Mechanical Systems and Signal Processing 60-61 (2015) 420–436

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Modeling and analysis of wet friction clutch engagement dynamics

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ARTICLE INFO

Article history:
Received 9 April 2013
Received in revised form
18 November 2013
Accepted 23 December 2014
Available online 19 February 2015

Keywords:
Wet-friction clutch
Extended reset-integrator friction model
SAE#2 test setup
Shudder vibration
Torsional vibration

ABSTRACT

In recent years, there has been a significant increase in the usage of wet-friction clutches. Presently researchers across the globe are involved in improving the performance and lifetime of clutches through testing and simulation. To understand the clutch vibrational and dynamical behavior, an SAE2 test setup mathematical model based on extended reset-integrator friction model is developed in this paper. In order to take into account the different phases of fluid lubrication during engagement cycle, the model includes the experimentally determined Stribeck function. In addition the model considers the viscous effect and the delay in the actuation pressure signal. The model is validated with the experiments performed on the SAE2 test setup in both time and frequency domains. By analyzing the set of experimental results, we confirmed that the amplitude of shudder vibration is independent of the amplitude of applied contact pressure fluctuation.

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1. Introduction

The vibrational behavior of wet-friction clutches not only affects the dynamics of the transmission system but also the vehicle as a result of excitation transfer to the body via suspensions and mountings. If the excitation level is severe then it may cause the wear of the driveline components and discomfort to the passengers. In wet-friction clutches there are two possible mechanisms causing unstable self-excited vibration namely stick-slip and oscillatory slipping. Stick-slip refers to a periodic oscillation with an alternating stick and slip episode whereas oscillatory slipping refers to the slipping state with oscillation, but without any real stick episode [1]. The oscillations produced by these mechanisms are often collectively termed as torsional vibration. So far it is not clear whether the torsional vibration is caused by stick-slip [2,3] or oscillatory slipping [4,5] or a combination of both mechanisms. Oscillatory slipping is also known as shudder or judder vibration. In the present research it will be referred to as shudder vibration. In general, stick-slip arises due to the difference between the static and dynamic coefficient of friction (COF), both assumed to be constant in [6], whereas the oscillatory slipping is attributed to a negative slope relation of the Stribeck curve $(\mu-\omega_r)$ [4,7]. The occurrence of these vibrations is determined by inertia, stiffness and damping forces in the system, as well as by the friction characteristics of the mating friction surfaces of

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http://dx.doi.org/10.1016/j.ymssp.2014.12.024
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Nomenclature

α	amplitude constant (dimensionless)
α	Stribeck slope (dimensionless)
α	Stribeck shape factor (dimensionless)
α	COF (dimensionless)
μ_s	static COF (dimensionless)
μ_d	dynamic COF (dimensionless)
μ_m	mean COF (dimensionless)
η	ATF dynamic viscosity (Pas)
ρ	ATF density (kg/m^3)
ω_i	input velocity (rpm)
ω_o	output velocity (rpm)
ω_r	relative velocity (rpm)
ω_s	Stribeck velocity constant (rpm)
A_c	contact area (m^2)
b	torsional damping (Nms/rad)
c	linear damping (Ns/m)
C_t	tangential contact damping (Nms/rad)
C	capacitive element (dimensionless)
d_p	piston displacement (mm)
F_n	net normal force (N)
F_o	nominal normal force (N)
F_e	external force (N)
F_s	spring force (N)
F_{pre}	pre-load (N)
h_i	spring installation height (mm)
I	inertia element (dimensionless)
J	inertia (kgm^2)
k_s	spring contant (N/mm)
k	linear stiffnes (N/mm)
K_t	tangential contact stiffness (Nm/rad)
K	torsional stiffness (Nm/rad)
N	number of frictional interface (dimensionless)
K_b	belt flexibility (Nm/rad)
P_c	contact pressure (bar)
P_o	average contact pressure (bar)
h	gap between disks (m)
Q	ATF flow rate (m^3/s)
r_o	outer radius of disk (mm)
r_i	inner radius of disk (mm)
R	resistive element (dimensionless)
R_e	effective radius (m)
σ_0	stiffness coefficient (Nm/rad)
σ_1	damping coefficient (Ns/m)
σ_2	viscous coefficient (Ns/m)
t_f	start time of filling phase (s)
t_e	start time of engagement phase (s)
t_l	lockup time (s)
T	ATF temperature (°C)
T_s	stiction torque (Nm)
T_{strib}	velocity weakening torque (Nm)
T_{visc}	velocity strengthening torque (Nm)
T_f	friction torque (Nm)
v_o	dead volume (m^3)
v_{atf}	ATF volume (m^3)
$V_{chamber}$	chamber volume (m^3)
z	presliding displacement (rad)
z_0	max. presliding displacement (rad)

the disks [4,6]. Friction characteristics, or to be more precise COF in turn depends on the relative velocity, normal force (contact pressure), and automatic transmission fluid (ATF) temperature that govern its dynamic viscosity.

Better understanding the engagement dynamics of wet-friction clutches can enable us to correlate the state of wet-friction clutches with the vibration characteristics. In [8], it is shown that the model parameters of the post-lockup torsional vibrations are useful as health indicators of wet-friction clutches. In addition, this understanding can enable us to accurately simulate the clutch engagement dynamics such that a control strategy can be developed and evaluated in model-based designed (co-simulation) fashion [9,10] to mimimize the vibration and the resulting wear and discomfort.

Nevertheless, publications on the effects of quality of external parameters like relative velocity, contact pressure, etc. on the vibrational and dynamical behavior of wet-friction clutches are limited. The friction models used to model the wet-friction clutches are simple, i.e. employing a linear Stribeck curve. In addition, the essential properties of the friction model i.e. which parameters are required to be introduced in the existing friction models so as to accurately model and simulate the vibrational and dynamical behavior of wet-friction clutches are unknown.

The objective of this paper is to study the vibrational and dynamical behavior of wet-friction clutches using an advanced friction model. In order to achieve the set goal an SAE2 clutch test setup mathematical model employing an adapted form of the reset-integrator friction model [11] is developed. The main effort in developing this model lies in adapting the reset-integrator friction model to make it suitable for wet-friction clutch applications. The adaptation incorporates the experimentally determined Stribeck function, viscous effect and delay in actuation pressure signal due to time required to fill the chamber with the ATF. The extended reset-integrator friction model retains the stick-slip logic as in the original model and works in a closed loop with the mechanical part of the test setup.

In order to validate the model, series of engagement cycle experiments are performed on an SAE2 test setup. Model simulation results are verified by the experimental results in both time and frequency domains. In addition by analyzing the set of experimental results, it is confirmed that the amplitude of shudder vibration is independent of the amplitude of contact pressure fluctuation. This observation supports the theoretical analysis of unstable vibration reported in [4,12]. Moreover, by simulation it is found that the post-lockup torsional vibration is influenced by the tangential contact stiffness and contact damping of the clutch disks. The time instant at which the clutch is fully locked is known as lockup time. The time prior to the lockup time instant is referred to as the pre-lockup phase, whereas the time after that is referred to as the

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