Mechanical Systems and Signal Processing 66-67 (2016) 811–828

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Studies on centrifugal clutch judder behavior and the design of frictional lining materials

Tse-Chang Li [a], Yu-Wen Huang [a], Jen-Fin Lin [a,b,*]

[a] Department of Mechanical Engineering, National Cheng Kung University, Tainan 701, Taiwan
[b] Center for Micro/Nano Science and Technology, National Cheng Kung University, Tainan 701, Taiwan

ARTICLE INFO

Article history:
Received 7 April 2014
Received in revised form
28 May 2015
Accepted 11 June 2015
Available online 3 July 2015

Keywords:
Clutch judder
Frictional lining materials
Taguchi method
Judder resistance

ABSTRACT

This study examines the judder behavior of a centrifugal clutch from the start of hot spots in the conformal contact, then the repeated developments of thermoelastic instability, and finally the formation of cyclic undulations in the vibrations, friction coefficient and torque. This behavior is proved to be consistent with the testing results. Using the Taguchi method, 18 kinds of frictional lining specimens were prepared in order to investigate their performance in judder resistance and establish a relationship between judder behavior and the T_s/T_d (T_s: static torque; T_d: dynamic torque) and $d\mu/dV_x$ (μ: friction coefficient; V_x: relative sliding velocity of frictional lining and clutch drum) parameters. These specimens are also provided to examine the effects and profitability with regard to the centrifugal clutch, and find the relative importance of the various control factors. Theoretical models for the friction coefficient (μ), the critical sliding velocity (V_c) with clutch judder, and the contact pressure ratio $p^*/\overline{p}$ ($p*$: pressure undulation w.r.t. $\overline{p}$; $\overline{p}$: mean contact pressure) and temperature corresponding to judder behavior are developed. The parameters of the contact pressure ratio and temperature are shown to be helpful to explain the occurrence of judder. The frictional torque and the rotational speeds of the driveline, clutch, and clutch drum as functions of engagement time for 100 clutch cycles are obtained experimentally to evaluate $d\mu/dV_x$ and T_s/T_d. A sharp rise in the maximum $p^*/\overline{p}$ occurred when the relative sliding velocity reached the critical velocity, V_c. An increase in the maximum $p^*/\overline{p}$ generally led to an increase of the (initially negative) $d\mu/dV_x$ value, and thus the severity of judder. The fluctuation intensity of $d\mu/dV_x$ becomes a governing factor of the growth of $d\mu/dV_x$ itself in the engagement process. The mean values of $d\mu/dV_x$ and T_s/T_d for the clutching tests with 100 cycles can be roughly divided into three groups dependent on the fluctuation intensities of these two parameters, for each of which there is a linear relationship.

1. Introduction

When a vehicle starts rolling the clutch engagement sometimes generates judder, which may damage the drivetrain components. Judder often manifests itself in the form of noisy torsional vibrations of the drivetrain or a violent surging of the vehicle. Transient torsional oscillations are related to judder. A special relationship between the friction coefficient and sliding

* Corresponding author at: 1 University Road, Tainan City 701, Taiwan (R.O.C.). Tel.: +886 6 2757575x62155.
E-mail address: jflin@mail.ncku.edu.tw (J.-F. Lin).

http://dx.doi.org/10.1016/j.ymssp.2015.06.010
0888-3270/

velocity becomes the most important source of judder. The torsional vibrations of the clutch system that lead to judder are induced by stick-slip processes at the interface of the clutch friction disc and the flywheel and at pressure plate interfacial contacts.

The friction discs of clutches are subjected to considerable thermal loading. High temperatures lead to thermal stress failures, such as surface cracks and permanent distortion [1,2]. Distortions often occur in multidisc clutches, and are in the form of a conical deformation or disc waviness. The temperatures and stresses in the friction discs of a multidisc wet clutch have been studied [3]. In general, the initial distribution of normal pressures on the friction surface can be nonuniform, although it can also be nonuniform due to thermal deformations. This thermoelastic transition is present in many sliding contact systems [4]. This process of pressure changes is unstable and is called thermoelastic instability [5]. In the model proposed by Kennedy and Ling [6] the influences of thermal deformation and wear on the normal contact pressure were taken into account. In contrast, Zagrodzki [7] presented a model of transient thermomechanical phenomena occurring in a multidisc wet clutch that considers the thermoelastic instability effect.

Bostwick and Szadkowski [8] studied the self-excited vibrations generated by an increase in the coefficient of friction on a clutch facing due to a decrease in the slip speed on friction surfaces. The amplitude of self-excited vibration depends on the system parameters alone. In Crowther and Zhang [9] a six-degree-of-freedom dynamic model for clutch engagement was used to investigate the effect of low-frequency transients on clutch engagement stick-slip behavior in powertrains. A commercially available sintered friction pad was coupled with a standard gray cast iron pressure plate and tested in a clutch dynamometer to determine the engagement characteristics for the prediction of useful life [10]. The microscopic features of worn sintered friction pads indicated that silica particles provided wear resistance for the pads. Commercial paper-based friction plates with standard steel reaction plates were tested with four stiffness and inertia combinations of a wet clutch system [11]. A low-inertia system showed faster degradation and shorter clutch life for high torsional oscillation. The system was also more shudder sensitive for lower natural frequencies in a less stiff system. An analytical procedure for determining pure stick to stick-slip motions was developed based on linear system analysis [12]. Stick-slip behavior was clearly observed to be a result of engine torque irregularity and nonlinear friction characteristics. Disc inertia significantly affects system dynamics. A study on a wet centrifugal clutch [13] simulated vehicle judder using a clutch unit tester, and the results were utilized as an evaluation index for judder. Based on this, the effects of the components of a friction material on judder were clarified. In Gregori [14] a bench test was developed to measure the judder sensitivity of a friction material used on clutch discs. A methodology was developed for the characterization of clutch facing sensitivity for judder. Stick-slip, present to some degree in almost all actuators and mechanisms with frictional contact, often leads to self-excited vibration. During the engagement process, some of the energy transmitted through the driveline is transformed into other forms of energy by positive damping effects. If for some reason the damping becomes negative, some of the energy transmitted by the clutch can induce self-excited torsional vibrations of the driveline, which can induce judder. Centea et al. [15] showed that the gradient of friction coefficient (μ) and slip velocity (V_x) is a negative value, if $d\mu/dV_x \geq -C/F_n$ (C: damping coefficient; F_n: normal load), the damping is positive and the system is stable. If $d\mu/dV_x < -C/F_n$, the damping coefficient of the driveline becomes negative and the vibration system becomes unstable. Karnopp [16] analyzed various friction models in the stick-slip region in terms of the variation of the friction force F_t with the relative interfacial contact velocity V_x. Centea et al. [17] investigated the torsional vibration mode of the clutch system. It was proved that judder is related to the type of friction lining material. A transient finite element analysis method was used to analyze the fully coupled thermoelastic instability problem for a brake system [18]. The reliabilities of the analysis technique and simulation model were verified.

The cause of judder in clutches has seldom been studied, and thus the present work aims to establish a theoretical model to interpret this behavior, and use the vibrations varying with time and their spectrum analysis to verify its validity. The severity of judder is governed by the rising rate of torque expressed by T_s/T_d (T_s: static torque; T_d: dynamic torque) and the intensity of torque fluctuations often denoted by $d\mu/dV_x$ (μ: friction coefficient; V_x: sliding velocity of friction lining). The map of these two governing parameters satisfying the small intensity demand of judders can thus be determined, and so the effects of the fabrication conditions and materials using in friction lining on judder prevention can then be evaluated. The relationships between T_s/T_d and $d\mu/dV_x$ for the specimens were also established in association with the rising rate of friction torque and the intensity of torque fluctuation.

2. Development of theoretical models

The present study analyzes the friction coefficient (μ) arising at the contact surface of the friction lining and the clutch drum of a centrifugal-type clutch. A centrifugal-type clutch generally consists of a spider as the input member, three sets of shoes and friction linings as the centrifugal members, and a round-type clutch drum as the output member. One end of the partial-arc shoe is fixed by a pivot (the central point of hinge pin, noted by A_1 in Fig. 1) as the input member; a point of this shoe is connected by spring 1 to the pivot side of the adjacent shoe. When the rotational speed of the input member (drive) is sufficiently high, the friction shoe is forced to move outward due to the centrifugal force, and the friction lining rotates to have an engagement with the clutch drum until the friction lining is tightly pressed against the inside surface of the clutch drum without relative sliding velocity. Fig. 1(a) shows the mechanical diagram of one friction lining before starting the engagement with the clutch drum; the subscript i denotes the initial state at this moment. Fig. 1(b) shows the diagram after finishing the full engagement.

Δs is defined as the increase in spring length when the friction shoe is subjected to a centrifugal force. The distance of the pivot center (A_1) from the clutch center (O) is a. Point C_1 and point C_2 (not shown in Fig. 1) are the two fixed ends of the