TRANSMITTED POWER AND ENERGY FLOW BEHAVIOR OF DEGRADING WET FRICTION CLUTCHES

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Abstract - Experiments and simulations performed in the framework of accelerated-life tests of wet friction clutches reveal that with the progression of degradation of clutches, the transmitted power decreases together with a change in the energy flow behavior, mainly in the pre-lockup phase. In addition, the engagement duration increases and the relative velocity fluctuation in post-lockup phase changes. These degradation effects are due to the reduction in friction torque and the change in the relative velocity profile caused by the changing friction characteristics of the clutch friction material with degradation. Simulations are performed in a bond graph methodology incorporating an adapted form of the Generalized Maxwell Slip (GMS) friction model, which calculates the friction torque taking into account the dynamic variation in relative velocity and the normal load.

Keywords: *power; energy; friction; degradation; wet friction clutch.*

I. INTRODUCTION

A wet-friction clutch is a mechanical device that transmits power from one component to another through frictional and viscous effects. In recent years, increasing use of wet-friction clutches for various applications has led researchers and engineers across the globe to study and improve the power transmission capacity and energy flow behavior of the wet friction clutches. Power transmission capacity is define as the maximum value of mechanical power that a wet friction clutch is able to transmit, (which is a product of the transmitted torque and the relative velocity), from a driver member to the driven member efficiently and effectively.

Basically, wet friction clutches consist of components like a hub, a drum, separator and friction disc. The friction disc is made of steel with a friction material bonded on both sides, and the separator disc is made of plain steel. To provide the cooling to the clutch while it is in operation, the discs are immersed in an automatic transmission fluid (ATF). The use of ATF reduces the power transmission capacity of the wet friction clutches, due to the reduction in coefficient of friction as compared to the dry clutches [1]. Hence to reach the required power transmission capacity, generally the wet friction clutches are assembled with several pairs of friction and separator disc. The design power transmission capacity is calculated by engineers considering the parameters of a fresh clutch, but as the clutch progresses towards its service life, it degrades. The degradations occurring in wet friction clutches are mainly caused by both friction material and ATF degradation [2]. The objective of this paper is to investigate the effects of degradation of wet friction clutch on the transmitted power and corresponding energy flow behavior through experiments and simulations. Accelerated life tests (ALTs) carried out on wet friction clutches, reveal that with the progression of the clutch degradation, the transmitted power and the corresponding energy flow behavior changes. In addition the engagement duration increases and the relative velocity fluctuation in post-lockup phase (once the clutch is fully engaged) changes [3]. To simulate the above-mentioned degradation effects, a clutch system is modeled, in a bond-graph methodology. The bond-graph approach is considered because of its ability to represent the power and energy flow variables between any two connected components in a simulation environment. An appropriately adapted form of the Generalized Maxwell Slip (GMS) friction model [4] is used in the simulations, in which the dynamic friction torque is not only a function of relative velocity between the hub and the drum of the clutch but also on the pressure acting on the piston. Moreover, as the degradation progresses, the Stribeck behavior and the tangential contact stiffness change [3], together with their respective parameters, this warrants a modification of the corresponding parameters in the friction model in an adaptive manner. The simulation results show that the transmitted power decreases and the corresponding energy flow behavior changes mainly in the pre-lockup phase. The reasons for these effects are explain here. Due to the degradation of clutch, the friction characteristics of the clutch friction material changes, causing a reduction in friction torque and a change in relative velocity profile as a function of engagement duration. Due to these changes the power transmission capacity decreases and the corresponding energy flow behavior mainly in pre-lockup phase changes.

II. EXPERIMENTAL CAMPAIGN

A. *Test setup and accelerated life test description*

An ALT of wet friction clutch is conducted with the support of the industrial partner, Dana Spicer Off

Highway Belgium, on the SAEII test setup. The schematic representation of the test setup is shown in Fig.1, which consists of three main sub-systems: the driveline, the control and the measurement system. The driveline consists of six components: input electric motor, input flywheel, the wet friction clutch assembly which consists of a drum, a hub, separator and friction discs, torque sensor, output flywheel and output electric motor. The control system is used for both controlling the input oil pressure to the clutch and for the velocity control of the input and output flywheel. Two electric motors with independent velocity controllers are used as main drivers. Both motors are connected to the input and the output flywheel by a timing belt transmission. The block scheme and bond graph model of the mechanical and hydraulic part of the SAEII test setup is fully described in [5].

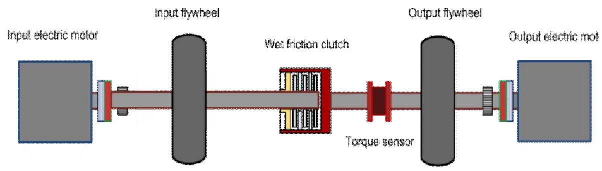
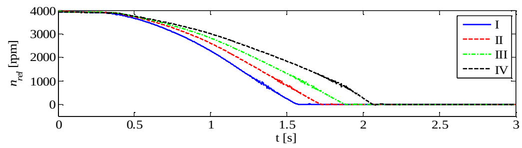


Fig. 1. Schematic representation of the SAEII test setup

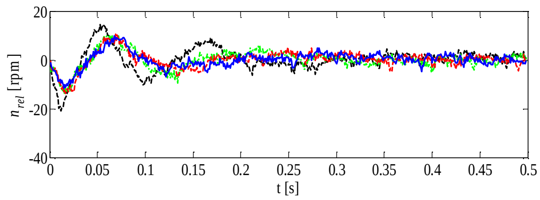
The ALT is carried out as follows. Initially, while both input flywheel (hub side) and output flywheel (drum side) are rotating at the same speed in opposite direction, the motors are powered-off and the pressurized ATF is simultaneously applied to the clutch pack. The oil thus actuates the clutch piston, pushing the friction and separator discs towards each other. While the applied pressure is increasing, contact is gradually established between the separator and friction discs. As a result, the transmitted torque starts to increase to reach its maximum value, and the relative velocity decreases on the other hand. The clutch is completely engaged when the relative velocity reaches zero value for the first time. Finally, at the end of the duty cycle, the applied pressure is reduced to zero. This procedure is repeated until a given number of duty cycles are attained. A multi channel data acquisition system is used to acquire the signal of interest.

B. *Experimental results*

An ALT is carried out on a paper based wet friction clutch. ATF is continuously filtered to preserve the ATF from degradation during the tests. Moreover, the inlet temperature of the ATF during the tests is controlled to be constant at 80 ^{o} C. The pressure signal is kept constant for each duty cycle, since only the effect of the friction material degradation on the transmitted power and corresponding energy flow behavior is the subject under investigation. With given inertias of the input and output flywheel, the only way through which we can apply higher energy level to the clutch system is by having a higher magnitude of the initial relative velocity. We have chosen an initial relative velocity of 4000 rpm, much higher than the normal operating conditions such that significant degradation of the friction material might be observed in a limited number of duty cycles. This initial velocity is also kept constant for each duty cycle. Figure 2(a) show the engagement duration observed during the test. I to IV degradation levels are recorded at 1, 3300, 6600 and 10000 duty cycles. Note that in Fig.2 (a) the signals are plotted with respect to the same reference time instant that is set to zero, i.e. the time instant at which the pressure is applied whereas in Fig.2 (b) the signals for degradation level II, III and IV is shifted to the instant when the relative velocity reaches zero for the first time for degradation level I, which is set to zero. One can clearly see in Fig. 2 that the engagement duration increases and the post-lockup relative velocity fluctuation changes. Post-lockup refers to the time span, starting from the time instant at which the clutch is completely engaged or relative velocity reaches zero for the first time.



(a)



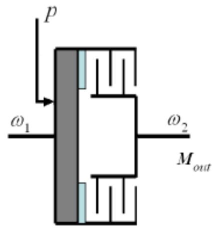
(b)

Fig. 2(a). Engagement duration, (b). Post-lockup relative velocity fluctuation for the degradation levels (Experiments).

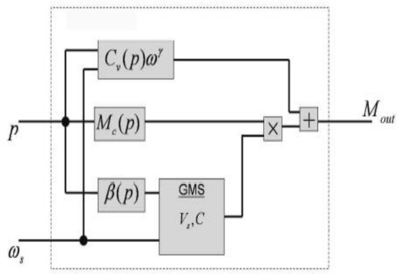
III. ADAPTIVE GMS FRICTION MODEL AND CLUTCH SYSTEM MODEL

A. *The adaptive GMS friction model*

The clutch system incorporates the adapted form of GMS friction model in which some parameters are made pressure (normal load) dependent, which is used to simulate the transmitted friction torque through the clutch [6,7]. Figure 3 represents a schematic diagram of a wet friction clutch, together with the key variables of the model. The friction torque is dependent on the relative velocity $\omega = \omega_1 - \omega_2$, (where ω_1 and ω_2 are the angular velocity of the hub and the drum) and the applied pressure p. The total friction torque M_{out} is the product of the normalized friction torque and the actual Coulomb friction torque M_c, which is dependent on the applied pressure and represents the normal dynamics of the clutch. In addition, the viscous friction torque, having a direct effect, is dependent on the applied pressure and the relative velocity. Note that the parameters of the friction model are correlated with the experimental data, being function of the temperature of the ATF at that time instant. Hence the effect of temperature of the ATF is not directly considered in the friction model. This temperature effect can easily be integrated in the viscous parameter C_v.



(a) **Physical representation of wet friction clutch.**



(b) Adaptive GMS friction model with variable parameters.

Fig. 3(a). Schematic representation of the clutch, (b). the friction model [6]

The structure of the adaptive GMS friction model, assuming quasi static pressure variations (i.e. ignoring pressure dynamics) is as follows:

1. *In sticking:*

$$\frac{dM_{fric}}{dt} = K_t(p)\omega \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..1$$

2. *In sliding:*

$$\frac{dM_{fric}}{dt} = sign(\omega)C\left(1 - \frac{M_{fric}}{s(\omega, p)}\right) \quad \ldots\ldots\ldots\ldots..2$$

with the Stribeck effect $s(\omega, p)$ formulated as:

$$s(\omega, p) = sign(\omega)M_c(p)\left(1 + [\beta(p) - 1]e^{-\left|\frac{Vs}{\omega}\right|}\right) \quad \ldots\ldots\ldots3$$

where,

$$M_c(p) = a_M p + b_M \quad \ldots\ldots4$$

$$\beta(p) = \min(1, \beta_\infty + [1 - \beta_\infty]e^{-\frac{p}{p_0}}) \quad \ldots\ldots5$$

and the viscous torque $M_{vis}(\omega,p)$ being,

$$M_{vis}(\omega, p) = sign(\omega)C_V(p)|\omega|^\gamma \quad \ldots\ldots6$$

where,

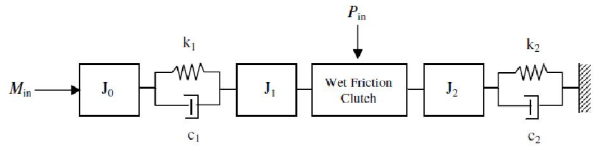
$$C_v(p) = a_c p + b_c \quad \ldots\ldots7$$

Hence, the friction torque M_{out} is given by:

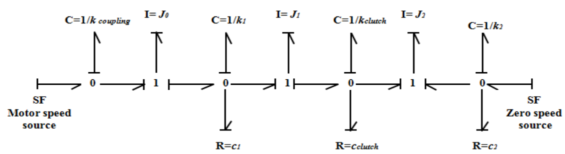
$$M_{out} = M_{fric} + M_{vis}(\omega, p) \quad \ldots\ldots8$$

B. *Clutch system model*

The clutch system model under investigation is modeled using the bond graph approach. The block scheme and the simplified bond graph of the model are shown in Fig. 4 and the parameters of the model are listed in Table I.



(a)



(b)

Fig. 4(a). Block scheme, (b). simplified bond graph of the clutch system

TABLE I.

Parameters	Values
J_0 [kgm^2]	0.5
J_1 [kgm^2]	0.2
J_2 [kgm^2]	0.3
k_1 [Nm/rad]	72000
k_2 [Nm/rad]	400000
c_1 [Nms/rad]	25
c_2 [Nms/rad]	15

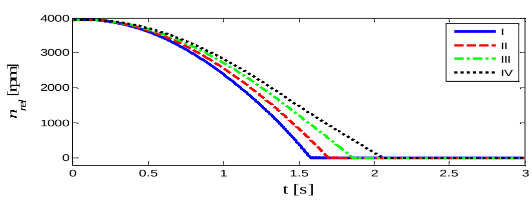
IV. SIMULATION RESULTS AND DISCUSSIONS

In order to study the effect of the degradation process of wet friction clutches on the power transmission and corresponding energy flow behavior, the clutch system model is constructed as explained earlier in section III. The friction model parameters for four degradation levels are listed in Table II. The level I, II, III and IV corresponds to 1, 3300, 6600 and 10000 duty cycles. The parameters at level I are correlated with the experiments carried out on the fresh clutch independently, while all the parameters at other degradation levels are assumed. This assumption is made such as to know the parameters at each degradation level. A dedicated set of experiments are require for parameter extraction, which is not feasible in the presented experimental case. The pressure signal is kept the same for all degradation levels, which consists of a ramp input starting from 0 to 8 bar in 1.43 sec, thereafter held constant until the end of the duty cycle. It is also important to note that although the mechanical structure of the SAEII test setup and the clutch system model under investigation are different, the dynamical parameters, namely relative velocity (n_{rel}) and pressure (p) which are the inputs to the friction model are obtained similarly in both the cases and hence the experimental procedure as explained earlier in section II. The clutch system and friction model explained earlier in the section III are implemented in AMESim® software.

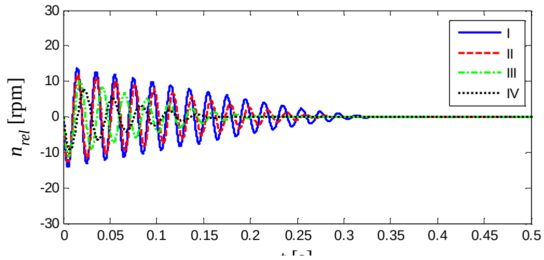
TABLE II.

Parameters	**Value at level**			
	I	**II**	**III**	**IV**
k_t [Nm/rad]	230	220	210	200
a_M [Nm/bar]	40	35	27	18
b_M [Nm]	0.1	0.1	0.1	0.1
a_C [Nm/(rad/s)^3/bar]	1.65	1.63	1.58	1.56
b_C [Nm/(rad/s)^3]	0.01	0.01	0.01	0.01
β_∞ [-]	0.25	0.15	0.10	0.07
p_0 [bar]	0.6	0.6	0.6	0.6
V_s [rad/s]	75	70	65	60
C [s^{-1}]	100	100	100	100
γ [-]	0.50	0.50	0.50	0.50

Simulation results show that the clutch engagement duration (Fig. 5(a)) and the relative velocity fluctuation in the post-lockup phase (Fig. 5(b)) are qualitatively correlated to the experimental results (Fig. 2) at four degradation levels. Note that in Fig.5 (a) the signals are plotted with respect to the same reference time instant that is set to zero, i.e. the time instant at which the pressure is applied whereas in Fig.5 (b) the signals for degradation level II, III and IV are shifted to the time instant when the relative velocity reaches zero for the first time for degradation level I, which is set to zero. This time represents the start of post-lockup time. The simulation results clearly show that the engagement duration increases and the post lockup relative velocity fluctuation changes. The reasons for these changes are explained earlier in section I.



(a)



(b)

Fig. 5(a). Engagement duration, (b). Post-lockup relative velocity fluctuation for the degradation levels (Simulations).

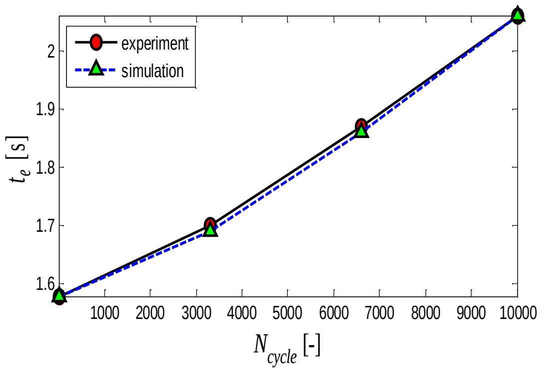


Fig. 6. Experimental and Simulation results of the engagement duration

Fig. 6. shows the engagement duration (t_e) in function of the duty cycles obtained from the experimental and simulation results. Similar observation through simulations and experiments is also reported in [7]. The markers in the figure represent the degradation level I to IV as seen from left to right. The plot shows that a good correlation is achieved between the experimental and simulation results. Also it is clear that the engagement duration increases as the number of duty cycle increases or as the wet friction clutch degrades. The power transmission capacity of the clutch decreases mainly due to the reduction in friction torque, which is due to the change in the friction characteristics of the clutch friction material. The transmitted power (P_t) is calculated using the relative velocity (n_{rel}) and transmitted torque (T_t) signals according to:

$$P_t(kW) = T_t(Nm) \times n_{rel}(rad/s) \times 10^{-3} \quad \text{..........9}$$

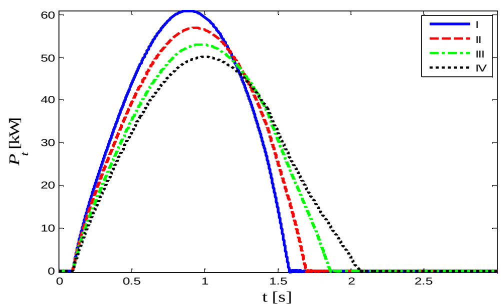


Fig. 7. Transmitted power for the different degradation levels