ON THERMAL GALLING OF OSCILLATING PIN-BUSHING ASSEMBLY

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ABSTRACT

Temperature induced galling in oscillating pin-bushing mechanisms subjected to heavy loads is known to be the cause of failure of many industrial machinery. Yet, surprisingly, very little information is available to shed light on this important failure mechanism. An examination of the open literature reveals that the published work on the thermal characteristics of pin-bushing type configuration has been limited to unidirectional rotation. For example, Gecim and Winer[1] developed an analytical method for predicting the surface temperature distribution of a shaft rotating at very high speed assuming the system to be at quasi-steady state. In the case of rotating shaft, the temperature distribution will be uniform over its entire circumference. In contrast, when either the bushing or the shaft is subjected to oscillatory motion, the generation of heat is concentrated primarily over the contact angle, which is dependent on the load and material properties. The severity of the temperature is a function of the oscillatory speed, load and the angle of oscillation. The prediction of thermally induced galling failure requires a transient heat transfer analysis with consideration of thermomechanical interaction of the contacting surfaces.

Hazlett and Khonsari[2] performed one of the first comprehensive finite element formulations to predict the failure of a journal bearing due to Thermally Induced Seizure (TIS). More recently Krithivasan and Khonsari[3] have developed design equations to predict the seizure time, as a function of operating conditions where in temperature is the only contribution to the seizure of the pin. All of these analyses are restricted to constant, unidirectional speeds.

In the present work we develop an analysis for the prediction of the thermal behavior of oscillatory mechanism. The objective of this study is to develop appropriate data that can be used at the design stage to guard against the occurrence of galling.

The method of solution is using the finite element modeling technique. A commercial FEM solver called FlexPDE[4] is utilized for this purpose. Referring to Figures 1 and 2, the governing equations of the system is the transient heat equation without internal heat generation in cylindrical co-ordinates. The boundary conditions are time dependent and take into account the applied flux in the bite angle region as well as heat loss by convection within the pin-bushing clearance and on the outer circumference of the bushing.

The governing heat equation and the related boundary conditions are:

$$\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}+\frac{1}{r^2}\frac{\partial^2 T}{\partial \phi^2}=\frac{1}{\alpha}\frac{\partial T}{\partial t}$$

At the outer surface of the pin:

$$k\frac{\partial T}{\partial r}=f(t)q+[f(t)-1]h_1 T^{\#} \quad \text{for } 0 \le \phi \le 2\theta \quad \text{and}$$

$$k\frac{\partial T}{\partial r}=-h_1 T \quad \text{for } 2\theta \le \phi \le 2\pi$$

At the inner surface of the bushing:

$$k\frac{\partial T}{\partial r}=q^{\#} \quad \text{for } 0 \le \phi \le \theta_b \quad \text{and} \quad k\frac{\partial T}{\partial r}=-h_1 T \quad \text{for } \theta_b \le \phi \le 2\pi$$

At the outer surface of the bushing:

$$k\frac{\partial T}{\partial r}=-h_2 T \quad \text{for } 0 \le \phi \le 2\pi$$

To model temperature and slope continuity in the contact region, this particular boundary condition is coupled with pin and bushing. Therefore, flux need not be applied on both the pin and bushing, and it is sufficient to apply this condition on either shaft or bush and coupled with the other.

The application of combined flux and convection on the pin due to oscillatory nature described in the boundary conditions is accomplished as per the illustration in Figure 2(b). The pin is divided into five sectors and on each sector, the boundary condition is defined by a Fourier series function *f(t)*. At any instant of time only either flux is applied or convection is applied on any particular sector. The idea of applying the time dependent boundary condition originated from the work of Glass and Ozisik[5] who determined the transient temperature distribution in a semi-infinite medium due to an on-off heat flux.

To begin with, a dimensional case is solved for with the following parameters,

Geometry: Pin radius, R_1=0.05 m; Bushing inner radius, R_2 =0.05025 m; Bushing outer radius, R_3=0.1 m; Length, L= 0.1 m.

Operating Conditions: Load, W = 25000 lbs = 111.2 kN; Oscillation speed, u = 0.08 m/s; Angular velocity, ω = 1.6 rad/s = 91.67 deg/s; Oscillation angle, q = ±15 deg from mean position (i.e. total of 30 degrees).

Material Properties: Both pin and bushing is made of carbon steel. Thermal conductivity, k = 52 W/m-K; Thermal diffusivity, $a = 1 \times 10^{-5}$ m^2/s.

Heat Transfer: Convective coefficient, h_1 = 80 W/m^2 K (within the clearance) and h_2 = 80 W/m^2 K (outside the Bushing).

Analysis: Using the Hertzian contact theory, the bite angle is predicted, to be: q_b = 25 deg.

Total frictional heat flux, $q = f.W.u/A_c$

$A_c = R_1.q_b.L = 2.279 \times 10^{-3}$ m^2 and friction coefficient, f = 0.1.

Therefore, the total frictional heat flux, q = 386801.74 W/m^2.

The time for one complete oscillation (one cycle) for the above case is 0.654 sec. Under these specifications, the steady state maximum rise in temperature of 180^0 C is attained around 9000 cycles, which is shown in Figure 3.

Work is in progress:

- To verify the validity of time dependent boundary conditions applied in FlexPDE, an analytical solution will obtained for the temperature distribution for the pin alone subjected to oscillating flux on its circumference for a particular oscillating angle using Duhamel's approach.
- To determine the galling time, (the time taken for failure, where in the temperatures attain a value such that the pin and bush tend to weld to each other).
- Realistic prediction of convection coefficient in the clearance is needed for an accurate heat transfer analysis.
- Thermal expansion of the pin and the bush are to be considered to calculate the instantaneous heat sources that occur from the interaction of the expanded pin and the bushing. These effects contribute in addition to the existing heat flux.
- Effect of protective coating on the pin surface requires multi-layer heat transfer analysis.

REFERENCES

1. Gecim B. and Winer W.O.' Steady temperature in a rotating cylinder subject to surface heating and convective cooling. *ASME Journal of Tribology*, 1984, **106**, 120-27.
2. Hazlett T.L. and Khonsari M.M.' Finite element model of journal bearing undergoing rapid thermally induced seizure. *Tribology International*, 1992a, **25**, No.3, 177-82.
3. Krithivasan R. and Khonsari M.M., Thermally induced seizures in journal bearings, 2002 ME Graduate Student Conference, LSU, Baton Rouge, Louisiana.
4. FlexPDE Users Manual, *PDE Solutions*.
5. Glass.D.E and Ozisik M.N., Transient temperature resulting from periodic on-off heat flux for a semi-infinite medium *ASME Journal of Heat transfer*, 1988, 110, 250-52.

FIGURES AND TABLES

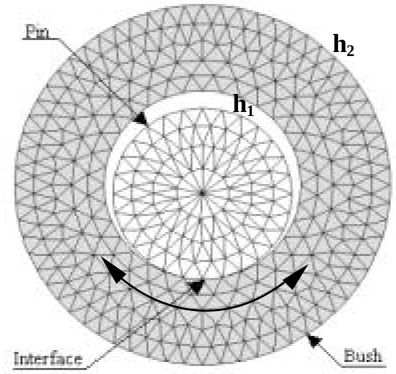
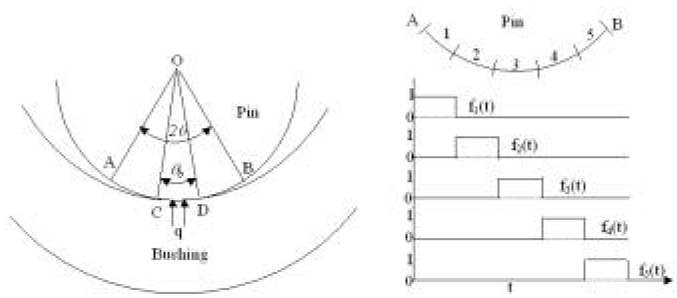


Figure 1 - Finite Element model generated by FlexPDE. The clearance is scaled by a factor of about 300 for clarity



(a) (b)

Figure 2 - Implementation of boundary condition on pin

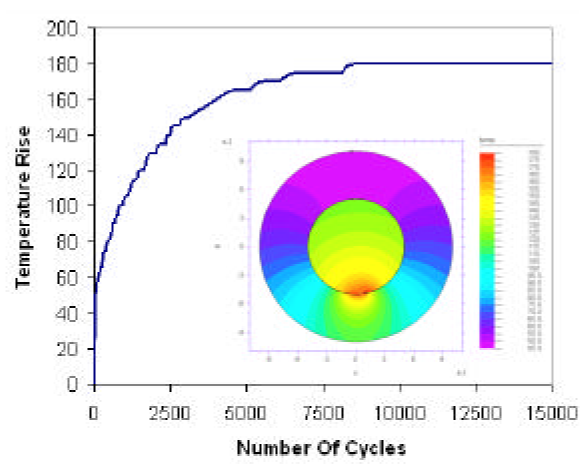


Figure 3 - Variation of Maximum Temperature rise with respect to Number of Oscillation cycles