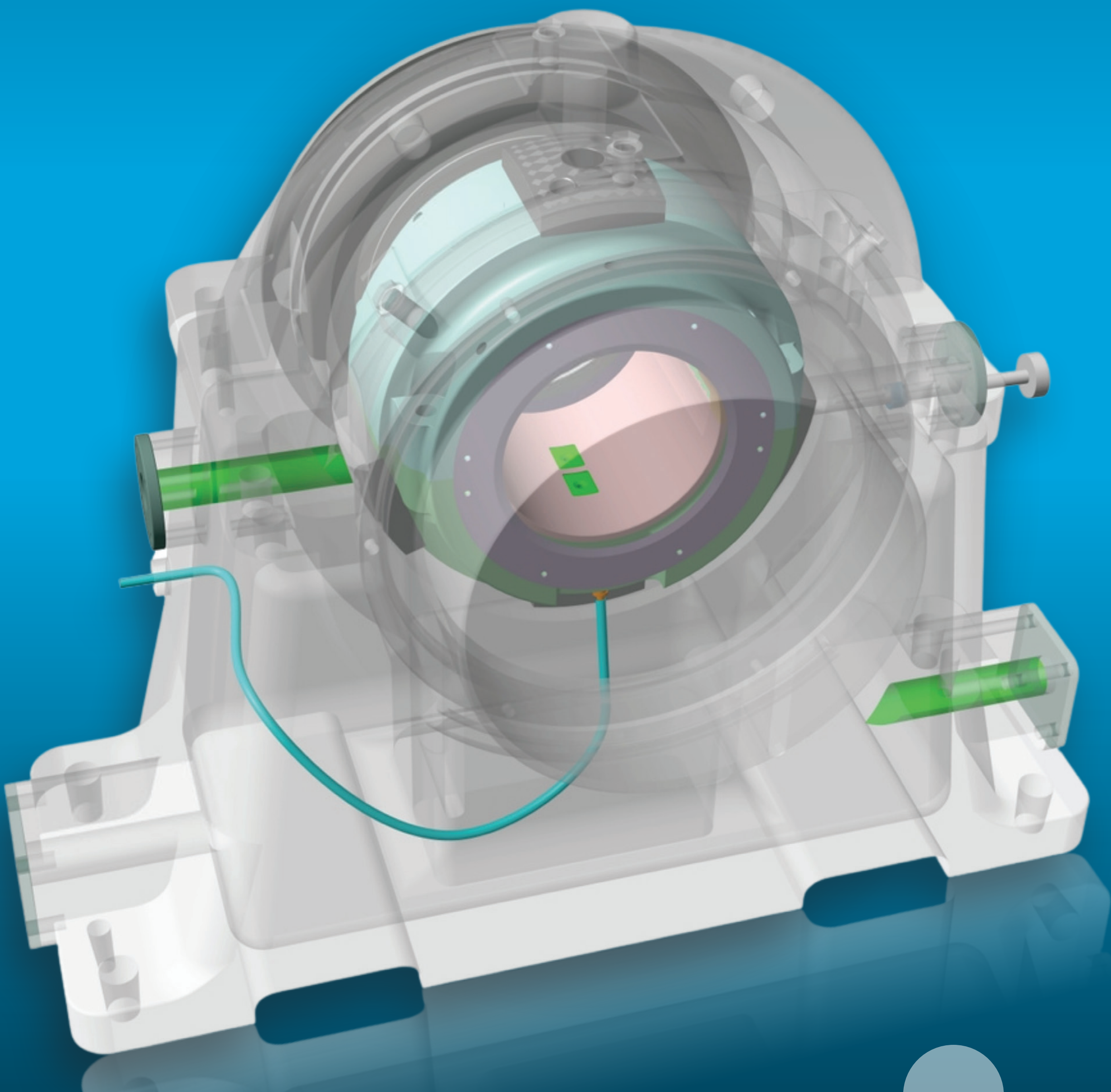
CYIENT

# THERMALLY-INDUCED SEIZURE IN JOURNAL BEARING

Finite Element Study



# CONTENTS

| | |
|---|---|
| Introduction | 1 |
| Literature Review | 1 |
| Finite Element Modeling | 3 |
| Material Properties | 5 |
| Boundary Conditions | 6 |
| Analyses | 9 |
| Results and Discussion | 10 |
| Conclusion | 11 |
| References | 11 |
| About the Author | 11 |
| About Cyient | 14 |

## Introduction

The study of the thermal effect on bearing performance has been considered an important subject since the evolution of tribology as a field of study. The driving force behind this is the frequent failure of tribological components due to metal-to-metal contact and the associated rise in frictional heating. Thermally-induced seizure (TIS) and galling are examples of such failures relevant to this work. Thermally-induced seizure occurs when the rise in operating temperature causes a partial or complete loss in operating clearance, leading to the seizure of the journal in the bearing. This paper focuses on the transient thermomechanical interactions of the journal and bearings during start-up.

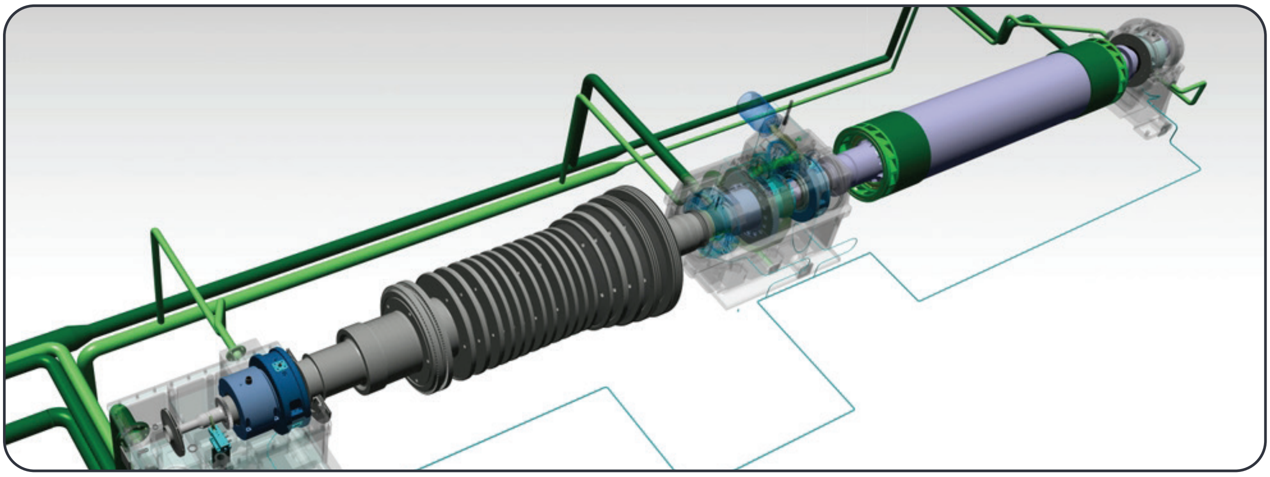
## Literature Review

Bishop and Ettles [1] analyzed the thermoelastic interaction of a journal in a plastic bushing that was interference-fit with the shaft. They mentioned that bearing seizure occurred when the temperature rise on the surface of the shaft exceeded 360$^0$ C.

A Dufrane and Kannel [2] study indicates that seizure occurred with the complete loss of operating clearance. The cause of this type of failure was identified to be dry metal-to-metal contact during the bearing start-up and the associated rise in the contact temperature. The seizure occurred within 30 seconds in most journal bearings operating in dry conditions.

A Khonsari and Kim [3] study showed that journal bearings undergo seizure during start-up due to misalignment of the shaft, which comes into contact with the bearing in a very small area, further aggravating the thermomechanical interaction.

Hazlett and Khonsari [4, 5] developed a thermomechanical finite element model using the finite element package ANSYS. The results established that TIS is triggered by the ovalization of the bushing and the formation of new contact patches at the top of the bearing. The establishment of new contact patches accelerates the seizure process by increasing the contact forces and thus increasing the frictional torque.



The bearings are required to survive with little or no oil under severe operating conditions such as those encountered during flight take-off, landing, and sudden maneuvering. The oil flow interruption typically lasts for 15 to 30 seconds. The aircraft engine bearings are not only required to survive these operating conditions but also to resume normal operation once the lubricant flow is re-established. Although this study was done to improve the performance of ball bearings in aircraft engines, it provided the inspiration to conduct a similar study on journal bearings. The effect of the oil flow interruption in lubricant supply took place in either of the two mechanisms described below.

A limiting temperature is taken as the condition for the onset of seizure. This limiting temperature corresponds to the clearance between the journal and the bearing is completely lost. A "no-seizure" condition is also derived based on the limiting temperature.

The seizure time was determined when the driving torque requirement exceeded a certain range. The thermal expansion of the shaft and its encroachment into the bushing was determined using a standard 2-D heat conduction equation. There was good agreement of theoretical and experimental seizure time.

The objective of this work is to perform a comprehensive study of seizure in bearings during start-up based on finite element analysis using ANSYS software. This approach can be used by designers to predict seizure time, which can help design instrumentation systems and warning devices to take necessary precautions.

**1**

Oil flow interruption $\Rightarrow$ Adverse $\Delta T$ $\Rightarrow$ Reduction in bearing clearance $\Rightarrow$ Excessive Hertzian stresses $\Rightarrow$ High heat generation $\Rightarrow$ Bearing seizure

**2**

Oil flow interruption $\Rightarrow$ Surface damage (Wear) $\Rightarrow$ High heat generation $\Rightarrow$ Reduction in bearing clearance $\Rightarrow$ Seizures

## Finite Element Modeling

The paper aims to study the thermomechanical interactions of the journal and bearing system during unlubricated bearing start-up. The finite element analysis is a simple and handy tool that is used with good accuracy in engineering. The commercial FEM software package ANSYS 18.2 was utilized to perform a detailed analysis of the thermoelastic interactions of the journal and bearing. The finite element analysis procedure, type of elements, and the boundary conditions used are presented below [6, 7].

The analysis of a bearing undergoing TIS during start-up comprises the following steps:

1. A 2-D static contact analysis is performed to determine the contact forces and the contact angle.
2. A transient heat transfer analysis is done to model the thermal effects of dry frictional heating on the journal and the bearing.
3. A transient thermoelastic analysis is performed to study the interactions of the journal-bearing pair during bearing start-up. The variation of radial clearance, contact forces, and ovalization of the bearing are studied in this analysis.

Finite element modeling is done using ANSYS 18.2. [8] software. The finite element model of the present work employs a finer mesh than the mesh used by Hazlett and Khonsari to evaluate the contact forces with more accuracy.

The model consists of a shaft rubbing on the inner surface of the bushing, as shown in Figure 1. The contact forces result in the generation of frictional heat on the entire surface of the shaft and in the area where it contacts the bushing's inner radius. Due to the rise in temperature, the shaft expands, and its encroachment on the bushing leads to a loss of clearance. At some point in time, the bearing clearance reduces to a minimum, and the shaft starts to encroach on the bearing. Analyses show that, typically, during TIS, the following three phenomena occur:

(i) Contact forces increase, increasing the heat generated

(ii) The contact angle increases, causing a higher percentage of heat entering the bush

(iii) New areas of contact are established, resulting in a chain reaction leading to a rapid loss in the operating clearance

In the simulations presented in this paper, these processes were implemented by performing a thermal analysis and a thermoelastic analysis in a stepwise linear fashion. The model utilized a one-half symmetry and neglected the heat conduction in the axial direction.

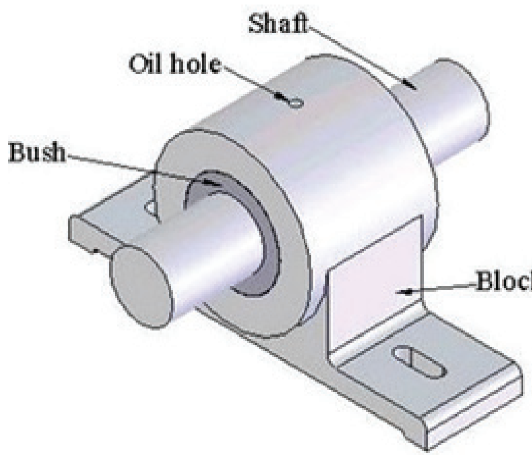



Figure 1: Journal bearing

## 1. Static contact analysis due to mechanical load

A 2-D static contact analysis must be performed to determine the contact forces and the contact angle. The analysis assumes that the contact pressure is uniform in the axial direction and no crowning or misalignment is present in the system. A half model is considered due to symmetry of geometry and load about the vertical axis.

A 2D plane 42 element with plane stress is considered for meshing and stress analysis. The shaft, graphite bush, and block are meshed using the plane stress element. A fine mesh is maintained to capture the contact area and contact forces accurately. The finite element model for 2D static contact analysis due to mechanical load is shown in Figure 2a. Finite element models of the journal, bush, and pillow block are shown in Figures 2b, 2c, and 2d.

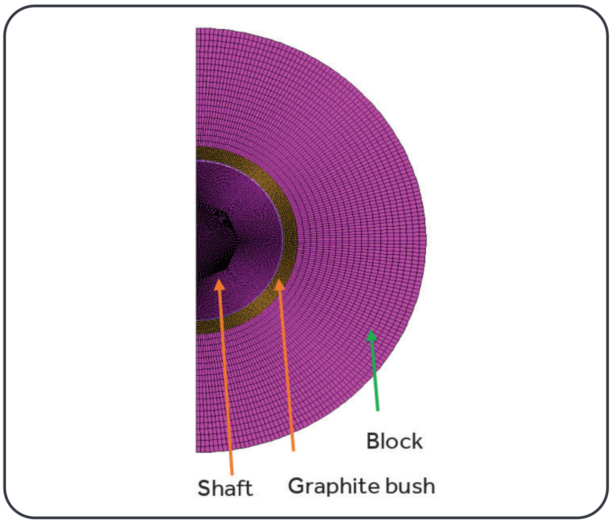



Figure 2a: 2D Finite element model Bearing assembly

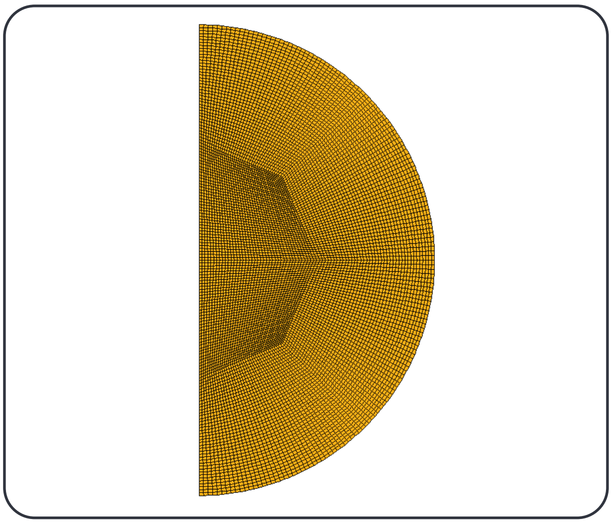


Figure 2b: 2D Finite element model—Journal

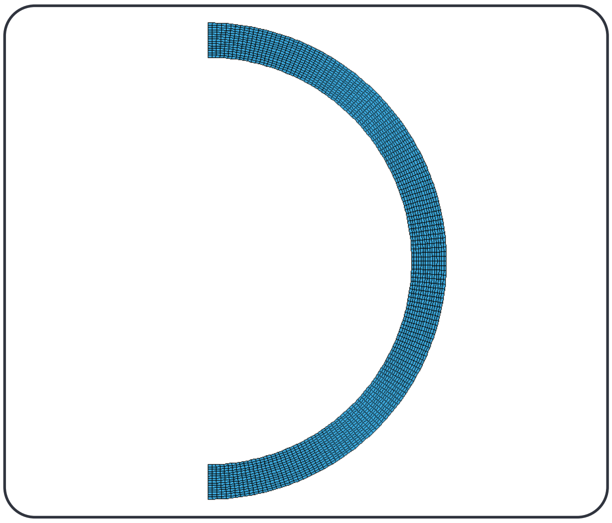


Figure 2c: 2D Finite element model—bush

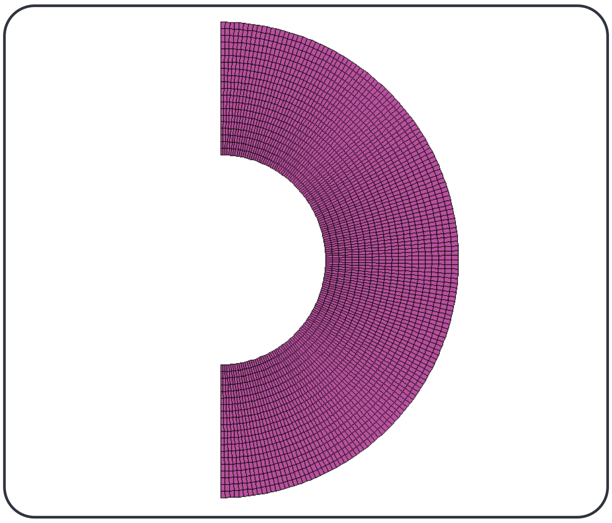


Figure 2d: 2D Finite element model—block

### 2. Transient thermal finite element analysis

Thermal analysis determines the temperature distribution in the journal and bearing. The mesh used for structural analysis is used for thermal analysis by converting structural elements to thermal element plane 55, which has a single degree of freedom.

The summation of the contact forces is equal to the total load (W) acting on the system. The frictional heat generated heats the entire surface area of the shaft in an on-off mode. Thus the surface of the shaft is intermittently heated in the contact area and cooled in the clearance area. The frictional heat generated heats only the surface of the bushing that is in contact, as shown in Figure 3. Temperature and flux continuity exists in the contact patch of contact of the journal and the bearing. The heat flux due to the frictional heating calculations is here.

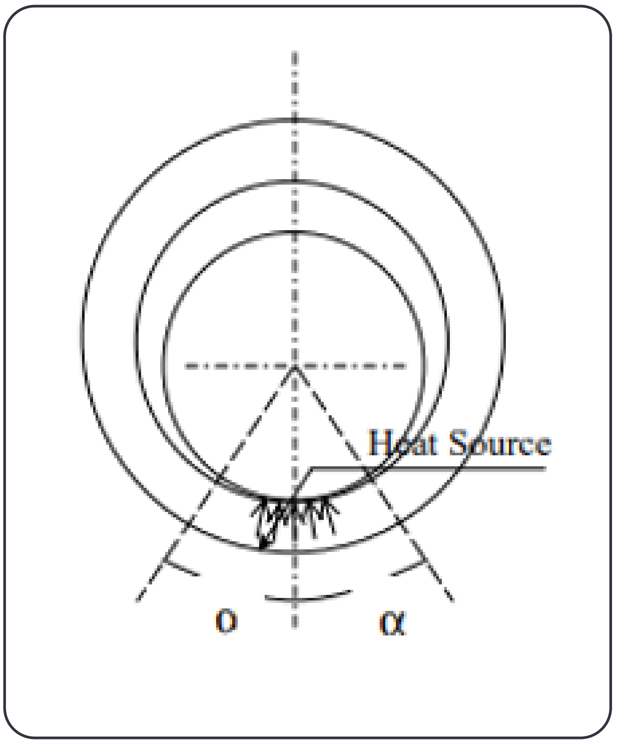



Fig. 3: Heat flux at contact area

## Material Properties

The material properties of the three parts used for analyses are listed below, in Table 1.

| Property | Shaft - hardened steel | Bush - graphite | Steel |
|---|---|---|---|
| Young's modulus N/ sq.mm | 2.2e5 | 2.0e4 | 1.75e5 |
| Poisson's ratio | 0.3 | 0.28 | 0.3 |
| Coefficient of thermal expansion /deg c | 1.3e-5 | 2.6e-6 | 1.2e-5 |
| Thermal conductivity | | | |
| W/mm-c | 5.2e-2 | 1.7e-8 | 3.5e-2 |

## Boundary Conditions

### a. Structural boundary conditions

A 2-D static contact analysis is to be performed to determine the contact forces and the contact angle. The mechanical load W is applied on the shaft in the negative y-direction.

Total load acting on bearing W = 420 N. The boundary condition plot is shown in Figure 4.

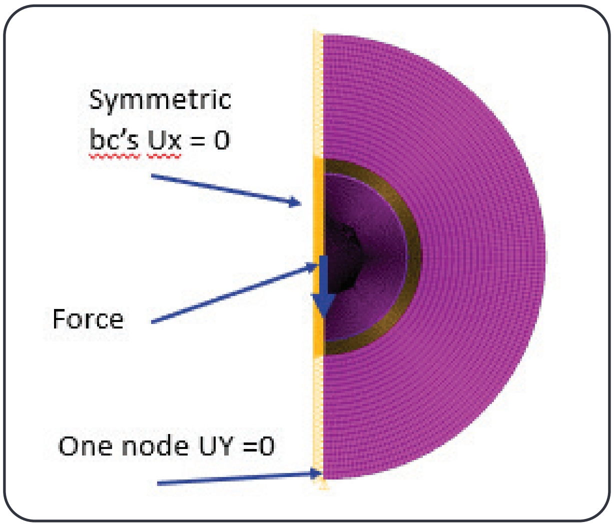



Figure 4: Structural boundary conditions

### b. Thermal boundary conditions

The rotating shaft is heated periodically when it contacts the bushing. This can be thought of as an on-off type of heating. It was shown by Hazlett [8] that on-off heating could be modeled as an average heat flux on the entire surface. Also, there is dissipation of heat by convective cooling by the air within the clearance of the journal and the bushing.

To represent the periodic heat dissipation in the finite element model, the nodes on the surface of the shaft are coupled. The temperature on the surface of the journal and the bushing at the interface is constant and is modeled by coupling the temperatures at the nodes on the interface. The outer surface of the block is subject to natural convection.

## Heat generation due to mechanical load

**The heat flux in a bearing per unit area**

- Q = f w v/A
- f = Coefficients friction, A =Journal area
- V = surface velocity of journal
- Load acting on bearing = W
- Surface velocity of shaft V= 2πRsN /60
- Area of the journal A = 2πRs L
- Length of bearing L, Shaft radius Rs
- Speed of the shaft N

Heat flux is applied on the shaft surface at the clearance side, and nodes at the initial contact area are coupled to maintain the same temperature, as shown in Figure 5a.

Natural convective boundary conditions are applied on the surface of shaft because air exists in the clearance. Heat transfer coefficient 20 W/m2/ °C and ambient temperature T = 21° C are considered for analysis as shown in Figure 5b. Similarly, heat transfer coefficient and bulk temperature are applied on the inner surface of the bush and the block's outer surface, as shown in Figures 5c and 5d.

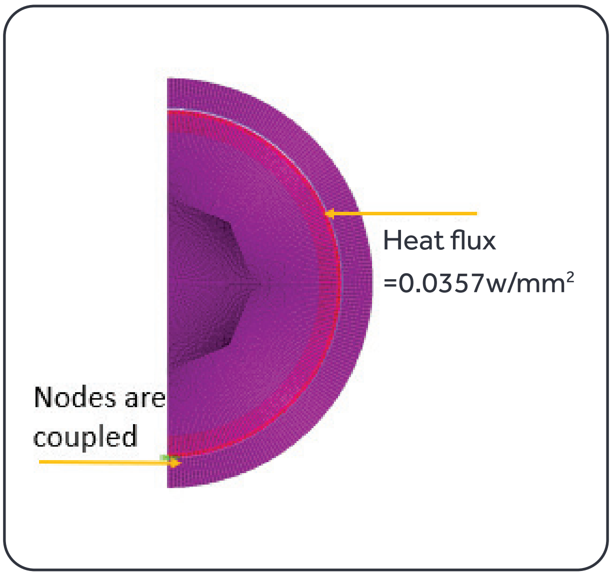



Fig 5a: Heat flux on journal surface

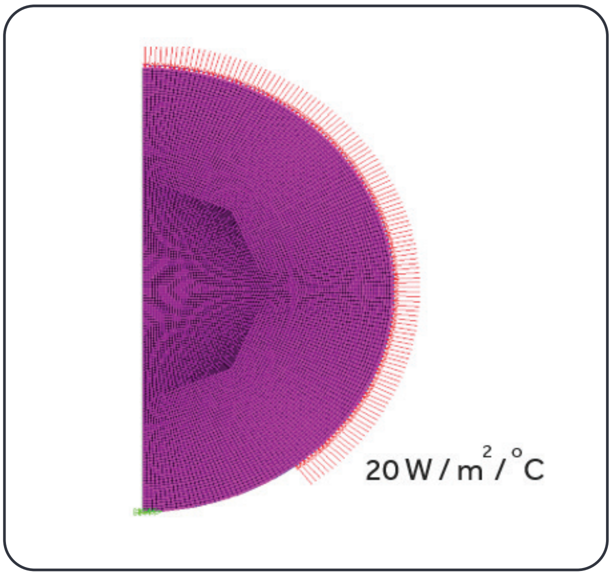



Fig 5b: HTC on journal surface

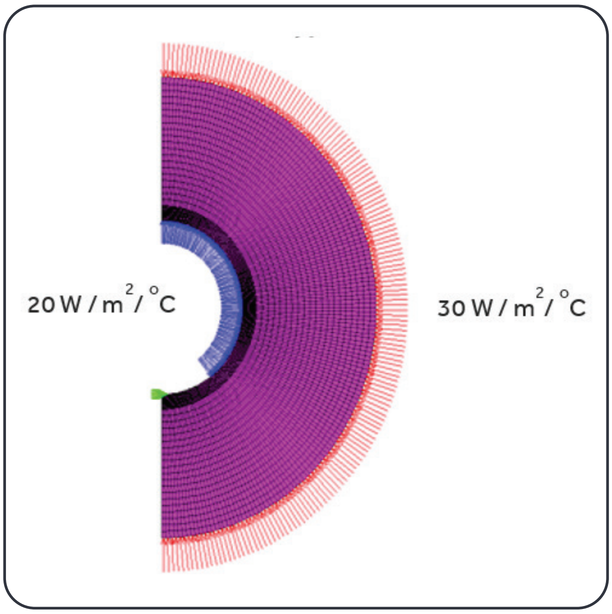



Figure 5c: HTC plot - bush and block

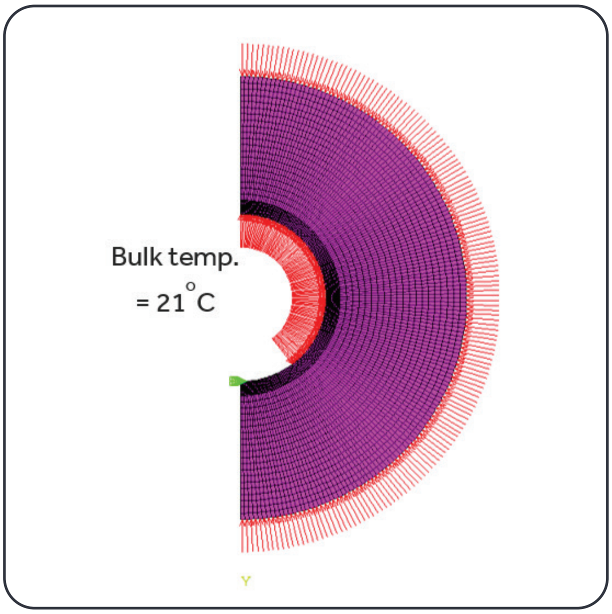



Figure 5d: Bulk temperature - bush and block

### c. Boundary conditions - thermoelastic analysis

Here we discuss steady-state analysis to find the contact forces and transient thermal analysis to determine the temperature. The final thermomechanical analysis is carried out using mechanical load and temperature at different time points.

The loading for the non-linear thermoelastic analysis consists of the thermal loads applied as nodal temperatures and mechanical load acting on the journal. The time-dependent thermal load is obtained from the results of the transient thermal analysis. The mechanical load w is applied to act in the negative y-direction on the shaft. As the model utilizes half-symmetry, a load of w/2 is applied.

Symmetric boundary conditions are used to model one-half symmetry as shown in Figure 6. The constraint of the bearing on its outer surface is modeled by fixing the bearing at the node under the shaft on the outer edge of the bearing on the symmetric plane.

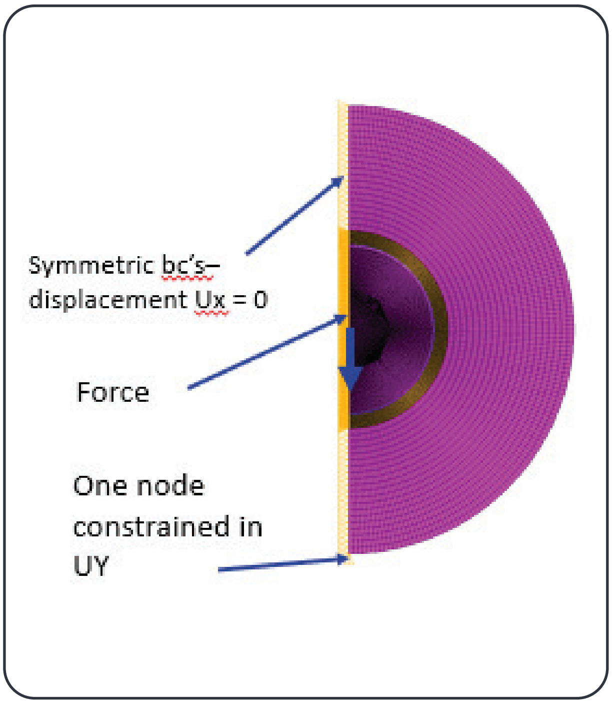



Figure 6: Structural boundary conditions

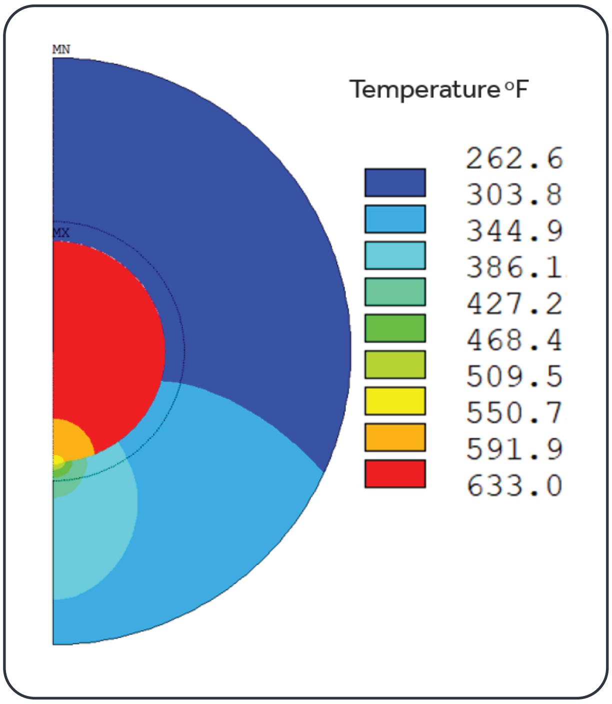



Figure 7: Temperature loading for seizure

## Analyses

A 2-D static contact analysis is performed to determine the contact forces and the contact angle. The analysis assumes that the contact pressure is uniform in the axial direction and no crowning or misalignment is present in the system. A half model is considered due to symmetry of geometry and load about the vertical axis. The obtained contact force distribution is used for further analysis.

In the second part, transient thermal analysis is carried out by applying heat flux on the shaft surface based on Power = 520W with convective boundary conditions and obtained temperature distribution for different time steps.

As a part of the third stage, mechanical and temperature loads are applied and carried for non-linear static analysis. This analysis is carried out by considering the metal temperature for each time step. The total load is applied incrementally as sub-steps. The seventh sub-step results indicate the occurrence of seizure.

### Seizure criterion

Frictional torque is the torque resisting the driving torque exerted by the motor. When the frictional torque increases beyond the extent of the driving torque capability, it can be concluded that the journal has seized in the bearing. The present model assumes that TIS is complete when the frictional torque reaches at least 10 times the driving torque or last but one load step results can be considered in case of non-convergence. The contact forces acting on the contact elements at any instant of time determine the frictional torque.

## Results and Discussion

### Static contact analysis due to mechanical load

This analysis is carried out to get the contact area and load distribution between the journal and the bush. The load distribution between the journal and bush is shown in Figure 8. This is highly localized pressure on a very small area.

### Transient heat transfer analysis

The transient heat transfer analysis is carried out by applying heat flux on the journal and convective boundary conditions. The temperature contour of the journal-bearing assembly obtained from transient heat transfer analysis at sub-step 7 is shown in Figure 9. The journal temperature contour at sub-step 7 is shown in Figure 10. The maximum temperature of the shaft is 633°F. The temperature contour plot of the bush and pillow block is shown in Figure 11. The maximum temperature of the bush is 530°F.

### Thermo-structural analysis

In the third stage, contact static analysis is carried out by considering mechanical and thermal loads for each time step. It is observed that the seizure occurs at sub-step 7.

The status of the contact surface is shown in Figure 12. The contact surface is indicated as sticking zone, sliding zone, and near contact zone. The contact area at TDC and BDC are sticking to each other. This indicates that clearance at the top and bottom contact areas is closed, leading to seizure. The contact pressure on the contact surface is shown in Figure 13. The contact pressure is high at the top and bottom contact zones of the journal and bush and gradually reduces to zero at the 3 o'clock position.

The encroachment of the shaft onto the bushing with a concomitant reduction in the clearance continues until the seizure is complete. The process is a complex, non-linear phenomenon. Analysis shows that TIS is initiated by the ovalization of the bearing combined with the uniform outward expansion of the shaft, yielding contact between the surface of the shaft and the inner bushing surface. This leads to an increase in the contact forces and the formation of an extra contact area.

An increase of contact forces raises the frictional heat flux and sets up a positive feedback that accelerates the loss of clearance. The increase in the frictional torque is abrupt once the ovalization of the bearing causes the shaft to encroach on the bushing, as there is further loss in the operating clearance. The frictional torque increases to exceedingly large values within a few seconds after the first instance of establishment of new areas of contact. In sub-step 7, both shaft and bush undergo significant radial deformation, as shown in Figure 14.

The variation of the frictional torque with respect to power supplied is shown in Figure 15. The frictional torque suddenly increases from 2342 to 21390 N-mm, causing shaft seizure. Suddenly, the change in frictional torque is almost 10 times more compared to the previous step.

## Conclusion

The analysis revealed that the thermoelastic deformation between the journal and the bearing led to a reduction in clearance in a non-linear fashion.

It is interesting to note that though the frictional torque increased to ten times the initial torque, the clearance had not reduced to zero at all points, proving that the frictional torque is a better seizure criterion than zero-clearance.

These simulations reveal that the frictional torque reaches very high values within 3 seconds after the first ovalization is experienced. The ovalization is realized in the analysis when additional contact is established at the top of the bearing.

Therefore, it will be assumed that the seizure happens within few seconds after the first instance of ovalization.

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## About the Author

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**Kondaiah Bommisetty** is a chief in the area of finite element modelling and structural analysis He has been associated with Cyient since 2002 and has an overall experience of 30 years in Aerospace domain. He has successfully completed multiple projects related to Aero engine stress analysis for PWC and PWA. Developed best practices and process definition documents to execute projects. As a chief from service area, he interacts with different teams across Cyient and transfer the knowledge.

## Contour Plots of Results

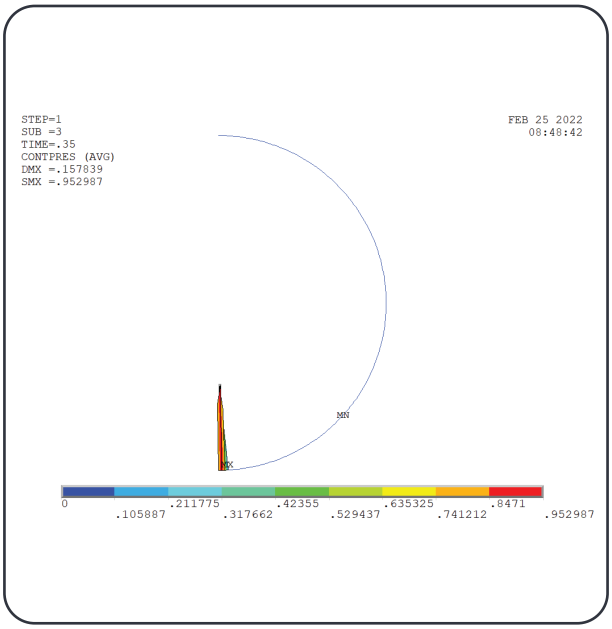


Figure 8: Contact pressure due to mechanical load

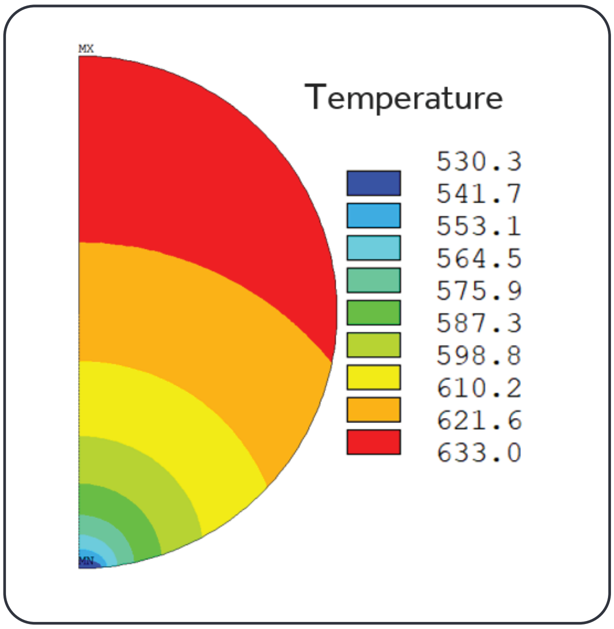


Figure 9: Temperature contour of shaft

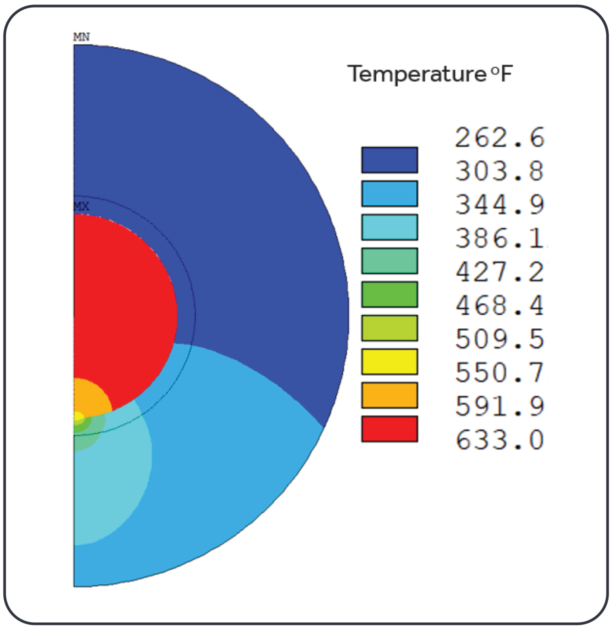


Figure 10: Temperature contour of bearing assembly at seizure

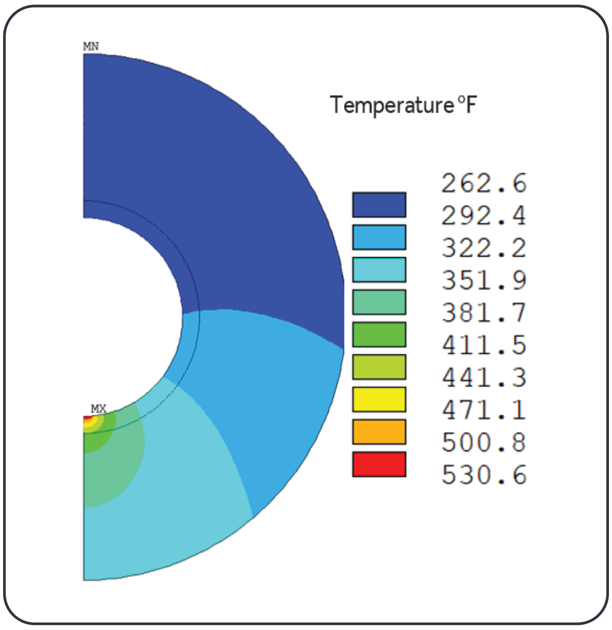


Figure11: Temperature contour of bush and block at seizure

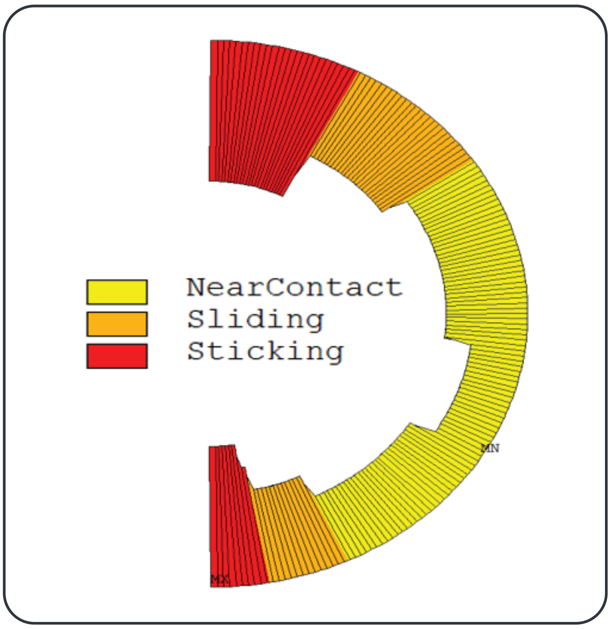


Figure 12: Contact status contour at seizure condition

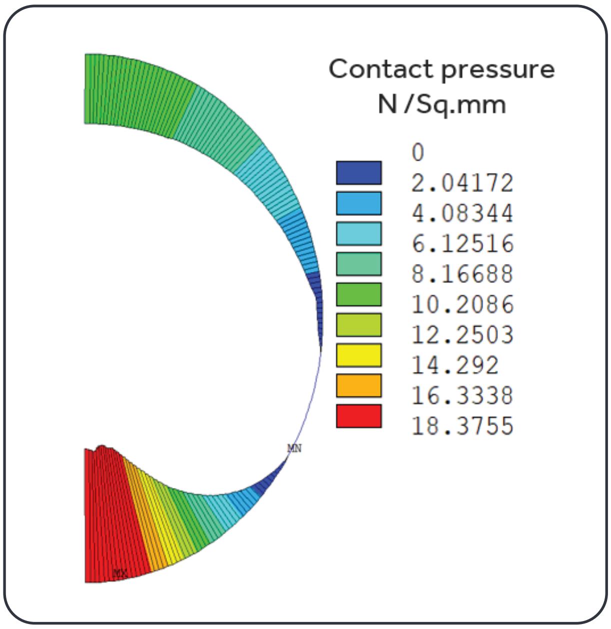


Figure13: Contact pressure distribution at seizure condition

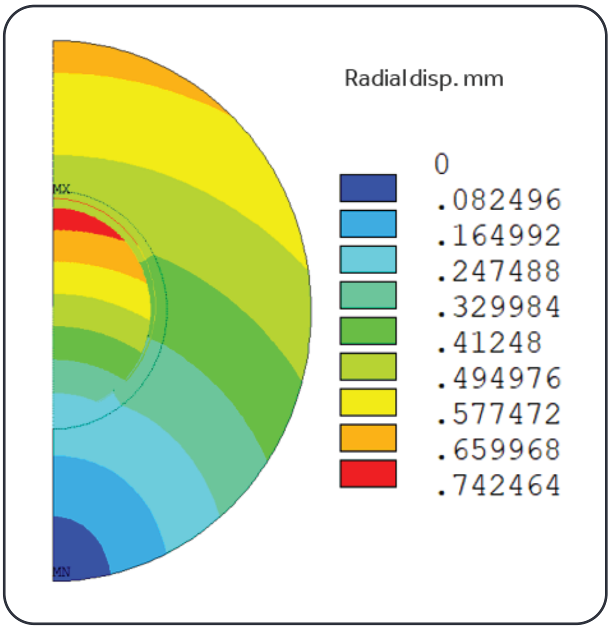


Figure 14: Radial displacement contour of bearing at seizure condition

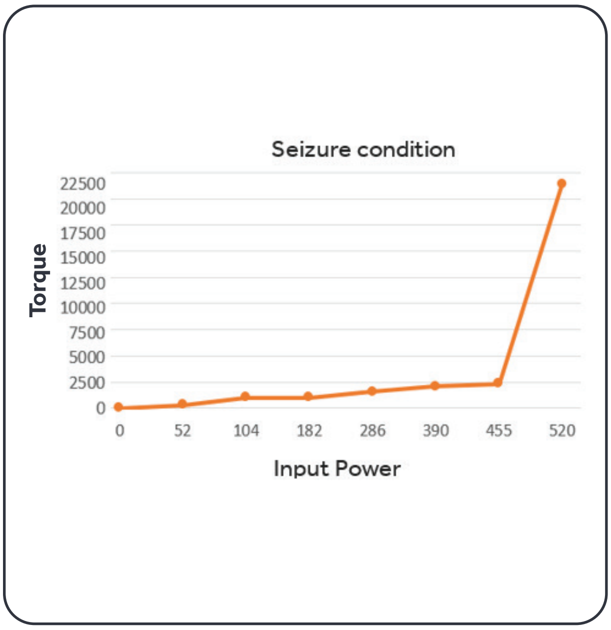


Figure15: Frictional torque (N-mm) Vs Input power

## About Cyient

Cyient (Estd: 1991, NSE: CYIENT) is a global Engineering and Technology solutions company. We collaborate with our customers to design digital enterprises, build intelligent products and platforms and solve sustainability challenges. We are committed to designing tomorrow together with our stakeholders and being a culturally inclusive, socially responsible, and environmentally sustainable organization.

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