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Study of Torque Response during Engagement of Wet Friction Clutch

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Abstract

Torque response in wet multi-plate clutch was modelled and studied in most of the study papers. There was a necessity to determine the model with most appropriate and accurate results. In this article an attempt to validate available models using SIMULINK and MATLAB was done. These models were developed using Reynolds equation for rough and permeable surface. Surface roughness, material permeability were some parameters included in such model. Torque response in wet multi-plate clutch was then obtained using force balance and torque balance equations. Since all data required for validation of results was not available in the respective papers, few values had to be assumed. At the same time few equations had to be modified based on the recent study papers to make the result most resembling with the available experimental data in the papers. The nature of plot hence obtained was compared with those provided in the study papers. A final set of equations was then obtained which can then be used for further analysis. Analysis showed that the maximum torque is seen when relative angular velocity is about 85% of its maximum value and 90% of maximum torque is seen to be transmitted at zero relative angular velocity.

Keywords: *Wet clutch, multi-plate clutch, friction, hydrodynamic torque, asperity torque.*

1. Introduction

The wet clutch is a key component in automotive automatic transmission, which can transfer torque from the driving engine to the driven wheel. Torque is transmitted from driving plate to driven plate when the two plates come closer and closer. At the same time if the clutch is a wet type, the viscosity of oil present in between also accounts for the hydrodynamic or also named as viscous torque. This is an additional torque component seen in case of wet type clutches than just a dry type clutch. Total torque is thus the addition of hydrodynamic torque and asperity torque. Hence torque response prediction in such wet multi-plate clutches is a bit complicated problem with multiple factors affecting the response.

To make the analysis a bit simpler the effect of change of viscosity of fluid due to change of local fluid temperature is neglected in further analysis.

1.1 Literature Review

To predict the torque response during engagement of wet friction clutches a model and computer program was developed. Such modified model for prediction of the torque response during engagement of wet friction clutches included the effect of liquid permeability, Young's modulus of friction material. It also considers the RMS surface roughness, slip factors, asperity tip radius and asperity density. The effect of friction materials properties and parameters on the torque curve are studied in this paper. Validation through experimentation for various operating conditions is done in this paper.(Yubo, 1998)

Similar study in another paper was done. In this paper a different modification of Reynolds equation was used. The influence of different oil viscosities on torque response during engagement of wet friction clutches was studied. Viscosity determines the viscous torque, which is the major torque that drives the steel plate at the beginning of engagement.(Guoqiang, 2012)

Influence of permeability of friction material on the torque response during engagement of wet friction clutch was also studied. Lower permeability makes the oil difficult to squeeze into the friction material, causing longer engagement time.(Guoqiang, 2012)

When influence of applied pressure on torque response was studied, it was seen that, there is rapid decrease in oil film thickness with high applied pressure. The asperity force and torque increase when the oil film thickness reaches its constant value, further shortening the engagement time.(Guoqiang, 2012)

2. Theory of Clutch Engagement Torque Response

Fig.1 shows a simple powertrain system with the location of clutch in the system. Few of the dimensional parameters required during prediction of the torque response are show in the figure.

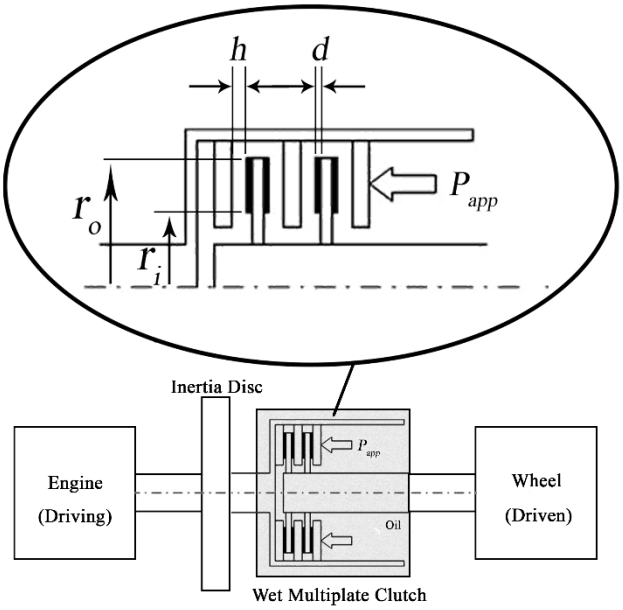


Fig.1 Wet multi-plate clutch system

2.1 Total Torque

The total torque that is been transmitted is the resultant of the sum of two different torques viz. Hydrodynamic torque and Asperity torque. Hydrodynamic torque is the one which is on account of motion of fluid present in between the clutch plates (rotating driving plate and the driven plate) even when they are not in contact. Just when the two plate asperities come in contact, the second component of torque is developed. This component is Asperity torque.

Total torque can thus be mathematically written as:

$$T = T_h + T_a \tag{2.1.1}$$

Where,
T = Total Torque,
T_h = Hydrodynamic Torque,
T_a = Asperity Torque.

Hydrodynamic torque can be determined by equation as below.

$$T_h = \frac{\pi}{2}\mu N_f \frac{\omega_{rel}}{h}\left(r_o^4 - r_i^4\right) \tag{2.1.2}$$

Where,
T_h = Hydrodynamic Torque,
μ = Viscosity,
N_f = Number of friction surfaces,
ω_{rel} = Relative angular velocity,
h = Instantaneous film thickness,
r_o = Lining outer radius,
r_i = Lining inner radius.

Asperity torque can be calculated by using the below equation.

$$T_a = \frac{2}{3}\pi\mu_f N_f P_a\left(r_o^3 - r_i^3\right) \tag{2.1.3}$$

Where,
T_a = Asperity Torque,
μ_f = Viscosity
P_a = Asperity Pressure

2.2 Film Thickness

The film thickness required in the above Torque equations is obtained using the modified Reynolds equation. Such approximate Reynolds equation for rough and permeable surfaces can be written as,

$$\frac{d\hat{h}}{dt} = -\frac{\xi(\hat{h})\delta(\hat{h})}{g(\hat{h})A_{red}}\gamma\hat{h}^3 \tag{2.2.1}$$

Where,

$$\hat{h} = \frac{h}{h_o} \tag{2.2.2}$$

h_o = Initial film thickness
A_{red} = Landed Area Percentage

The dimensionless term $\xi(\hat{h})$ in the equation 2.2.1 can be defined as:

$$\xi(\hat{h}) = \frac{P_{app} - P_a(\hat{h})}{P_{app}} \tag{2.2.3}$$

$$P_a = E\frac{A_R}{A_N} \tag{2.2.4}$$

$$\frac{A_R}{A_N} = \frac{2}{3}\pi N\beta\sigma\left(\frac{\sigma}{\beta}\right)^{\frac{1}{2}} F_{1.5}\left(\frac{h}{\sigma}\right) \tag{2.2.5}$$

$$F_l\left(\frac{h}{\sigma}\right) = \frac{1}{\sqrt{2\pi}}\int_{\frac{h}{\sigma}}^{\infty}\left(s - \frac{h}{\sigma}\right)^l e^{\left(-\frac{s^2}{2}\right)} ds \tag{2.2.6}$$

Where,
P_{app} = Applied Pressure
Pa =Asperity Pressure
E = Young's Modulus
A_R = Real contact area
A_N = Lining surface area
N = Asperity density
β = Asperity tip radius
σ = Lining RMS roughness

The dimensionless term $\delta(\hat{h})$ in the equation 2.2.1 can be defined as:

$$\delta(\hat{h}) = \frac{\hat{h}^3(1-3\eta)+12\hat{K}_{perm}\hat{d}}{\hat{h}^3} \quad (2.2.7)$$

$$\eta = \frac{1}{1+\chi^{\frac{h}{\sqrt{K_{perm}}}}} \quad (2.2.8)$$

Where,
η = Slip factor
K_{perm} = Lining Permeability
χ = Slip coefficient

The dimensionless term $g(\hat{h})$ in the equation 2.2.1 can be defined as:

$$g(\hat{h}) = \frac{1}{2}\left[1+erf\left(\frac{\hat{h}}{\sqrt{2}\hat{\sigma}}\right)\right] \quad (2.2.9)$$

$$erf(x) = \int_0^x \frac{2}{\sqrt{\pi}} e^{(-t^2)} dt \quad (2.2.10)$$

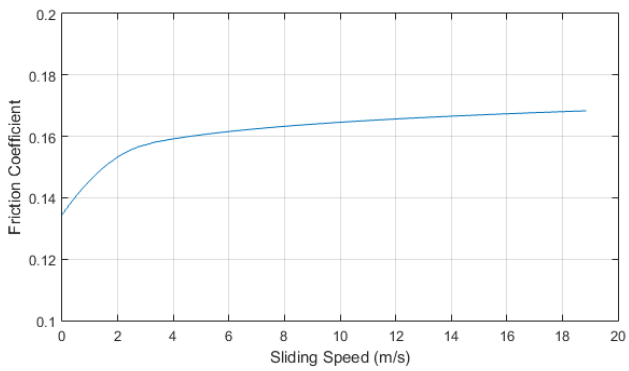
The dimensionless term γ in the equation 2.2.1 can be defined as:

$$\gamma = \frac{P_{app} h_o^2 r_o^4}{12\mu r_i^2 Q} \quad (2.2.11)$$

$$Q = \int_{r_i}^{r_o} \frac{r^2 + (r_o - r_i)^2 \frac{\ln(r/r_o)}{\ln(r_i/r_o)}}{4} r dr \quad (2.2.12)$$

2.3 Friction Coefficient

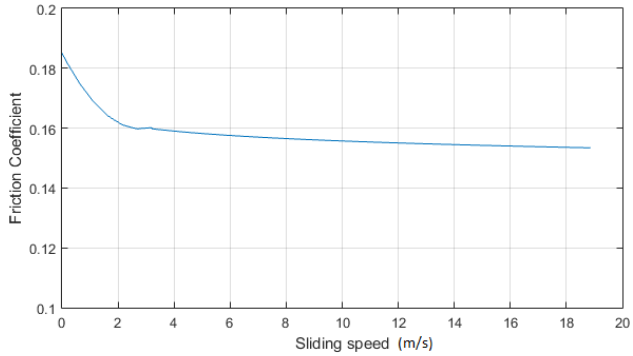
For the analysis purpose we will be considering two different coefficient of frictions as below:



Graph.1 Friction coefficient as function of sliding speed using equation 2.3.1

$$\mu_f = \begin{cases} 0.1345 + 0.013v + 0.0018v^2 .....v < 3.2m/s \\ 0.151 - 0.0059\log(v).....otherwise \end{cases} \quad (2.3.1)$$

The Graph.1 clearly shows an initially rapid rise in the coefficient of friction till sliding speed reaches 3.2 m/s, then the rate of change of coefficient of friction with sliding speed is constant and positive.



Graph.2 Friction coefficient as function of sliding speed using equation 2.3.2

$$\mu_f = \begin{cases} 0.185 - 0.018v + 0.0032v^2 .....v < 3.2m/s \\ 0.164 - 0.0036\log(v).....otherwise \end{cases} \quad (2.3.2)$$

In Graph.2 we find initial rapid drop in the coefficient of friction till sliding speed reaches 3.2 m/s, then the rate of change of coefficient of friction with sliding speed is constant and negative.

2.4 Torque Response

To determine torque response based on these torque equations, we need to equate the torque equation with the equation of motion. Thus we prepare a force balance equation as below:

$$T = I\frac{d\omega_2}{dt} \quad (2.4.1)$$

3. Parameters used in Model Simulation

Table 1 Parameters used in Model Simulation

PARAMETERS	NOTA-TION	UNIT	VALUE[1]	VALUE[2]
Number of Friction Surfaces	N_f	units	6	-
Lining Outer Radius	r_o	m	0.0731	0.114
Lining Inner Radius	r_i	m	0.0603	0.086
Landed Area Percentage	A_{red}	%	79	78
Lining Thickness	D	m	0.00056	0.001
Applied Pressure	P_{app}	Pa	826000	$1x10^6$

Lining Young's Modulus	E	Pa	$600x10^6$	$4840x10^6$
Lining Permeability	K_{perm}	m	$0.05x10^{-12}$	$4x10^{-12}$
Asperity Density	N	m^{-2}	$25x10^6$	$70x10^6$
Asperity Tip Radius	B	m	$0.15x10^{-3}$	$0.8\ x10^{-3}$
Lining RMS Roughness	σ	m	$8.4\ x10^{-6}$	$9\ x10^{-6}$
Initial Film Thickness	h_o	m	0.0001	0.0001
Moment Of Disk Inertia	I	$Kg.m^2$	0.701	1
Initial Rotating Speed	ω_o	rpm	2700	1200

The parameters used for validation of the torque response equations were picked from the reference papers.

4. MATLAB and SIMULINK model

The above equations in the torque theory were modelled in SIMULINK and MATLAB. Since SIMULINK has limitation of solving definite integral, few terms in the equations had to be solved using MATLAB to create a lookup table which was then considered as know graph in the SIMULINK model.

4.1 Input Data Collection

The first MATLAB program was to collect input parameter values. These values were then fed to SIMULINK model for analysis.

4.2 Lookup table for $F_l(h/\sigma)$

$F_l(h/\sigma)$ term had to be calculated using equation 2.2.6. This equation contains definite integral term. Hence use of MATLAB program was done to calculate value of $F_l(h/\sigma)$ for (h/σ) value varying from 0 to 4 at the step of 0.1. The rest of the values are interpolated when used in the SIMULINK model.

4.3 Calculating Q term

Q term in equation 2.2.12 had to be determined using MATLAB program since it included definite integral term. A particular value obtained was then used in the model.

4.4 Calculating g(h) term

The g(h) term was again a function of error function which can be determined using already available table for error function or solving definite integral. Here method of solving definite integral was used.

4.5 Simulink model for torque response

The complete SIMULINK model is represented in Fig.2. This model has a subsystems. Those which are important are represented in Fig.3.

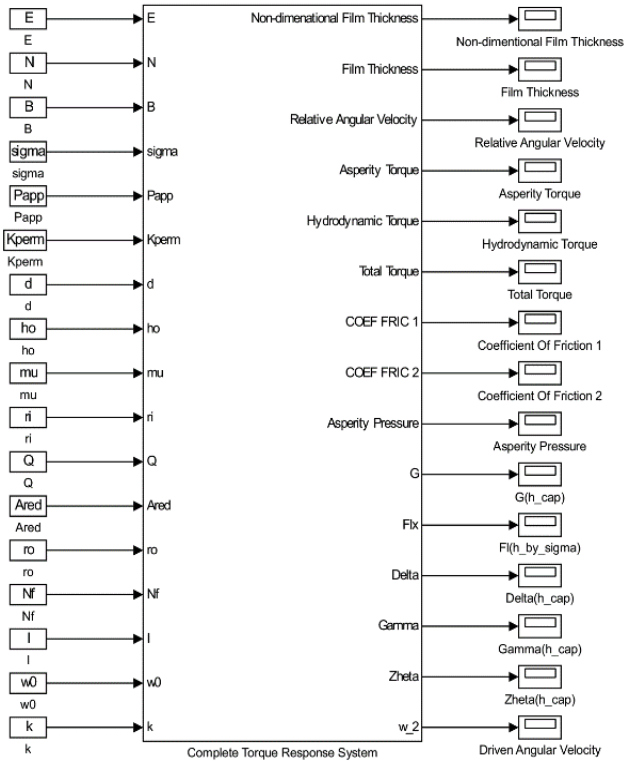


Fig.2 Complete Torque Response System in SIMULINK

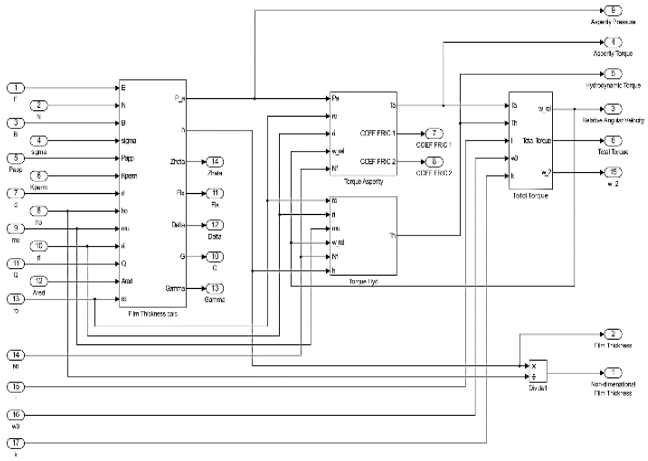


Fig.3 Complete Torque Response Sub-System

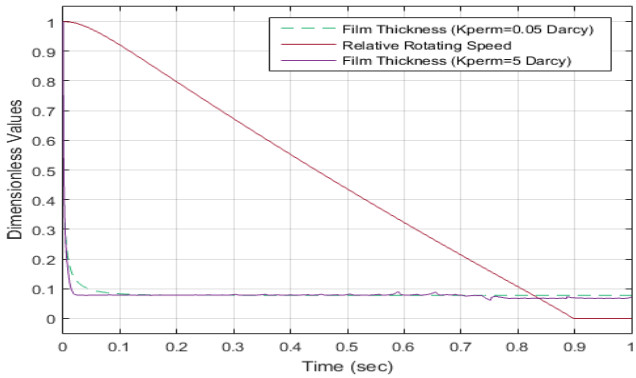
5. Results and Discussion

The MATLAB programs mentioned above were run first to get the initial values [1] required for SIMULINK. The results required for comparison of data in previous study papers was obtained through multiple SIMULINK runs. The results obtained can be presented according to different categories as below.

5.1 Coefficient of Friction

The Graph.1 and Graph.2 are the graphs obtained after simulation. These graphs were found to resemble to great extent with the graphs in previous study papers.[1]

5.2 Film Thickness and Relative Angular Velocity as function of Time



Graph.3 Film Thickness and Relative Angular Velocity as function of Time

The plot shown in the Graph.3 shows that the dimensionless film thickness drastically drops initially (from 1) and then reaches a minimum value (approximately 0.08) that remains constant further. When the same program was run for two different permeability values it was seen that film thickness drops at a higher rate for higher permeability values. When permeability value was 0.05 Darcy, the time required for the film thickness to reach the constant minimum value was 0.1 sec and for 5 Darcy it was approximately 0.02 sec. But in both cases dimensionless film thickness stabilizes at the constant value of 0.08.

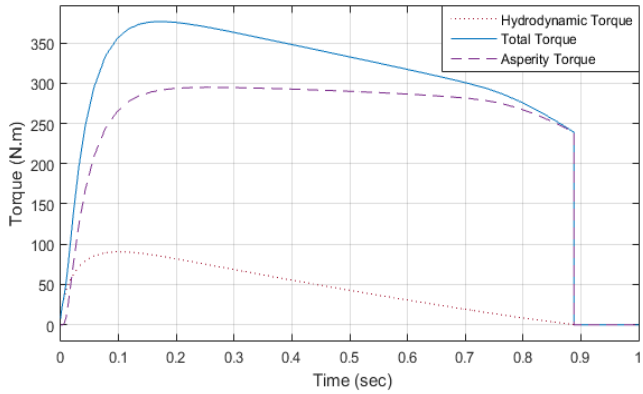
There is a gradual linear drop seen in the relative velocity till it reaches zero at 0.9 sec. Which means that the velocity of driven plate approaches and gains the velocity that of the driving plate.

5.3 Hydrodynamic, Asperity and Total Torque as function of Time using COF represented by equation 2.3.1

As we know that the Total torque is sum of asperity and hydrodynamic torque, the Graph.4 clearly shows the same. It is the plot obtained for the rising nature of coefficient of friction with increasing sliding velocity as shown in Graph.1.

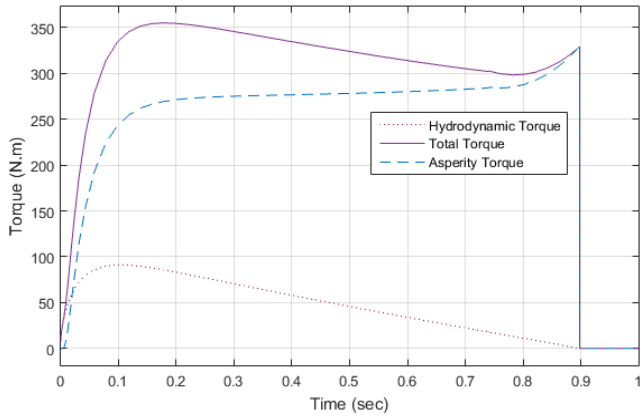
Initially when the two plates are apart the only torque that is transmitted is hydrodynamic torque which reaches a maximum value of 90 Nm in 0.1 sec. Asperity torque comes in picture only when the two plate asperities come in contact approximately after 0.02 sec. Hence initially total torque goes on rising. As plates come closer the hydrodynamic torque goes on approaching zero. Finally it is only the asperity torque that accounts for the major part of total torque.

The maximum total torque seen in this case is 360 Nm. It occurs at the time of 0.15 sec.



Graph.4 Torque as function of Time using COF represented by equation 2.3.1

5.4 Hydrodynamic, Asperity and Total Torque as function of Time using COF represented by equation 2.3.2



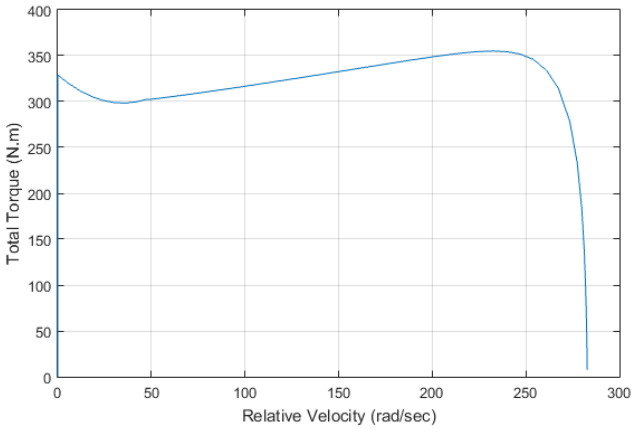
Graph.5 Torque as function of Time using COF represented by equation 2.3.2

Graph.5 is the plot obtained for the dropping nature of coefficient of friction with increasing sliding velocity as shown in Graph.2. This is the kind of friction model in which static coefficient of friction (0.185) is more than that of the dynamic coefficient of friction.

Even in this type of system, only hydrodynamic torque is dominant initially and reaches maximum value of 90 Nm in 0.1 sec and then gradually drops to zero at 0.9 sec. Asperity torque becomes the major component of total torque after 0.03 sec.

The end part of total torque shows a rise up to 330 Nm at 0.9 sec which is due to sudden peak in asperity torque.

5.5 Total Torque as function of Relative Velocity



Graph.6 Total Torque as function of Relative Velocity

Graph.6 is the plot showing how torque varies as relative velocity varies. Initial drop in torque is seen with increasing relative velocity (300 Nm at 40 rad/sec). Then it gradually rises to its maximum value (360 Nm at 240 rad/sec) and suddenly drops to zero as relative velocity approaches to its maximum value i.e. 284 rad/sec.

Conclusions

The results obtained in multiple simulations can be concluded by following points.

1) As permeability of the friction lining material increases, film thickness *h* drops at faster rate. That is when permeability value was 0.05 Darcy, the time required for the film thickness to reach the constant minimum value was 0.1 sec and for 5 Darcy it was approximately 0.02 sec. At the same time there is no change seen in the minimum film thickness *h* value (0.08) with change in permeability.

   The relative velocity drops to zero at 0.9 sec.

2) For rising nature of coefficient of friction with relative sliding speed (Graph.1), the torque increases suddenly in 0.15 sec to its maximum value of 360 Nm, then drops to zero gradually till the relative velocity becomes zero i.e. at 0.88 sec approximately in this case.

   Hydrodynamic torque boosts to its maximum value of 90 Nm in 0.1 sec then gradually drops to zero at 0.9 sec.

   Asperity torque is seen to rise only after minimum initial time (0.02 sec) required for the plates to come in actual contact.

3) Hydrodynamic torque is independent of coefficient of friction, hence no change is seen in it when the friction model was changed. (i.e. Graph.2)

   Asperity torque starts rising after 0.8 sec where relative velocity is low. This is the region where coefficient of friction drops drastically with rising relative sliding velocity.

4) When two plates are apart, relative velocity is maximum, then low torque i.e. only hydrodynamic torque is transmitted.

   Maximum torque 360 Nm is seen to be transmitted when relative velocity is about 85% of its maximum value (241 rad/sec).
   90% of the maximum torque 325 Nm is seen to be transmitted at zero relative velocity.

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