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# DESIGN AND TORSIONAL VIBRATION ANALYSIS OF A COMPLEX VEHICLE POWERTRAIN SYSTEM TEST RIG

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**Abstract** This paper presents the design and analysis of a test rig that is used for experimental investigation of the transient characteristics of a nearly completed vehicle powertrain system equipped with an automatic transmission. The free and forced torsional vibration of the complex test rig is performed and compared to that of an existing car. It is found that the first global vibration mode of the test rig varies significantly when the gear ratio of an automatic transmission changes. In addition, it is shown that the dynamic characteristics of tyres and vehicle inertia significantly affect the vehicle powertrain system dynamics and their inclusion into the analysis will improve the simulation accuracy.

**Keywords**: torsional, vibration, powertrain, test rig

## 1. Introduction

Performance of the powertrain system is directly linked with the fuel efficiency, drive quality and passenger comfort of the vehicle. In powertrain systems equipped with automatic transmissions, the behaviour of the transmission is a major contributor to the overall performance of the powertrain. Engineering sciences and disciplines such as mechanics, hydraulics, electronics, control and ergonomics are applied to the design of automatic transmissions. Furthermore, many laboratory and/or road based experiments are required to gain in-depth understanding of automatic transmissions and powertrain systems generally and specifically.

An automatic transmission in a vehicle provides smooth start, makes driving easier and reduces driver fatigue. Its performance is important for obtaining better vehicle dynamic characteristics and driveability. In particular, the transient characteristics of an automatic transmission have significant influence on shift quality and driver comfort. Therefore, the study of the transient characteristics of an automatic transmission is an essential task for improving the gear change performance of a vehicle powertrain system. A number of studies have been carried out to research the transient characteristics of an automatic transmission with a torque converter[1], and several kinds of test rigs have been designed and utilized by different car manufacturers and research institutes[2]. These test rigs were usually designed for simulating the operating conditions of automatic transmissions and testing their performance. However, the effects of some major components in a vehicle powertrain,

such as tyres and vehicle inertia, have not been taken into account and this significantly undermines the accuracy and capability of such test facilities.

This paper presents the design and analysis of a comprehensive test rig for vehicle powertrain systems equipped with an automatic transmission. The rig will be used for: experimental validation of theoretical predictions of the transient characteristics of automatic transmissions during gear changes; the implementation of closed loop control of gear shifts; and in particular, experimental investigations of torsional vibration of whole powertrain systems caused by clutch stick-slip behaviour.

All of the major components of a vehicle powertrain system are integrated in the test rig, including a flywheel subsystem that simulates the inertia of the vehicle. The torsional vibration characteristics of the test rig are determined and compared to that obtained from an existing car. The results show that this new test rig is a very good approximation to a real car and is thus suitable for experimental investigations of the transient characteristics of automatic transmissions. In addition to this, the test rig has capacities for testing manual transmissions and other powertrain components.

## 2. Design of the Test Rig

The performance of the test equipment and the experimental results obtained are crucial for the validation of mathematical and computer models developed for simulating the transient characteristics of automatic transmissions used in vehicle powertrain systems. The test equipment was therefore designed to satisfy the requirements specified for the study of the transient characteristics of such automatic transmissions. The test rig designed to meet these requirements is shown in Fig. 1 and consists of a six-cylinder engine, a four speed automatic transmission, propeller shaft, differential gear, half shafts and tyres. It also incorporates a flywheel system that simulates the vehicle inertia, and a dynamometer that simulates the aerodynamic drag and road resistance. The flywheels are driven by the car wheels, allowing the dynamic characteristics of tyres to be taken into account in the dynamic analysis.

In an actual vehicle, when the output speed of a transmission increases or decreases, the inertia of the vehicle itself affects the performance of the transmission. Therefore a test rig to simulate a vehicle powertrain system would be incomplete if the vehicle inertia were not included. In the design of the test rig reported here, the inertia of the vehicle is simulated by the flywheel system. In order to take into account the dynamic characteristics of tyres, the flywheel system

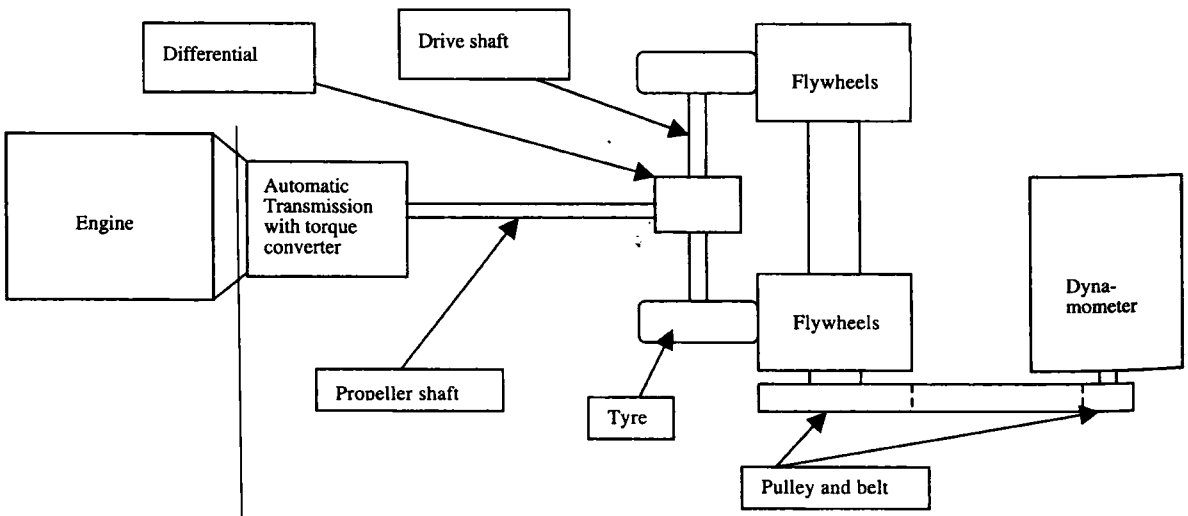


Fig. 1 The schematic diagram of the test rig

has been designed so that there is no slipping between the flywheels and the tyres. The equivalent inertia of the flywheels is calculated by using the powertrain specifications, including the output rotational velocity of the engine, the gear ratio of the automatic transmission and the differential gear, the dimensions of the tyres and flywheels.

The output rotational velocity of tyres is limited by the engine speed and gear ratios as all the powertrain components used in the test rig are those used in existing cars. Also, the radius of the tyre is smaller than that of the flywheel so the flywheel rotational speed is

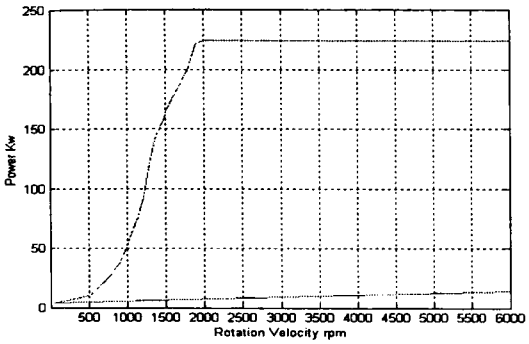


Fig. 2 The power range of the dynamometer

relatively low. Given the power curve of the dynamometer shown in Fig. 2, the dynamometer power is limited when the input rotation velocity is less than 1000rpm. For this reason, in this test rig, the dynamometer input shaft speed is increased by a pulley and belt system between the flywheel and the input shaft so that the dynamometer operates in the speed range of best performance.

The following data is required by this research and will be measured by the test rig instrumentation: engine and turbine speed; and automatic transmission output speed, torque and oil temperature. Two torque transducers are to be installed in the test rig, one between the engine output shaft and the pump of the torque converter and the other between the output shaft and the propeller. The dynamic characteristics of the torque transducers have been included in the analysis.

The differential gear, half shafts and tyres as well as the flywheels are mounted on the rear frame of the test rig. The differential gear drives two tyres through two half-shafts, all of which are standard parts of existing cars.

## 3. Dynamic Model for Torsional Vibration Analysis

An automatic transmission in a vehicle powertrain system performs automatic gear changes as it interacts with engine and driveline. To improve the performance of an automatic transmission, the performance of the whole powertrain system must be well understood. The torsional vibration analysis for an existing vehicle and this test rig are discussed below.

### 3.1 The dynamic model of an existing car

In this analytical model of the torsional vibration for a Ford Falcon (Australian version) car equipped with a six-cylinder Ford engine, not only the engine and automatic transmission are included, but also the propeller shaft, differential gear, half shafts, tyres and vehicle inertia.

### 3.2 The dynamic model of the test rig

The mathematical model for torsional vibration analysis of the test rig comprises all the components of the powertrain, flywheels and dynamometer.

At different gears, the engagement of the rotating elements of the planetary gear set in an automatic transmission is different. Thus, different models are developed for different gears, such as $4^{th}$, $3^{rd}$, $2^{nd}$, $1^{st}$ and reverse gears. For example, Fig. 3 shows a schematic of the test rig model when the automatic transmission operates at $4^{th}$ gear (lock-up).

The main differences between a car and the test rig are listed below.

(1) Vehicle inertial is simulated by a flywheel system that is driven by car tyres.

(2) Aerodynamic drag and road resistance is provided by a dynamometer.

(3) The engine block and the automatic transmission casing are mounted on a stationary foundation (not a car body), see the boundary A in Fig. 3.

(4) The chassis suspension system is mounted to the stationary foundation (not car body), see the boundary B in Fig. 3.

## 3.3 Equations of motion

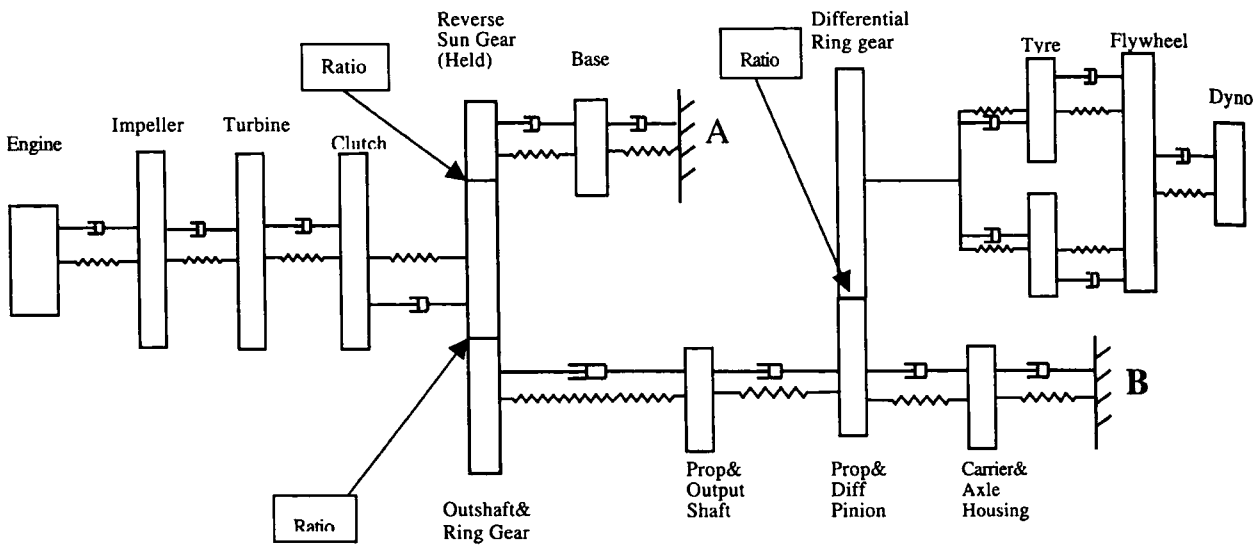


Fig. 3 Torsional Vibration diagram for 4th gear (lock-up)

The equations of motion are derived from the free-body diagrams of the powertrain elements. As an example, at 4th gear (lock-up), the powertrain system includes 13 degrees of freedom and its equations of motion are given below.

$$I\ddot{\Theta} + C\dot{\Theta} + K\Theta = Q \qquad (1)$$

where $\Theta = [\theta_{eng}, \theta_{imp}, \theta_{tur}, \theta_c, \theta_{gear}, \theta_b, \theta_{po}, \theta_{pp}, \theta_h, \theta_{tryel}, \theta_{tyrer}, \theta_{flywheel}, \theta_{dyno}]$(for details, see Fig. 3).

$\ddot{\Theta}$, $\dot{\Theta}$ and $\Theta$ represent the angular acceleration, velocity and displacement vectors of the dynamic system respectively. $I$, $C$ and $K$ are the matrixes of mass moment of inertia, damping, and stiffness. The gear ratios, including the transmission ratio, differential gear ratio, the ratio between tyres and flywheels, and the pulley ratios, are considered in the determination of these matrices. $Q$ represents the external torque vector.

# 4. Results and Discussion

## 4.1 Free vibration analysis

The natural frequencies and mode shapes of the powertrain system are determined from the mass, stiffness and damping coefficient matrices by solving the eigenvalue-eigenvecter problem of Equation (1).

### 4.1.1 Free torsional vibration of an existing car

In this model, the dynamic characteristics of tyres and the vehicle inertia are taken into account. The natural frequencies and mode shapes obtained are shown in Fig. 4.

In Fig. 4, the length of the lines on the 15 points show the normalized vibration mode shape in this natural frequency. Point 1 is the engine, point 2 is the impeller, point 3 is the turbine, 4 is the clutch, 5 is the planet carrier (equivalent), 6 is the engine mount and transmission case, 7 is the vehicle "roll" inertia, 8 is the propeller shaft, 9 is the differential

pinion gear (equivalent), 10 is the differential gear carrier and the axle housing, 11 is the vehicle "pitch" inertia, 12 and 13 are the left and right tyres, point 14 and 15 are the vehicle inertia on the two tyres. The points 6, 7 and points 10, 11 show two branches in the model.

At 4th gear, the obtained first global natural frequency of the powertrain system is 8.49 Hz and the second global mode natural frequency is 27.64 Hz.

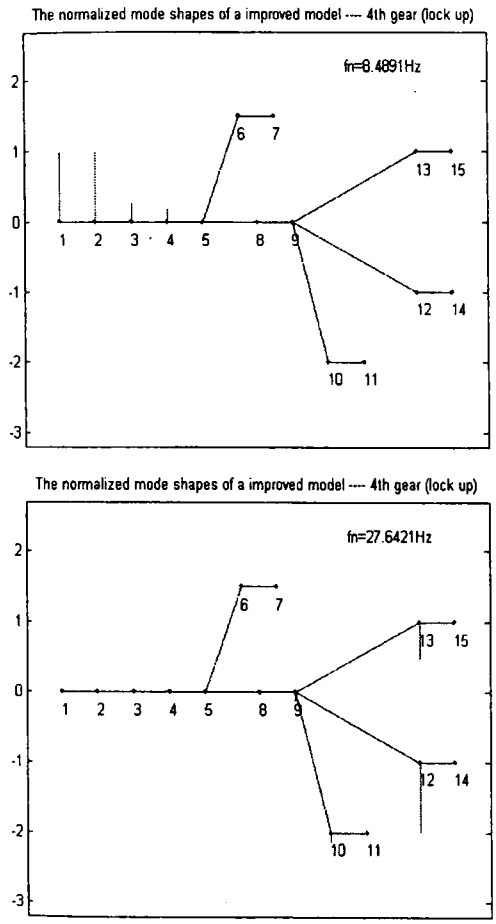


Fig. 4 The vehicle natural frequencies and mode shapes of a improved vehicle model

Moreover, according to this model, it is shown that including vehicle and tyre inertia has significant influence on the system.

The natural frequencies and mode shapes of the existing car at 3rd gear and reverse gear are also obtained. For example, the first two global natural frequencies at 3rd gear (lock-up) are 7.75 Hz and 27.04 Hz. It is noted that the first global natural frequency of the vehicle powertrain system varies significantly when the gear ratio changes. However, the second global natural frequency varies slightly when the gear ratio changes.

### 4.1.2 Free vibration of the test rig model

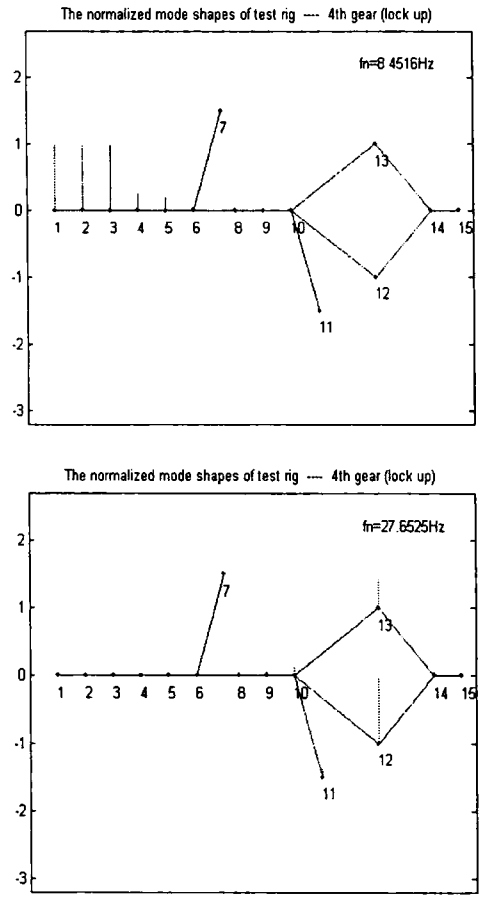


Fig. 5 The test rig natural frequencies and mode shapes

This model is used to investigate the torsional vibration characteristics of the test rig. The physical model is shown in Fig. 3. By solving the eigenvalue problem of Equation (1) of the test rig system, the first two global vibration modes are obtained and shown in Fig. 5.

In Fig. 5, the line length on the 15 points shows the normalized vibration mode shape for this natural frequency. Point 1 is the engine, point 2 is the first torque transducer, point 3 is the impeller, 4 is the

turbine, 5 is the clutch, 6 is the planet carrier (equivalent), 7 is the engine mount and transmission case, 8 is the second transducer, 9 is the propeller shaft, 10 is the differential pinion gear (equivalent), 11 is the differential gear carrier and the axle housing, 12 and 13 are the left and right tyres, point 14 is the flywheel and point 15 is the dynamometer. Point 7 and point 11 show the dynamic branches in the model.

From the results, we can see that both the natural frequencies and the mode shapes of the test rig are very similar to those obtained from the existing car. It is noted that the inclusion of the tyres and flywheels in the test rig increases the accuracy of simulations of the dynamics of a vehicle powertrain system.

## 4.2 Forced torsional vibration analysis

Forced torsional vibration analysis of the existing car and the test rig were carried out using the engine torque as input. Fig. 6 shows the car wheels' response obtained from the existing car and the test rig under a step input of engine torque from 0.1 second. It is observed that the response of the test rig is in a good agreement with the response of the existing car. However, there are significant errors in the response obtained from the simplified vehicle powertrain model in which vehicle inertia was ignored.

Fig. 7 shows the vehicle wheels' response under a step input of engine torque obtained by using different vehicle powertrain models. The response of a powertrain system that incorporates the tyre dynamic charcteristics is quite different from that of a system that does not take into account the tyre dynamic characteristics.

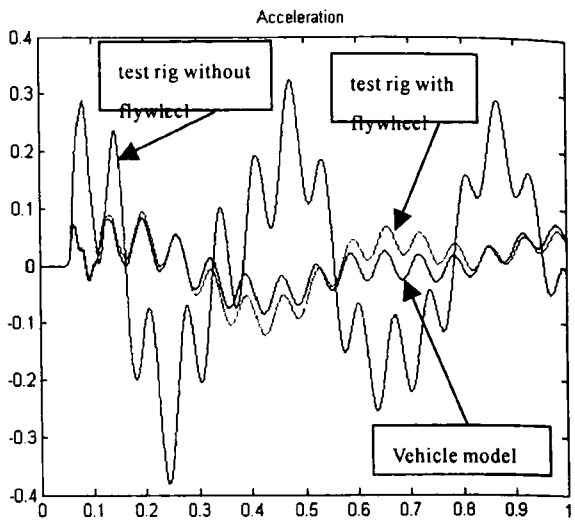


Fig. 6 The wheel's response 1

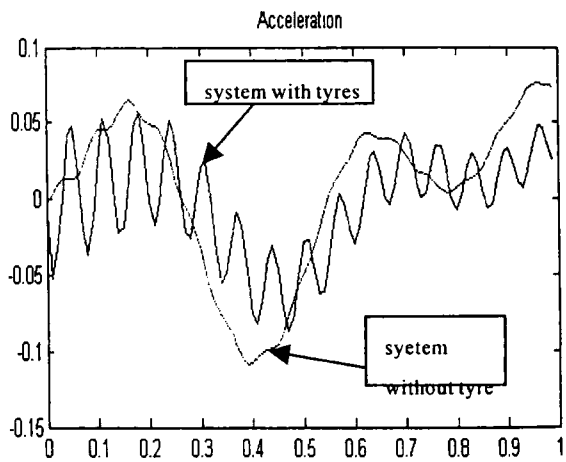


Fig. 7 The wheel's response 2

## 5. Conclusion

A complex vehicle powertrain system test rig has been designed and analyzed. All important powertrain components, including tyres and vehicle inertia have been included in the test rig system. It has been demonstrated that this test rig can accurately simulate real conditions for automatic transmission testing. The free and forced torsional vibration of the complex test rig has been performed and compared to that of an existing car. It is found

that the first global vibration mode of the test rig varies significantly when the gear ratio of an automatic transmission changes. In addition, it is shown that the dynamic characteristics of tyres and vehicle inertia affect the vehicle powertrain system dynamics significantly and their inclusion in the analysis will improve the simulation accuracy.

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