Dynamic Friction Behavior of Paper-Based Wet Friction Material Subjected to Contact Pressure Fluctuation

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In this research, dynamic friction behavior of paper-based wet friction material subjected to contact pressure fluctuation was investigated experimentally and theoretically. Complex friction coefficient obtained by the ratio between dynamic components of friction and normal force was defined as an index of dynamic friction characteristics. First, the frequency dependence of complex friction coefficient was measured changing the contact surface dimension and compressive modulus of specimen as parameters. As a result the amplitude and phase angle of complex friction coefficient decreased with the increase of pressure fluctuating frequency and this tendency was significant for larger dimension and for lower modulus. Then, calculations were done combining the stress-strain analysis with an analytical model based on the theory of poroelasticity and the assumption in which the solid part at contact surface only contributed to friction. It was found that the increase in load sharing ratio by fluid caused by the flow resistance made the solid contact relaxed and delayed, which resulted in the decrease in amplitude and phase angle of complex friction coefficient. The calculated results showed similar tendency to the experimental ones, thereby the analytical model was appropriate and the mechanism of dynamic friction behavior of paper-based wet friction material was demonstrated.

Keywords: dynamic characteristics, friction coefficient, paper-based friction material, poroelasticity, pressure fluctuation, wet clutch

1. Introduction

Paper-based friction material for wet clutches in automotive automatic transmissions has netlike structure of fibers. For that reason, it can contain lubricant inside when used in wet condition, and can be deformed easily by external load. When such material is subjected to fluctuating contact pressure, by an interaction between material deformation and fluid flow, the lubricant is carried through the material and is squeezed out and absorbed in at the contact surface, which is considered to have influence to friction behavior. As contact pressure tends to fluctuate in actual clutch operation, this phenomenon might affect the performance and stability of wet clutch systems.

Many studies have been reported concerning friction characteristics of paper-based wet friction material so far [1]. However, engaging process or steady sliding was targeted in most cases, and there have been no research works dealing with pressure fluctuation. As a study in similar situation, Kaneko et al. examined the characteristics of a rotating porous rubber block pressed by oscillating force against an impermeable rigid plane [2]. But the condition treated in this study was the one in which oil film was made enough between two surfaces, the interaction between material deformation and fluid flow was not concerned.

One of the authors studied dynamic compression characteristics of paper-based wet friction material where the interacting phenomenon was considered by regarding the paper material containing lubricant inside as a poroelastic body [3]. In the present report, dynamic friction behavior of paper-based wet friction material subjected to contact pressure fluctuation is investigated experimentally and theoretically. Contact surface dimension and compressive modulus are chosen as parameters to examine the effect of the lubricant behavior at contact surface. Then, comparing the both results, mechanism of dynamic friction behavior is discussed.
2. Evaluation of Dynamic Friction Characteristics

We consider a body pressed to moving plane with constant velocity. When a harmonically vibrating normal force with an amplitude $N\Delta$ and an angular frequency $\omega$ is applied to the body as Eq. (1), the friction force obtained can be written in the form of Eq. (2) with an amplitude $F\Delta$ and a phase angle $\phi$.

\[ N = N_0 + N\exp[\imath \omega t] \]
\[ F = F_0 + F\exp[\imath(\omega t + \phi)] \]

The ratio between the dynamic components of friction and normal force become a complex constant. As this ratio can be an index representing the friction characteristics in dynamic condition, we define it as complex friction coefficient $\mu$ and express it by the amplitude $\mu'$ and phase angle $\phi$ as follows,

\[ \mu = \frac{AF\exp[i(\omega t + \phi)]}{AN\exp[i\omega t]} = \frac{AF}{AN}\exp[i\phi] = \left| \mu' \right| \exp[i\phi] \]

3. Experiment

3.1. Specimens and Apparatus

![Figure 1](shape_and_dimension_of_specimen.png)

Fig. 1 Shape and dimension of specimen

![Figure 2](experimental_apparatus.png)

Fig. 2 Experimental apparatus

Experiments were performed under the conditions shown in Table 1. Contact surface dimension was changed at three levels, on the basis of 5 mm, to 3 mm and 7 mm. In addition, compressive modulus was also changed at three levels, on the basis of 200 MPa, to 70 MPa and 350 MPa. It can be set by changing the mean contact pressure on the basis of 1.0 MPa, to 0.25 MPa and 2.0 MPa by using the nonlinear pressure-strain relation as explained in Fig. 3. Harmonically vibrating pressure with the amplitude of 0.1 MPa was applied, changing the exciting frequency from 1 to 30 Hz. The underlines seen in the table indicate standard conditions. A commercial ATF (Automatic Transmission Fluid) was used as lubricant and all experiments were done at room parameter. Thickness of specimen is fixed to 0.5 mm.

![Figure 3](nonlinear_pressure-strain_relation.png)

Fig. 3 Nonlinear pressure-strain relation and change in compressive modulus. Compressive modulus for small vibration $E$ can be adjusted by changing mean contact pressure $p_0$ by using nonlinear relation between pressure $p$ and strain $\varepsilon$.

<table>
<thead>
<tr>
<th>Contact surface dimension $a$ [mm]</th>
<th>3, 5, 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive modulus $E$ [MPa]</td>
<td>70, 200, 350</td>
</tr>
<tr>
<td>(Mean contact pressure $p_0$ [MPa])</td>
<td>(0.25, 1.0, 2.0)</td>
</tr>
<tr>
<td>Frequency $f$ [Hz]</td>
<td>1 ~ 30</td>
</tr>
</tbody>
</table>
temperature between 15 and 20°C under constant sliding velocity of 0.33 m/s (velocity for rotational speed 40 rpm at radial position 80 mm).

Figure 4 is the experimental result showing the frequency dependence of complex friction coefficient. Fig. 4(a) shows the effect of contact surface dimension. The amplitude of complex friction coefficient changed with the exiting frequency in various ways. However, the change became more decreasing for larger contact surface. The phase angle decreased with frequency more also for larger contact surface. Fig. 4(b) shows the effect of compressive modulus. The tendency that the amplitude and phase angle decreased with frequency became more significant for lower modulus.

The results above can not be explained without the condition change at contact surface by lubricant behavior. Thus, the dynamic friction characteristics peculiar to poroelastic material like paper-based friction material containing lubricant inside were recognized experimentally. From these two cases, largeness of contact surface and compliance of material were experimentally. From these two cases, largeness of contact surface and compliance of material were recognized experimentally. From these two cases, largeness of contact surface and compliance of material were demonstrated to have the same effect in this tendency. According to the fact, it is supposed that flow resistance of the internal lubricant inside the paper-based friction material became larger in those conditions and that simultaneous fluid pressure rise made the solid contact relaxed and delayed.

4. Theoretical Analysis

4.1. Theoretical Treatment

To account reasonably for the experimental results obtained above, dynamic friction behavior of paper-based friction material is investigated theoretically combining the stress-strain analysis of poroelastic material under dynamic condition and the evaluation of friction force considering load sharing between solid and fluid at contact surface. Since the consideration is done under some particular assumptions to obtain an analytical solution of this problem, these assumption may not be suitable for the actual experimental situation. However, the aim of this investigation is to certify the effect of some parameters on the dynamic friction behavior qualitatively, and some discrepancy in the assumption is not so significant for this purposes.

As shown in Fig. 5, two dimensional deformation of a poroelastic slab of width \( a \) and thickness \( h \) is considered when it is put between two rigid impermeable planes and subjected to harmonic compression with an amplitude \( w_0 \), and an angular frequency \( \omega \) on the top surface. Poroelastic material is a two-phase, solid-fluid aggregate. The solid material forms the skeleton which has small interconnected pores filled with fluid. The skeleton is linearly elastic, and the fluid is viscous and compressible. The dynamic characteristics of poroelastic material was formulated by Biot [4,5] taking into account both dissipative and inertia effects. In this study, quasistatic treatment is taken for this formulation neglecting the inertia term as

\[
GV^2\mathbf{u} + (A + G)\varepsilon - \text{grad}p_f = 0
\]  

\[
\alpha \text{grad}p_f = \frac{\eta_0 \alpha^2}{\beta} \frac{\partial}{\partial t} (\mathbf{u} - \mathbf{U})
\]

\[
p_f = -K_f \left( \frac{1 - \alpha}{\alpha} e_s + e_f \right)
\]

\[
\text{Stress-free boundary}
\]

\[
\text{Impermeable rigid plane}
\]

\[
\text{Poroelastic body}
\]

\[
\text{Viscous fluid}
\]

\[
\text{Fig. 4 Frequency dependence of complex friction coefficient (experiment)}
\]

\[
\text{Fig. 5 Analytical model of paper-based wet friction material}
\]
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where \( u = (u, w) \) and \( U = (U, W) \) are the displacement of the solid and fluid, respectively, \( e_r = (\text{div } u) \) and \( e_f = (\text{div } U) \) are the volumetric strain of the solid and fluid, respectively, and \( p_f \) is the fluid pressure. As for the solid skeleton, \( G \) and \( A \) are Lamé's elastic constants, \( \alpha \) is the porosity and \( \beta \) is Darcy's coefficient of permeability, while as for the fluid, \( K_f \) is the bulk modulus and \( \eta_f \) is the viscosity. Eqs. (4) and (5) are the equilibrium equations considering the interaction between solid and fluid due to flow resistance, and Eq. (6) is the continuity relation. Taking the divergence of Eq. (5) and using the relation (6) to eliminate \( e_f \), the following equation is obtained:

\[
\nabla^2 p_f = \frac{\eta_f \alpha}{\beta} \frac{\partial}{\partial t} \left( p_f + \frac{\epsilon_r}{\alpha} \right)
\]  

(7)

The boundary conditions for this problem are given by

\[
p_f \bigg|_{t=a/2} = 0
\]

(8)

\[
\sigma_r \bigg|_{t=a/2} = \left[ 2G e_r + \Lambda e_r - (1-\alpha) p_f \right] \bigg|_{t=a/2} = 0
\]

(9)

\[
\frac{\partial \tau}{\partial z} \bigg|_{z=0, h} = 0
\]

(10)

\[
u_{l\to h} = 0
\]

(11)

\[
u_{l\to w} = 0
\]

(12)

\[
u_{h\to w} = w_o \exp[0.5\omega t]
\]

(13)

\[
\frac{\partial e_r}{\partial z} = \frac{\partial^2 w}{\partial z^2} = 0
\]

(14)

\[
\gamma = \frac{\partial u}{\partial z} = \frac{\partial w}{\partial x} = 0
\]

(15)

The set of equations (4) and (7) can be solved analytically with the boundary conditions (8) to (14) and the assumptions (15) and (16) [3]. The solution becomes

\[
u = 0
\]

(17)

\[
v = \frac{w_o}{h} \exp[0.5\omega t]
\]

(18)

\[
p_f = \frac{k_o w_0}{k_h} \left[ \cosh(\alpha h) \right] \left[ \cosh(\alpha x / 2) \right] \exp[0.5\omega t]
\]

(19)

where

\[
k_o = \frac{2G}{\alpha^2 (A + 2G)}
\]

(20)

\[
k_i = \frac{\eta f}{\beta} \left( \frac{1}{A + 2G} + \frac{\alpha}{K_f} \right)
\]

(21)

\[
\kappa = (1 + i)\sqrt{\frac{\alpha k_i}{2}}
\]

(22)

Solid contact pressure \( p_c \) and fluid pressure at contact surface \( p_f \) are obtained by the result of stress-strain analysis of poroelastic material as follows:

\[
p_f = \left[ 1 - \alpha \right] \left[ (2G \epsilon_c + \Lambda \epsilon_r) - \alpha p_f \right] \bigg|_{t=0}
\]

(23)

\[
p_f = p_f \bigg|_{t=\infty}
\]

(24)

The ratio of solid contact area is set constant of \( 1 - \alpha \) which is the same value as the inside of material because surface geometry like roughness is not considered at contact surface in this analytical model. Giving the friction coefficient at solid contact part \( \mu_s \), complex friction coefficient \( \mu' \) can be estimated as the expectation value weighted by load sharing ratios of solid and fluid parts, i.e. under the assumption in which the solid part at contact surface only contribute to friction,

\[
\mu' = \frac{\mu_s(1-\alpha) p_c + \mu_s \alpha p_f}{p_c + p_f}
\]

(25)

4.2. Calculation and discussions

Several calculations were done fitting the constants to the experimental ones. Table 2 shows the constants used here. Lamé's modulus \( A \) was set to 0 because the Poisson’s ratio was supposed to be close to 0. Shear modulus \( G \) was decided from compressive modulus \( E \) to be set using the relation between elastic moduli in isotropic linear elastic body. Viscosity of lubricant \( \eta_f \) was specified referring to the measured value at 20°C which is close to the experimental temperature. Friction coefficient at solid contact part \( \mu_s \) was set to 0.2 in the reference of actually measured value. For other parameters, typical values were chosen.

Figure 6 is the calculated result showing frequency dependence of complex friction coefficient. Generally speaking, the amplitude of complex friction coefficient \( \mu' \) decreases with the increase of exciting frequency.

<table>
<thead>
<tr>
<th>Paper-based friction material</th>
<th>Contact surface dimension ( a ) [mm]</th>
<th>3, 5, 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear modulus ( G ) [MPa]</td>
<td></td>
<td>35, 100, 175</td>
</tr>
<tr>
<td>Lamé's modulus ( A ) [MPa]</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Darcy's permeability ( \beta \times 10^{-12} \text{ m}^2 / \text{s} )</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Porosity ( \alpha )</td>
<td></td>
<td>0.55</td>
</tr>
<tr>
<td>Lubricant</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Viscosity ( \eta_f ) [mPa·s]</td>
<td></td>
<td>56</td>
</tr>
<tr>
<td>Bulk modulus ( K_f ) [GPa]</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Others</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Friction coefficient at solid contact part ( \mu_s )</td>
<td>0.2</td>
<td></td>
</tr>
</tbody>
</table>

Table 2  Constants for calculation
The phase angle $\phi$ also decreases with frequency. This tendency is considered to occur by the following reason: For higher frequency, flow resistance of lubricant becomes larger, and it causes larger load sharing ratio by fluid and relatively smaller one by solid, which leads to lower amplitude of complex friction coefficient. Then, during harmonically vibrating cycle, the flow resistance changes earlier to material compression because it is proportional to compression velocity, while solid contact changes at the same time as compression displacement. Therefore, when load sharing ratio by fluid becomes large and that by solid becomes small, the phase angle of complex friction coefficient relatively becomes negative.

Fig. 6 (a) and (b) show the effect of contact surface dimension and compressive modulus, respectively. The tendency that the amplitude and phase angle of complex friction coefficient decreases with the exciting frequency is larger for larger contact surface dimension and for lower compressive modulus. Because large dimension and low modulus as well as high frequency are the conditions in which the flow velocity of internal viscous fluid becomes large, the increase in flow resistance is turned out the common cause of these cases. These features is the same as that of the experimental results, and this shows that the analytical model for calculation is valid and the mechanism of dynamic friction behavior of paper-based friction material has been demonstrated.

5. Conclusions

Dynamic friction behavior of paper-based wet friction material subjected to pressure fluctuation was measured as frequency response of complex friction coefficient. Contact surface dimension and compressive modulus of specimen was changed as parameters. From the experimental result, the amplitude and phase angle of complex friction coefficient decreased with the increase of pressure fluctuating frequency and this tendency was significant for larger dimension and for lower modulus. Then, calculations were done combining the stress-strain analysis with an analytical model based on the theory of poroelasticity and the assumption in which the solid part at contact surface only contributed to friction. It was found that the increase in load sharing ratio by fluid caused by the flow resistance made the solid contact relaxed and delayed, which resulted in the decrease in amplitude and phase angle of complex friction coefficient. The calculated results showed similar tendency to the experimental ones, thereby the analytical model was appropriate and the mechanism of dynamic friction behavior of paper-based wet friction material was demonstrated.

6. Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>contact surface dimension [m]</td>
</tr>
<tr>
<td>$e_f$</td>
<td>volumetric strain of fluid ($= \text{div } U$) [1]</td>
</tr>
<tr>
<td>$e_s$</td>
<td>volumetric strain of solid ($= \text{div } u$) [1]</td>
</tr>
<tr>
<td>$E$</td>
<td>compressive modulus of solid [Pa]</td>
</tr>
<tr>
<td>$f$</td>
<td>frequency of excitation [Hz]</td>
</tr>
<tr>
<td>$G$</td>
<td>shear modulus of solid [Pa]</td>
</tr>
<tr>
<td>$F$</td>
<td>friction force [N]</td>
</tr>
<tr>
<td>$h$</td>
<td>thickness [m]</td>
</tr>
<tr>
<td>$K_f$</td>
<td>bulk modulus of fluid [Pa]</td>
</tr>
<tr>
<td>$N$</td>
<td>normal force [N]</td>
</tr>
<tr>
<td>$p_c$</td>
<td>solid contact pressure [Pa]</td>
</tr>
<tr>
<td>$p_f$</td>
<td>fluid pressure [Pa]</td>
</tr>
<tr>
<td>$p_{cp}$</td>
<td>fluid pressure at contact surface [Pa]</td>
</tr>
<tr>
<td>$t$</td>
<td>time [s]</td>
</tr>
<tr>
<td>$u$</td>
<td>$(u, w)$</td>
</tr>
<tr>
<td>$u, w$</td>
<td>tangential, normal displacement of solid [m]</td>
</tr>
<tr>
<td>$U$</td>
<td>$(U, W)$</td>
</tr>
<tr>
<td>$U, W$</td>
<td>tangential, normal displacement of fluid [m]</td>
</tr>
<tr>
<td>$w_0$</td>
<td>normal displacement amplitude of excitation [m]</td>
</tr>
<tr>
<td>$x, z$</td>
<td>tangential, normal coordinate [m]</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>porosity [1]</td>
</tr>
</tbody>
</table>
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$\beta$ = Darcy’s permeability [m$^2$]

$\varepsilon_x, \varepsilon_z$ = tensile strain in tangential, normal direction [1]

$\gamma$ = shear strain [1]

$\phi$ = phase angle of friction force to normal force [deg]

$\eta_f$ = viscosity of fluid [Pa·s]

$\Lambda$ = Lamé’s modulus [Pa]

$\mu_s$ = friction coefficient at solid contact [1]

$\mu_f$ = friction coefficient at fluid support [1]

$^*\mu$ = complex friction coefficient [1]

$\sigma_x, \sigma_z$ = tensile stress in tangential, normal direction [Pa]

$\tau$ = shear stress [Pa]

$\omega$ = angular frequency of excitation [s$^{-1}$]

References


