THEORETICAL AND EXPERIMENTAL INVESTIGATION OF
FRICIONAL AND THERMAL BEHAVIOR IN
OSCILLATORY SLIDING LINE CONTACT

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ABSTRACT
A model is developed to predict the thermal behavior of two sliding bodies undergoing oscillatory relative motion. The thermal model is capable of predicting the temperature rise distribution within the pin-bushing pair and the housing. The bodies geometrically form a pin-bushing configuration and the Hertzian line contact theory is used to approximate the contact pressure and the width. A quasi-three dimensional temperature model is developed by averaging the temperature in the axial direction. The resulting dimensionless heat equations and proper boundary conditions are solved by the finite element method. A series of dimensionless equations for use at the design stage is presented. A test rig capable of inducing oscillatory motion under heavy loading condition is used for measuring friction and temperature. The measured coefficient of friction history, which is curve fit as a function of time, is used in the simulations. The description of the test rig, modeling aspects, and the future extension of the research comprise the contents of this paper.

INTRODUCTION
Heavy-duty pin-bushing assemblies used in wheel loaders undergo oscillatory contact under high intermittent contact pressures. Their contact experiences large temperatures making the component susceptible to fail prematurely by thermal galling and scuffing.

This paper deals with the theoretical and experimental analysis of frictional and thermal behavior in pin-bushing pairs operating at a sinusoidal sliding speed under a constant applied load. A quasi-three-dimensional thermal analysis is considered where axial effects are accounted for based on an averaging of the 3D heat equation along the axial direction and considering the end boundary conditions. This averaging method leads to an internal heat generation term that depends on the temperature distribution, as well as thermal and geometric properties. A Hertzian model is assumed to approximate the frictional heat flux distribution within the contact region. The formulation of the problem is based on a test rig model that is used for experiments.

EXPERIMENTAL SETUP
Measurements of friction and temperature on an oscillating pin-bushing assembly are conducted on a friction tester (Lewis Research Inc.; LRI-8H). Figure 1 shows a photo apparatus of the Lewis LRI-8H tester used in experiments. The machine is capable of steady rotational as well as oscillatory motion. In the test rig, the pin is oscillating, while the bushing is stationary. For oscillating mode, the pulleys and belts used for rotation are replaced by a crank-rocker arm (15). The crank arm (15) is connected at the bottom to the DC motor (16) via a jack shaft (19) and to spindle hub (11) at the top. The pin is directly connected to the spindle hub.

THEORETICAL MODEL
In the test rig, the pin is oscillating while the bushing is stationary. Moreover, the contact patch is stationary and is located symmetrically at the point of application of the applied load. The mathematical model derived in [1] is modified to include the convective term in the heat equation for the pin, and implement axial averaging. The resulting equation of heat conduction is quasi-3D. In order to simplify the solution, the ball bearings and load cartridge segments are ignored in the computational model. That is, the outer housing boundary is assumed to be exposed to ambient convective cooling, $h_{e} T_{e}$. See Figure 2.

A Hertzian line contact model is assumed in the theoretical solution. The Hertzian contact pressure for line contact is used for estimating the contact width [2]. A dimensionless thermal model formulation is considered, and a numerical solution is carried out using the Finite Element method.
EXPERIMENTAL RESULTS

Figure 3 shows the temperatures and friction measurements for a steel pin-production bushing pair. Under the conditions tested, the steady state was reached in about 4 hours as seen in Figure 3. An average COF of $\mu_c = 0.12$ was observed throughout the test. Computations were performed with the values of the friction coefficient as input. Presently, the model shows some limitations in its capability to accurately capture the transient behavior of the experiment. Namely, the time constant is lower and generally, larger error is accumulated at locations farther away from the contact.

Work is in progress to include thermomechanical interaction of pin-bushing into the model. It is anticipated that thermal expansion and deformation will play a role in the development of the transient temperature response of the machine.

CONCLUSIONS

The oscillatory behavior of heavily-loaded pin-bushing systems presents a challenging modeling problem. The difficulties in developing an analytical tool for this purpose are compounded by the paucity of available experimental results to guide the theoretical development. This paper reports the initiation of a comprehensive effort toward fulfilling this need. Depending on the magnitude of the applied load and the oscillation speed, the temperature rise at the interface either reaches a steady state or grows rapidly, signifying scuffing failure. Continuous measurement of friction coefficient as a function of time is needed to capture these effects in the model. Also important is consideration of thermomechanical interaction between the pin and the bushing with proper implementation of the expansion/contraction of the surfaces. Work is in progress toward achieving these goals.

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