300 [degC] for bottom side.

The aim of the numerical analysis is to determine the temperature field distribution in the geometry based on boundary conditions prescribed at the edges. Furthermore, the aim is to determine the deformation history and its maximum values. These are plotted in the Fig. 5 below.

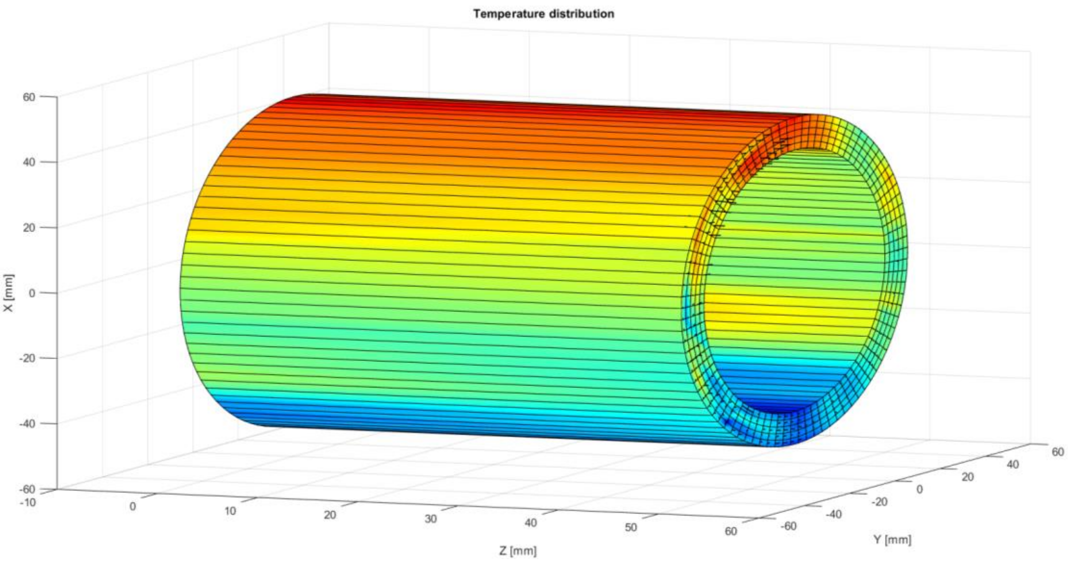

Fig. 5: Temperature distribution and deformation of Rotor Bowed Rotor calculated by developed FEM tool.

The results of the developed FEM model of the rotor systems show a significant effect of the non-uniform temperature field distribution. The effect of the non-uniform temperature field results in a deflection of the rotor system called the Rotor Thermal Bow.

3. Conclusions

The calculation of the rotor system deformation under natural convection conditions using the developed finite element model was studied. The mathematical model of the FEM tool and the choice of its meshing and creation of computational elements were described. The geometry was simplified into a rotor, and the temperature field distribution was calculated based on boundary conditions. Furthermore, the rotor was chosen to be supported in two bearings, one allowing axial displacement due to thermal expansion second support is fixed. Next, the total deformations were studied. The temperature differences generate an additional deformation which results in the deflection of the whole shaft. The results of the temperature field distribution and an indication of the deformation vectors were plotted in the figure.

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