30th International Conference
ENGINEERING MECHANICS 2024
Milovy, Czech Republic, May 14 – 16, 2024

PREDICTION OF NON-STATIONARY DEFORMATION OF GAS TURBINE USING MACHINE LEARNING APPROACH COUPLING BETWEEN CFD AND FEM MODEL

Pařez J.[*]**, Vampola T.**[**]

Abstract: *After shutdown, the gas turbine rotor system cooling primarily through natural convection and radiation. It is presenting a common engineering challenge prevalent across various applications. In power engineering, this phenomenon has long been acknowledged and addressed through gradual startup and shutdown procedures of the rotor system. However, within the aircraft engine domain, this issue is more necessary due to the variable operating conditions and temperatures changes by flight modes or engine shutdown events. Moreover, engine aftercooling proves particularly arduous owing to the intricate geometry and equipment constraints. This paper delves into the application of a developed Finite Element Method (FEM) tool for predicting rotor thermal bow induced by temperature discrepancies between the upper and lower sides of the rotor. The paper meticulously elucidates the mathematical model of the FEM tool and expounds upon the calculation methodology for rotor deflection based on the selected geometry.*

Keywords: Rotor thermal bow, natural convection, gas turbine engine, 3D FEM.

1. Introduction

The operational temperature, trend monitoring, and control system of parts and components have a substantial impact on their reliability and lifespan across various industries. This impact is particularly pronounced in aviation, where it directly influences flight safety. The temperatures of aircraft engines, such as turboprop engines, and their adjacent components are influenced by internal engine mechanisms (compressor, combustion chamber, turbine) as well as external devices within the nacelle that dissipate heat. This paper discusses the prediction of rotor bow resulting from non-uniform temperature distribution in turbine engines. Previous studies by Pařez et al. (2022a, 2021) have addressed the issue of heat transfer during engine cooling via natural convection and radiation. While initial studies utilized a 1D Finite Element Method (FEM) solver (Pařez et al., 2022b), it was insufficient for comprehensive rotor system analysis, leading to the development of a 2D FEM solver (Pařez et al., 2022c). However, relying solely on a 2D solver does not accurately represent the real 3D geometry and physical principles, necessitating the development of a complete 3D FEM solver to accurately model temperature distribution and strain.

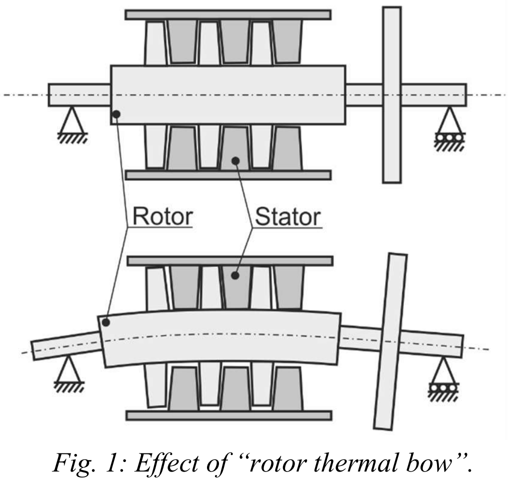

Fig. 1: Effect of "rotor thermal bow".

---

[*] Ing. Jan Pařez: Department of Mechanics, Biomechanics and Mechatronics, Faculty of Mechanical Engineering, Center of Aviation and Space Research, Czech Technical University in Prague; Technicka 4; 160 00, Prague 6; Czech Republic, jan.parez@fs.cvut.cz

[**] Prof. Dr. Ing. Tomáš Vampola: Department of Mechanics, Biomechanics and Mechatronics, Center of Aviation and Space Research, Faculty of Mechanical Engineering, Czech Technical University in Prague; Technicka 4; 160 00, Prague 6; Czech Republic, tomas.vampola@fs.cvut.cz

doi: 10.21495/em2024-226

Research on understanding thermal bow in turbomachinery has been conducted by Deepthikumar et al. (2014), while Yuan et al. (2009) employed Computational Fluid Dynamics (CFD) to model thermal bow resulting from convective airflow within compressor shafts. Marinescu and Ehrsam (2012) conducted a similar analysis on a steam turbine, highlighting the significant cooling time required. Due to computational complexity, they initially worked with a 2D simulation and adjusted the results to account for 3D effects. Pennacchi and Vania (2004) focused on model-based diagnostic techniques to detect thermal sag in generators, while Penara et al. (2015) studied the numerical determination of temperature distribution dependence on rotor vibration stability. Although literature touches on aeronautical applications, the presence of thermal bow in aircraft gas turbines is marginally discussed, including in works by Deepthikumar et al. (2014) and recent studies by Smith and Neely (2013) on aircraft engine compressors, which also delved into rotor dynamics and vibration.

2. Mathematical method

The Finite Element Method (FEM) solver operates through a series of Matlab scripts. The control script systematically executes various stages of the calculation process. Initially, input data regarding the computational mesh geometry, material properties, physical characteristics, and boundary conditions for temperatures and node supports are gathered. Based on this information, the computational mesh is generated. Subsequently, a calculation scope is determined, encompassing tasks such as temperature distribution, structural analysis, or dynamic property assessment.

The generation of the computational node mesh commences by discretizing the rotating component, adhering to specified node counts along the circumference and radial layers. Within this mesh, the computation domain is delineated based on the rotor system boundaries, with boundary edge points being included. This straightforward mesh structure facilitates the calculation of trapezoidal elements. These elements, comprising five sets of four points delineating the front, back, and middle planes in a counter clockwise orientation, are iteratively created for all relevant points within the calculation domain.

The calculation first determines the temperature distribution in the geometry based on the input boundary temperatures. The boundary temperatures are entered using a machine learning approach. Temperature distributions where non-stationary ambient airflow primarily due to natural convection affects the surface temperature as shown in Fig. 2. Thus, the temperatures are entered by a correlation function for specific correlation parameters and prescribed to the edge nodes of the geometry in Fig. 3.

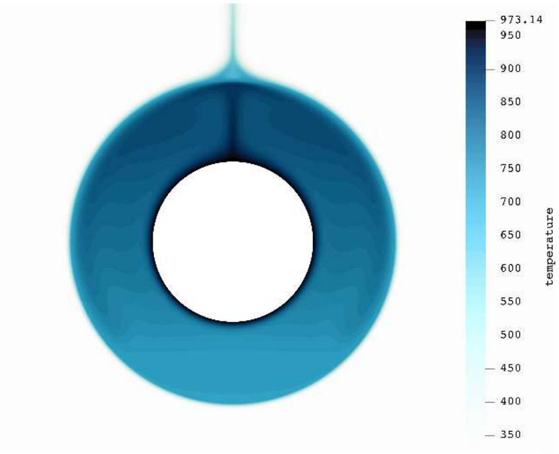

Fig. 2: Temperature distribution in single annular for flow path temperature 700 [°C].

The temperature field and deformations are calculated through a multi-step process. Initially, the temperature field is computed by constructing a heat conduction matrix for sub-elements, which are subsequently assembled into a comprehensive matrix incorporating the entire geometry and boundary conditions. Solving this matrix yields the temperature distribution for each node within the mesh. Once the temperature field distribution is established, a stiffness matrix is similarly constructed for the entire geometry, comprising the sub-elements. The displacement of each node within the computational mesh is determined by solving this stiffness matrix. The entire calculation process is conducted through linear calculations.

3. Computational model

The computational model of the rotor system simplifies the geometry into an annular cylindrical shape. The 3D mesh comprises 9 000 equally spaced elements along the inner radius, with 10 radial layers and 6 axial planes. The rotor system is supported by two-bearing supports: one fixed to prevent radial displacement, while the other allows axial displacement to compensate for thermal expansion. It's the same with an aircraft rotor. The rotor material, conventional steel, is characterized by known properties. The temperature field distribution is based on measurements obtained from the double annulus under engine cooling conditions after-shutdown, with initial values set at 700 °C for edge nodes. This is followed by cooling by natural convection. The numerical analysis aims to ascertain the temperature field distribution within the geometry, incorporating prescribed boundary conditions at the edges. Additionally, the analysis seeks to determine the deformation history and its maximum values, depicted in Fig. 3 below.

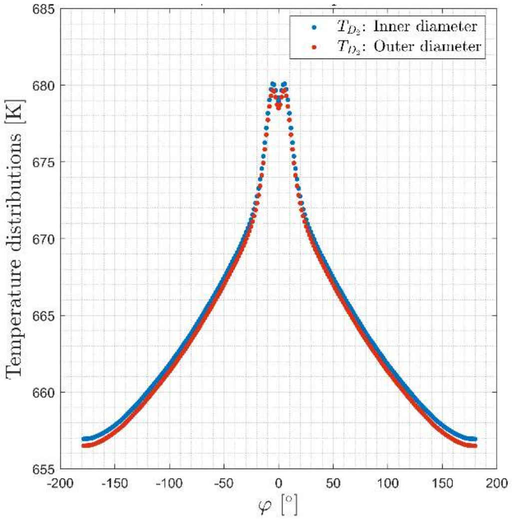

Fig. 3: Machine learning predicted temperatures for edge nodes at time $t > 0$.

The results from the developed FEM model of the rotor system highlight the significant impact of the non-uniform temperature field distribution. This is plotted in Figs. 4–7. Effect of asymmetrical deformation of upper and lower part leads to deflection in the rotor system, known as Rotor Thermal Bow.

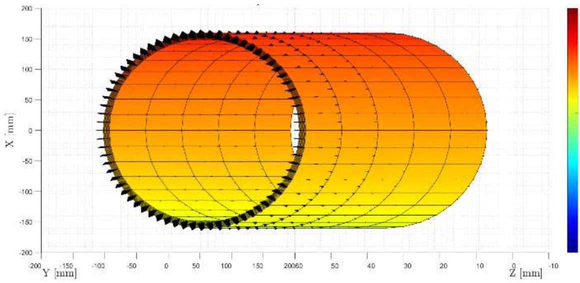

Fig. 4: Temperature field in time t_1.

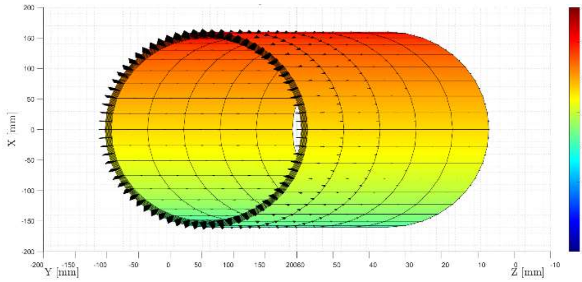

Fig. 5: Temperature field in time t_2.

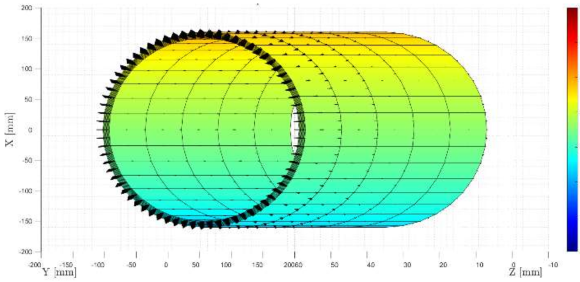

Fig. 6: Temperature field in time t_3.

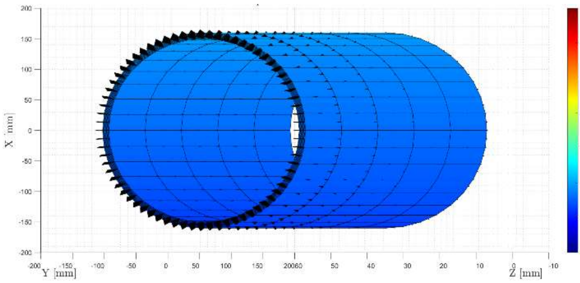

Fig. 7: Temperature field in time t_4.

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 Fig. 8.

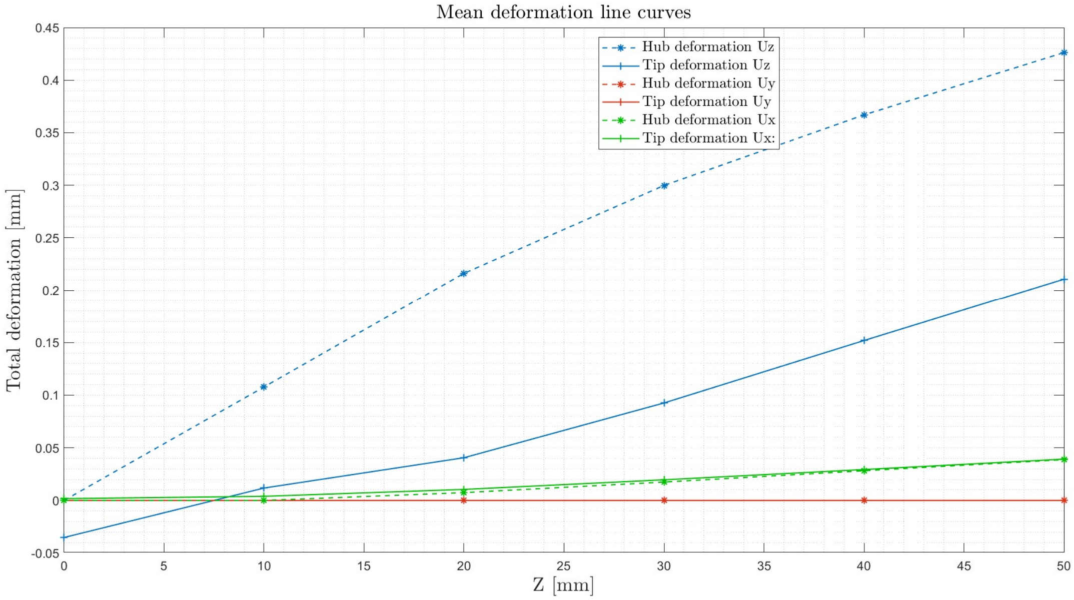

Fig. 8: Deformation for time t_2.

Acknowledgement

Authors acknowledge support from the ESIF, EU Operational Programme Research, Development and Education, and from the Center of Advanced Aerospace Technology (CZ.02.1.01/0.0/0.0/16_019/0000826), Faculty of Mechanical Engineering, Czech Technical University in Prague. This work was supported by the Grant Agency of the Czech Technical University in Prague, grant No. SGS22/151/OHK2/3T/12.

References

Deepthikumar, M. B., Sekhar, A. S. and Srikanthan, M. R. (2014) Balancing of flexible rotor with bow using transfer matrix method. *Journal of Vibration and Control*, 20(2), pp. 225–240.

Marinescu, G. and Ehrsam, A. (2012) Experimental Investigation Into Thermal Behavior of Steam Turbine Components: Part 2–Natural Cooling of Steam Turbines and the Impact on LCF Life. *Turbo Expo: Power for Land, Sea, and Air*, vol. 44700, pp. 1111–1120. American Society of Mechanical Engineers.

Penara, D., Baldassarre, L., Griffin, D., Mattana, A., Panconi, S. and Meli, E. (2015) Numerical prediction and experimental validation of rotor thermal instability. In: *Proc. of the 44th Turbomachinery Symposium. Turbomachinery Laboratories*, Texas A&M Engineering Experiment Station.

Pařez, J., Tater, A., Polanský, J. and Vampola, T. (2022a) Experimental and numerical study of natural convection in 3D double horizontal annulus. *EDP Sciences*. vol. 264, p. 01027.

Pařez, J., Rohan, P. and Vampola, T. (2021) Heat Transfer in Double Annular due to Natural Convection. *IOP Conference Series: Materials Science and Engineering*. vol. 1190, no. 1, p. 012002.

Pařez, J. and Vampola, T. (2022b) Numerical 1D Stiffness Matrix Model of Thermal Bowed Rotor. In: *30th Workshop of Applied Mechanics*. Prague, pp. 39–42.

Pařez, J., Kovář, P. and Vampola, T. (2022c) Sensitivity Analysis of Thermodynamical Parameters on the Thermal Bowed Rotor Using 2D Finite Element Mode. In: *Proc. of Computational Mechanics*. Plzeň: University of West Bohemia, pp. 103–106.

Pennacchi, P. and Vania, A. (2004) Accuracy in the identification of a generator thermal bow. *Journal of Sound and Vibration*, 274(1-2), pp. 273–295.

Smith, E. O. and Neely, A. (2013) Shaft thermal bow modelling in gas turbines-an initial study. In: *Proc. 21st International Symposium on Air Breathing Engines*, pp. 9–13.

Yuan, H. Q., Zhu, X. Z., Li, D. and Wen, B. C. (2009) Dynamic characteristics of transient thermal starting up of a rotor system. Zhendong yu Chongji, *Journal of Vibration and Shock*, 28(7), pp. 33–37.