*Advanced Materials Research Vols. 230-232 (2011) pp 1362-1366*
*Online available since 2011/May/12 at www.scientific.net*
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*doi:10.4028/www.scientific.net/AMR.230-232.1362*

# Experimental verification of stick–slip motion between two rolling contact surfaces

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**Key words**: friction, stick-slip, experimental verification, noise, vibration, powertrain.

**Abstract**: In this paper, a simplified drive train model with stick-slip nonlinearity is introduced for the study of stick-slip motion between the driving tires and the flywheel. Laboratory based tests are designed to investigate stick-slip motion of the tires contacting with the flywheels which simulate vehicle inertia. A description of the powertrain test rig, the associated instrumentation, the test inputs and operation conditions are provided. The experimental results are similar to those obtained from the numerical analysis using the introduced drive train model. They verify the validity of the stick-slip model, and demonstrate that stick-slip occurred frequently between the driving tires and the flywheels. The normal tire force applied to the flywheel is one of the key parameters affecting stick-slip motion. And there exists an upper limit beyond which the tire and flywheel will stick together at all time. It is found that the frequency of stick-slip motion is independent of normal tire force and is close to the natural frequency of the tire-flywheel contacting power transmitting system.

## 1 Introduction

Although technology advancement continuously improves vehicle performance, vibration and noise is still one of the main noise sources for which residents and local councils continually complained. Hence research on friction induced torsional vibration in a power transmitting system is still primary interest of automotive engineers. The stick-slip motion is a typical friction induced and non-smooth vibration observed during low sliding speeds. It occurs due to a combination of the complex characteristics of the mechanical systems (inertia, stiffness, and damping) and the mechanical properties of contact surfaces. It causes speed transmission inaccuracy of mechanical systems, stress and wear of contacting surfaces, positioning problems, as well as noise and vibration problems. The study of stick-slip vibrations is technically challenging as two different friction mechanisms exist during the stick-slip motion. The modelling of the static friction mechanism and that of the kinetic friction mechanism yield a set of differential equations with discontinuities.

Numerical and analytical results reported in the literature [1, 2, 3] have shown that stick-slip behaviour between tires and ground is greatly affected by the driving inputs, the tire normal pressure and other system parameters. In particular, it has been found that different types of stick-slip motions were resulted from different operating conditions. A detailed model has been developed for analyzing stick-slip within the brake subsystem in [4, 5]， and it is only briefly introduced below.

The introduced model in Fig. 4 treats the complete drive train model with tires stick-slip with flywheels. The double stick-slip mechanisms are much more complex than the singular one, since the singular one has only one state [5].

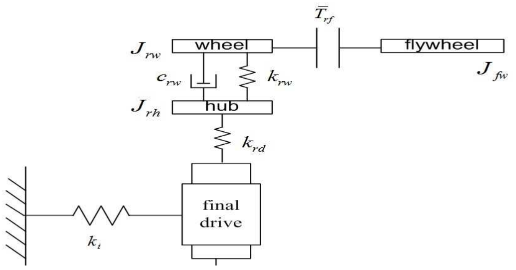


Figure 1. Reduced drive train model half stick-slip model

Table 1. Possible working states of the double stick-slip drive train model

| State | A | B | C | D |
|---|---|---|---|---|
| Right side | stick | stick | slip | slip |
| Left side | stick | slip | slip | stick |

As shown in Table 1, the model has four different possible working states. The general elements of the model in matrix form have been derived by Ashley to assemble the overall system model [6]. Although many similar experimental works like reference [6] have been carried out in the past decades, most of the obtained observations are hard to be used to verify the theoretical work.

In this paper, the powertrain test rig developed at the Dynamics Laboratory of University of Technology, Sydney (UTS) is used to examine experimentally the stick-slip motion occurred between the driving tires and the flywheels which simulate vehicle inertia. In the following sections a description of the test rig and associated instrumentation is provided. The test inputs and operation conditions are detailed. And, finally, the results are presented and discussed in detail. The mechanism of stick-slip motion between the driving tires and the flywheel is explained.

## 2 Experiment Test Setup

### 2.1 Apparatus

In this section, the UTS powertrain test rig is operated under certain conditions to obtain stick-slip motions occurred on the contact surface between tires and flywheels. The friction induced vibration, i.e., stick-slip, will be tested and the test results will provide fundamental understandings of its characteristics, as well as verification of modelling and analysing work introduced above.

Figure 2 is the schematic of the powertrain test rig. The test rig consists of all the components of a vehicle from the engine, automatic transmission, drivetrain, tires, and equivalent vehicle mass as well as chassis accessory assembly. It has been used for dynamic testing on individual components, free torsional vibrations, steady state and transient response for gear shifting process. These tests can provide further understanding of vehicle responses under different operating conditions, and verify numerical and analytical analysis on vehicle powertrain system. The flywheels are to simulate the equivalent vehicle inertia in motion and are driven by the tires. The flywheels and tires are in contact under certain normal load and hence rotate against together, while somehow there is slippage taking place in some cases. Although, the centres of these contacted bodies are fixed, a relatively low tire pressure allows slippage to happen. The powertrain test rig main parameters have been identified before and listed in [6].

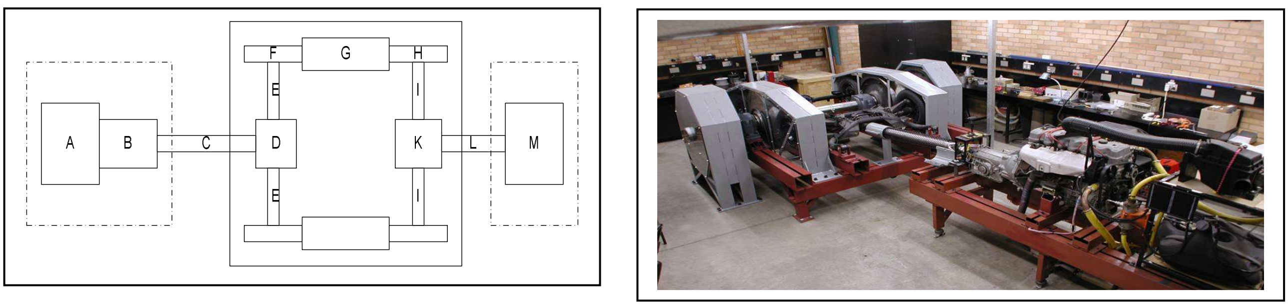


Figure 2. UTS Powertrain Test Rig schematic: A) Engine; B) AT transmission; C) Propeller shaft; D) Final Drive; E) Drive shaft; F) Wheels; G) Groups of flywheels; H) Wheels; I) Rear drive shaft; K) Rear final drive; L) Dynamometer shaft; M) Dynamometer

### 2.2 Test procedures

The detailed testing procedure is described below. Note that all tests are carried out with torque converter lock up clutch engaged, as the required empirical information of the torque converter (TC) transient characteristics is currently not available.

Firstly, identification of stick-slip motion: (1) the engine is started with transmission in neutral position, and then drives the whole system once transmission was putting in D (driving); (2) A constant drag is provided by the dynamometer to simulate the actual air drags on real vehicle; (3) the throttle is suddenly increased by pushing the controlling handle; (4) throttle position, propeller shaft torque, and drive shaft torque describe the transient response of the system during tests, and these data are measured and recorded by the data acquisition system. Engine speed, vehicle speed, and a set of solenoid valve single data are also monitored.

The aim of this test is to capture stick-slip motion between tires and flywheels. This provides verification for stick-slip modeling (system parameters and dynamic model) and simulations of the test rig [6].

Secondly, normal load and stick-slip behavior: 1) several tests were carried out by varying the tire pressure from 25 *psi* to 45 *psi* (according to safety instruction from manufacturers, tire pressure 35 *psi* is the maximum tire pressure allowed); 2) the test rig was run with a sudden change of throttle position; 3) the dynamometer provides constant drag on tires; 4) Throttle position, propeller shaft torque, and drive shaft torque describe the transient response of the system during tests, and these data are measured and recorded. Engine speed, vehicle speed, and a set of solenoid data are also recorded.

These tests are designed to investigate the impact of normal load on stick-slip behavior. For higher tire pressure, the stick-slip motion between tires and flywheels could be observed with a higher throttle position (larger inputs).

## 3 Results and discussion

The test rig is started with engine, processing computer and dynamometer turned on. The four speed automatic transmission (AT) is placed in drive. Tires and flywheels will roll against each other; stick and slip exists and is distinguished by whether or not there is relative speed between the two contacting surfaces. Then the control handle is pushed up quickly to increase throttle position. In turn, the engine torque is raised quickly and the vehicle is in a hard acceleration process. Transient vibrations should present firstly due to the driveline shuffle. Stick-slip between tires and flywheels occurs once the stick-slip criterion is met (the internal friction torque exceeds the maximum static friction torque). The vibration is captured through the torque accelerometers on drive half shafts and propeller shaft. Meanwhile a short period of high level noise would be heard.

Torque telemetry system is calibrated to ensure that the data measured and processed appropriately. One end of a bar is attached to the wheel hub and masses are placed on the other end. The drive shaft will be twisted slightly according to masses hang on the other end. In doing this, a voltage-torque curve will be obtained for future procession. Table 2 lists the calibration results of right and left drive shaft. The measured slope of voltage-torque curve at left and right shaft is -0.002049 V/Nm and -0.002525 V/Nm.

Table 2. Calibration of Whole Torque Telemetry System at LH Half Shaft

| Load Condition | Input Torque | | ATI Display Loading | Computer Measurement Loading |
|---|---|---|---|---|
| | Load | Torque | | |
| | *N* | *Nm* | *V* | *V* |
| bar + mass hanger | 0 | 0 | 0.02 | -0.1 |
| above + mass | 100 | 200 | -0.24 | -0.6 |
| | 200 | 400 | -0.49 | -1.1 |
| | 300 | 600 | -0.75 | -1.65 |
| | 400 | 800 | -1.00 | -2.1 |
| ATI Measurement Trendline Slope | -0.002525 *V/Nm* | | | |
| 1/Trendline Slope | -396.04 *Nm/v* | | | |

Figs. 3 show a sample result of the stick-slip vibration with tire pressure of 36 *psi* (the maximum tire pressure allowed according to manufacturer safety instruction is 35 *psi*). Figure 5 shows the recorded engine throttle position changes. The stick-slip motion causes the drive shaft torque oscillation, in contrary, when there is no stick-slip, this torque oscillation disappears as in Fig. 3. With transmission placed in drive, engine drives the vehicle. Throttle position, fuel flow rate, AT solenoid and torque are collected a thousand times per second, while speed is captured once very second. The data is processed and visualized in LabView.

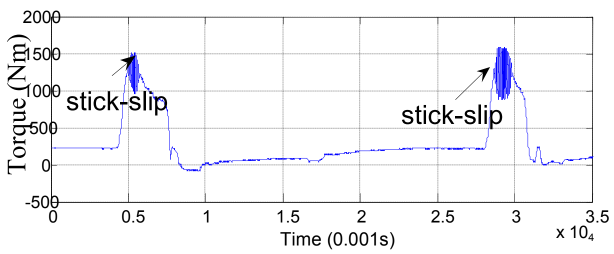


Figure 3 Transient torque in LH shaft showing stick-slip impact between tires and flywheels

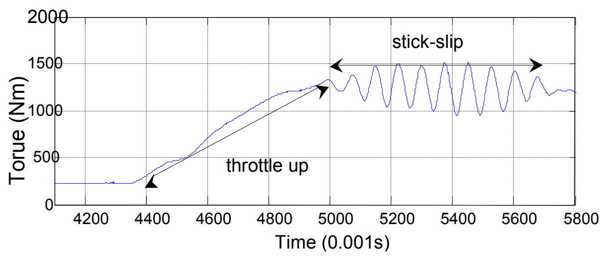


Figure 4 Transient LH shaft torque enlarged plot

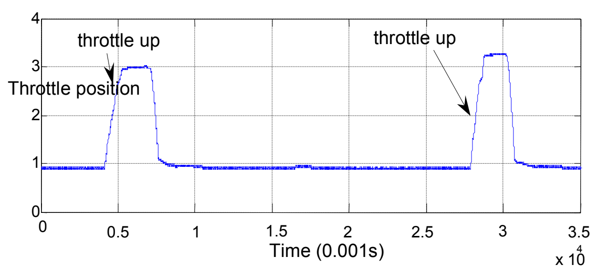


Figure 5. Throttle position plot

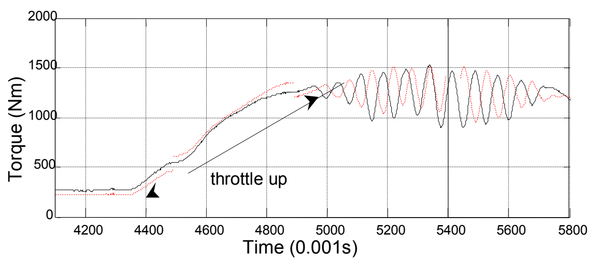


Figure 6. Transient LH (dotted line) and RH(solid line) shaft torque compared

The throttle is pushed up from 10% to 30% as shown in Fig. 5. Once the noise generated from the tire-flywheel is heard, keep the throttle position still, in this case at 30%. The torque recorded on left and right drive shaft oscillates at a frequency of 14 *HZ* approximately; see Fig. 3 and 4. The frequency is calculated as the number of vibrations $N$ during the stick-slip divided by the stick-slip period $T$, i.e. $f=N/T$. The mean torque (during stick-slip) is found to be around 1230 *Nm.* The vibration dies out in about 0.7 second. After the stick-slip noise disappeared, pull back the throttle position to 10%. Waiting until the test rig running in steady state, push the throttle position up again to 30% and the stick-slip noise is captured again, seen from Fig. 3 to Fig. 5. The torque on the right and left drive shaft is compared in Fig. 5 The vibration of tires at the right and left shows a phase difference (roughly 0.5T). In detail, the left shaft torque lags behind the right by half a period. Note that there is also a value difference between them. This could be caused by the residual torque within the differential gear box. The stick-slip vibration occurs once the throttle was pushed to 3.0 (seen from Fig. 5).

Table 3. Impact of normal force on stick-slip behaviour

| Tire pressure [psi] | 26 | 28 | 30 | 32 | 34 | 36 | 38 | 40 | >40 |
|---|---|---|---|---|---|---|---|---|---|
| Mean torque[Nm] | --- | 1104.5 | 1160.6 | 1125.0 | 1175.9 | 1230 | 1308.0 | 1335.1 | --- |
| Time [s] | 1.645 | 1.565 | 1.500 | 1.050 | 1.040 | About 0.7 | 0.758 | 0.500 | --- |

By varying the tire pressure from 26 to 46 by 2 in each time, several times of experiments are conducted to further investigate the impact of normal force on stick-slip behaviour. According to safety instruction, the tire is allowed to be pumped up to 35 *psi*. However, for research interest, we study more cases beyond this limitation, and find that the frequency is roughly 14 HZ all the time. From the table 3, it can be seen that the observed stick-slip behaviour from the test rig dies out in a short period. Furthermore, the noisy periods vary with different tire pressure. The higher the pressure is the shorter the period will be. The mean value of the tested shaft torque seems to be increasing with the rise of tire pressure. The required throttle position to induce stick-slip motion varies with the increase of tire pressure.

## 4 Conclusions

In this paper, the stick-slip behaviour between two rolling contact surfaces is experimentally investigated on a powertrain test rig. The tests simulate the hard accelerations of a vehicle with various throttle inputs and tire pressures. Under these operating conditions, stick-slip occurred frequently between the driving tires and the flywheels, and was confirmed from the observed noise and the wear on the driving tires. A large amount of the torque measured from the two driving shaft have proved the existence of stick-slip motions.

The main findings resulted from this study are: 1) the normal tire force applied to the flywheel is one of the key parameters affecting stick-slip motion and there exists an upper limit beyond which the tire and flywheel will stick together at all time; 2) the frequency of stick-slip motion is close to the natural frequency of the tire-flywheel rolling contact and power transmitting system and the stick-slip frequency is independent of normal tire force.

## Acknowledgements

Financial support for this research was provided by the Australian Research Council (DP0988429) and Key Project of Chinese National Programs for Fundamental Research and Development (Grant 2010CB832705).

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