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Research paper

Numerical investigation on thermal deformation of friction pair in hydro-viscous drive

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HIGHLIGHTS

- Transient thermal deformation model is established.
- Indirect coupling numerical method is developed.
- There are three types of saucer-shaped warping deformation.
- There is one type of wave-shaped warping deformation.
- Deformation size is decided by the location and number of constraints.

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ABSTRACT

Thermal deformation of friction pair has a significant effect on the working performance of hydro-viscous drive. In order to investigate the combined effect of temperature variation and constraints on the thermo-elastic-plastic deformation of friction pair in hydro-viscous drive during the soft-start, transient thermal deformation model is established for numerical simulation. Thermo-elastic-plastic constitutive equations coupled with thermal strain and mechanical strain are described in detail. Using the constitutive equations derived, indirect coupling numerical method based on the finite element program is developed and used to predict distributions of the temperature, displacement and stress of the disks. The research results show that there are three types of saucer-shaped warping deformation and one type of wave-shaped warping deformation with regard to different constraints. The characteristics of various kinds of displacement and stress are concerned with thermal conductivity and constraints. When the disks are under double constraints, the maximum stress that surpasses the yield stress appears in the disk. When the disks are not under any constraints, minimum stress leads to minimum displacement. To a large extent the deformation size is decided by the location and number of constraints.
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1. Introduction

Hydro-viscous drive (HVD) transmits power by using shear force of oil film, which is a new type of fluid power transmission, and has characteristics of high-efficiency and energy-saving, synchronous drive, small impact and stepless speed regulations. In a typical soft-start, the lubrication regime undergoes a transition from hydrodynamic to mixed or boundary lubrication regime. During the soft-start process, a large amount of frictional heat is generated both due to viscous dissipation and also as a result of interaction of surfaces.

If the disks are not subjected to any restrictions, there is smaller stress in the friction pair in spite of thermal expansion caused by high temperature concentrations. Clearly, excessively large thermal stresses could be set up in the bounding surfaces when thermal deformation is restricted from the outside. Second, large temperature gradient within the friction pair can result in large thermal stress even if it is not subjected to any restrictions. Third, it is assumed that a set of friction pair is composed of one friction disk and one separator disk that are made of different materials. Even if the efficiency of heat conduction within one of the disks is the same as the other, large thermal stress can also be induced by different thermal properties of the materials. Two types of warping deformation can be observed, as shown in Fig. 1, in the special experimental conditions [1].

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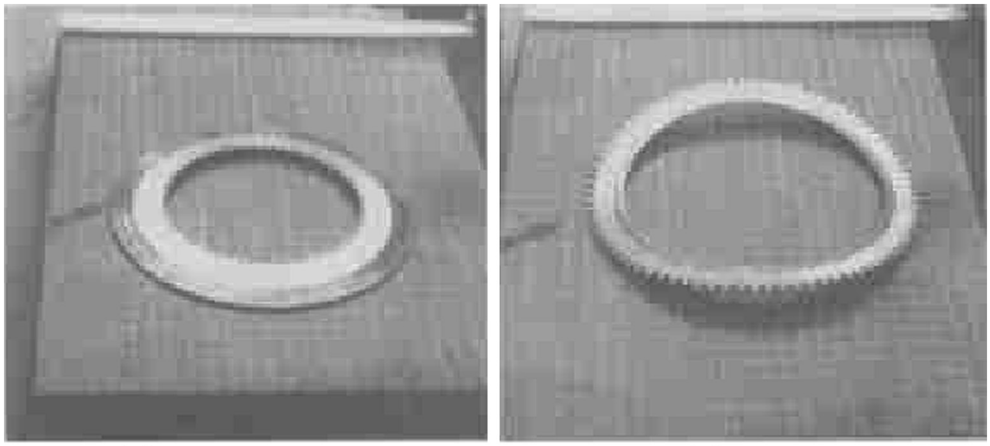

Fig. 1. Two types of warping deformation.

There is a rich volume of archival research publications dealing with the thermoelastic problems. The earliest work in this field can be traced back to Barber [2], who conducted a detail investigation on the mechanism for thermoelastic instability (TEI). Many direct transient simulations on the thermoelastic effects were also performed in various research groups (Zagrodzki et al. [3]; Kennedy and Ling [4]; Afferrante et al. [5]) P. Zagrodzki [6] found that thermal deformations could have a great influence on the distributions of normal pressure on the friction surfaces of a multidisc clutch or a brake. J. Y. Jang [7–12] analyzed the phenomenon of TEI, which was known to be directly related to the occurrence of hot spots in friction systems. It was a failure process where the local frictional heat, thermal expansion, contacting pressure and temperature growed rapidly over a certain critical value of the operating speed. Recent developments of the theory have been in two fronts: a. robust finite element formulation of the problem and construction of an eigen-value system; b. extension of the theory to include surface roughness, lubricant film, and surface porosity [13].

Gao and Barber [14] investigated the effect of different parameters such as roughness, viscosity and grooved area on the engagement process of a wet clutch. Zagrodzki and Truncone [15] investigated hot spotting by thermal analysis, which is an important phenomenon in wet clutches. Marklund and Larsson [16] developed an engineering tool to simulate wet clutches working under boundary lubrication conditions. Their method made it possible to easily and quickly investigate the behavior of wet clutches with a variety of friction materials and groove patterns. Yun-Bo Yi [17] found that dynamic and thermoelastic effects were coupled at low sliding speed in both single-material and multi-material sliding systems but show very weak coupling at speeds above the critical TEI sliding speed in the multi-material systems. Afferrante et al. [18] used a simple elastic layer model confined between thermoelastic and elastodynamic can actually lead to instabilities at an arbitrary small sliding speed. The same research group further attempted to solve the problem considering the effect of the shear wave propagation. They showed that when the frictional shear traction is considered for elastic deformation, different boundary conditions can result in four possible categories of problem cases. Lei Wu et al. [19] found that the wheel/rail friction thermal load had a significant influence on the residual deformation, plastic strain and residual stress at the rail surface. Wang [20] developed approaches combining micro and macro models along the multiscale methods to reduce the computation time and or the mesh density [21]. Jianzhong Cui et al. [22] used transient heat transfer model to analyze the process of the disk's heat conduction. There may not be clear deformation both at the grooved regions and near the grooved regions. However, due to the intensive computations for iterations in the time domain, the transient modeling is only applicable to relatively simple geometries such as one dimensional rod or two-dimensional layers.

As a result, the formation of thermal stresses is thought to be a consequence of thermal disturbance and restrictions. In general, temperature distribution in the disks is almost the same as that in the oil film under certain conditions. First, as the film thickness is relatively small, the oil temperature along the direction of film thickness keeps unchanged when the volume flow rate is large. Furthermore, temperature variations at the grooved regions can be neglected due to negligible tangential velocity.

Secondly, we assume a Gaussian height distribution which is known to be representative of the surfaces of frictional pairs. At any time it is thought that the surface of frictional disk is the same as that of separator disk except the grooved regions. Due to viscous shear and friction, kinetic energy is dissipated into heat. All the frictional heat can be transferred to the contact regions of the disks by means of the boundary conditions of heat flux. Therefore the soft-start process can be seen as a static heat transfer process.

Thirdly, the majority of the analytical papers have restricted their attention to the modeling of single frictional disk or single separator disk. The main disadvantage of the existing analytical models for thermal deformation lies in that almost all the models involved do not consider the squeezed deformation or dislocation deformation caused by small clearance between the disks due to local large thermo-elastic expansion. In this paper, we will focus our attention on a set of frictional pair to analyze the problem of thermal deformation.

2. Thermo-elastic-plastic analysis

To demonstrate the proposed methodology, HVD consists of a series of separator disks and core disks to which friction lining materials are bonded. The core and the separator disks are arranged alternately to a clutch hub that accommodates axial actuation as they are pressed together. The separator disks are generally made of steel and the friction material is a copper-based, typically made of copper and filler particles curved by other metal powder. To assess the effect of temperature disturbance on the thermo-elastic-plastic

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