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Parametric analysis for a paper-based wet clutch with groove consideration

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ABSTRACT

A three-dimensional thermohydrodynamic analysis of a wet clutch is performed that covers the entire cycle of engagement from slip to lock to detachment. The contact condition of the rough surface is formulated by the statistical micro-contact model to incorporate the elastic-plastic asperity contact, which is characterized by the plastic index. Based on the parametric analysis, it is shown that the performance of a wet clutch is influenced by various groove effects. The evolution profile and the distribution of temperature provide insight into the thermal behaviors and the potential application.

1. Introduction

As a crucial component of the transmission system, a wet clutch plays an important role in the automotive industry. Operating under lubricated conditions, a wet clutch's function is to provide smooth power transfer. The key elements of a wet clutch are: several core disks to both sides of which the friction material is bounded, a series of mating separator disks, and automatic transmission fluid (ATF) that lubricates the surfaces, which is shown in Fig. 1. These elements must function in perfect harmony in terms of hydrodynamics, contact mechanics and heat transfer for the transmission system to run smoothly.

From the design and performance analysis viewpoint, the engagement simulation of a wet clutch has always been an important research topic in the tribology where hydrodynamic, elastohydrodynamic, mixed and boundary lubrications modes are all present during the clutch engagement process. Further research interests revolve around durability analysis of the friction material which experiences repeated engagements and disengagements during its life. The necessary step for this purpose is to perform a systematic study of the performance parameters with provision for thermal effects involved during the full engagement cycle from slip to lock and finally detachment of the surfaces.

The most common type of the friction material is a phenolic resin with a porous and deformable structure with rough surface features that resembles a sand paper. The ATF soaked into the friction material is squeezed out by the engagement load, which partially improves the heat transfer mechanism by its cooling action. The use of a pertinent groove type and profiles on the friction material allows control of temperature rise and reduction of degradation and wear.

Modeling and simulations of clutch engagement have been investigated by many researchers. Since previous publications and results are abundant, only a brief review of most pertinent research is presented here. Natsumeda et al. carried out one of the first theoretical analysis and hydrodynamic simulation of a paper-based wet clutch with consideration of permeability, compressive strain, and asperity contact [1,15]. Yang et al. [2] provided mathematical models with similar considerations and verified the results with experimental measurements favorably. Based on Natsumeda's work, Jang and Khonsari [3] developed a comprehensive model by adding the slip boundary and centrifugal terms in the hydrodynamic equation. They developed the three-dimensional heat transfer equations to predict the temperature field, during the engagement stage. Later, the effects of groove including the radial and waffle type are discussed based on the 3-D thermohydrodynamic analysis [4]. These papers concentrated on the first stage of the engagement process, i.e. from the initial squeeze to lock-up. Furthermore, in these papers, the surface roughness was modeled using the Greenwood and Williamson asperity contact model (GW), which is restricted to elastic deformation. Recently, Kogut and Etsion [5] developed an elastic–plastic model (KE) for the contact of rough surface by the finite element analysis to incorporate the full regime of asperity contact. Since

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Nomenclature

a	inner radius of the disk (m)
A_r	real area of contact per unit nominal area
b	outer radius of the disk (m)
d	thickness of the friction material (m)
d_c	thickness of the core disk (m)
d_s	thickness of the separator disk (m)
α	spiral groove angle (rad)
E	Young's modulus (Pa)
ν	Poisson's ratio
E'	effective Young's modulus (Pa)
E_1	Young's modulus of steel (Pa)
E_2	Young's modulus of friction material (Pa)
K	hardness factor
H	hardness of friction material (MPa)
y_s	distance between the mean of summit heights and that of the surface heights (m)
$\overline{\varpi}$	dimensionless interface
z^*	dimensionless asperity height
β	asperity radius (m)
σ_s	standard deviation of surface heights (m)
E_r	elastic coefficient for real area of contact (Pa)
f	friction coefficient
h	film thickness (m)
$\overline{h}$	dimensionless film thickness
h_{gr}	groove depth (m)
h_{oi}	initial film thickness (m)
H_g	groove depth ratio
h_T	average gap (m)
I	mass moment of inertia (kg m^2)
k	thermal conductivity (W/m K)
L	the length of computation domain in θ direction
m	permeability (m^2)
n	number of grooves
N	rotational speed (rpm)
N_w	waviness number
P_c	contact pressure (Pa)
$\overline{P}_c$	dimensionless contact pressure
P_h	hydrodynamic pressure (Pa)
$\overline{P}_h$	dimensionless hydrodynamic pressure
P_o	average load per unit area (Pa)
q	frictional heat flux (W/m^2)
q_b	frictional heat flux into friction material (W/m^2)
q_s	frictional heat flux into separator disk (W/m^2)
r	coordinate in radial direction (m)
t	time (s)
T_c	torque due to contact pressure (N m)
T_h	torque due to hydrodynamic pressure (N m)
T	total torque (N m)
W_h	average load supported by hydrodynamic pressure per unit area (Pa)
W_c	average load supported by asperity contact pressure per unit area (Pa)
z	coordinate in axial direction (m)
ε	compressive strain
ξ	error tolerance
ϕ	ratio of grooved area to total area
ϕ_r, ϕ_θ	pressure flow factors in radial and circumferential directions
ϕ_s	shear flow factor
ϕ_f, ϕ_{fs}	shear stress factors
γ	asperity tip radius (m)
η	number of asperities per unit area (m^{-2})
κ	thermal diffusivity (m^2/s)
λ	aspect ratio of groove
μ	viscosity (Pa s)
μ_i	initial viscosity (Pa s)
θ	coordinate in circumferential direction (rad)
ρ	density (kg/m^3)
σ	rms roughness
ω_L	angular speed of separator disk
ω_H	angular speed of friction material
Θ	temperature (°C)
$\overline{\Theta}$	dimensionless temperature
Θ_i	initial temperature (°C)
Θ_∞	ambient temperature (°C)

Subscripts

i	initial value
s	separator disk
f	lubricant
b	friction material
c	core disk
∞	ambient

the determination of contact pressure plays a significant role in the engagement simulation, consideration of the elasto-plastic and plastic behavior of the surfaces warrants further investigation.

The study of thermal effects on the performance of wet clutch has received much attention in the literature from several viewpoints such as the influence on torque transfer [19] and on the duration of the engagement time [20]. However, investigation of important tribological performance associated with friction material degradation and frictional instability requires one to first perform a comprehensive analysis for the temperature history during the full engagement cycles. This is the subject of the present study.

In the present paper, a parametric analysis of a wet clutch is presented using the following procedure: the groove geometry is considered by including the variation of film thickness over the planar domain; micro-contact condition of asperities for the rough surface are described by KE model; the thermal behavior of a wet clutch is predicted that spans the entire operation cycles, including engagement, soaking, dwell, and stabilization periods. Results and discussions are presented to probe into the analysis of different factors influencing the engagement performance. Also presented is a discussion on the temperature evolution during the entire engagement cycle and the role of different energy levels.

2. Theory

2.1. Entire cycle of clutch operation

Generally, the operation states of a wet clutch can be divided into three phases: slip, locked, and detached. In terms of lubrication of the separator disk and the friction lining interface, the complete cycle translates into the engagement stage, soaking period, dwell period, and stabilization period [6].