

Theoretical/Experimental Study on the Vibrations of a Car Engine

Luis E. Muñoz, Massimiliano Gobbi,
Giampiero Mastinu and Mario Pennati
Politecnico di Milano

Copyright © 2008 SAE International

ABSTRACT

The influence of the inertia properties (mass, centre of gravity location, and inertia tensor) on the dynamic behaviour of the engine-gearbox system of a car is studied in this paper, devoting particular attention to drivability and comfort. The vibration amplitudes and the natural frequencies of the engine-gearbox system have been considered. Additionally, the loads transmitted to the car body have been taken into account. Both the experimental and the theoretical simulations confirmed that the engine-gearbox vibrations in the range 10 – 15 Hz are particularly sensitive to slight variation of the inertia properties. The effects on engine-gearbox vibrations due to half-axes, exhaust system, pipes and inner engine-gearbox fluids have been highlighted.

INTRODUCTION

The dynamics of the many vehicle subsystems is the true origin of the vehicle overall behaviour. Several papers have studied such mechanical subsystems, often numerical methods [1-4] were exploited. The inertia properties (mass, centre of gravity location, and inertia tensor) of the many vehicle subsystems are often unknown. This paper presents a study on the influence of the inertia properties on the dynamic behaviour of the engine-gearbox system of a car. The study will be focused on a front wheel drive car. The subsystem of interest is the powertrain of the vehicle without the final half-shafts [5].

In the literature, a number of papers have shown the influence of the inertia properties on the dynamics of the whole vehicle, but according to the knowledge of the authors, no papers have been published on the influence of the inertia properties of the engine-gearbox system on its dynamic behaviour.

Two frequency ranges of vibration have been considered, namely 4-25 Hz (referring to the engine-gearbox motion excited by road unevenness), and 25-200 Hz (referring to engine-gearbox motion excited by unbalances and gas pressure) [6].

Multi-body models of the engine-gearbox system have been derived [7-9], particular attention was devoted to the study of the engine mounts, two different models (Kelvin, Maxwell) [6,10] were used. The inertia tensor and centre of gravity location were measured with a special test-rig available at the Politecnico di Milano, named *InTensino* test rig. The *InTensino* test rig is used for the measurement of the inertia properties of vehicle subsystems [11,12]. The validation of mathematical models of the engine-gearbox was performed.

Nowadays, there are no standards in the world stating the uncertainty by which the inertia properties of vehicle subsystems have to be known. The results of the sensitivity analysis performed in this paper may be considered as an early attempt to contribute to such a standard [13-15].

According to the common knowledge referring to the dynamic behaviour of cars, at relatively high speed, the vibrations of the engine-gearbox system in the range 10-15 Hz can seriously decrease comfort and even affect safety [16]. The new information provided in the paper refers on how to compute the addressed phenomena in a very accurate way (which does not seem commonly made by automotive engineers).

The paper deals with the modelling of the vibrations of the engine-gearbox system, the validation of the derived model, the analysis of the parameters affecting such vibrations, the assessment of the allowable uncertainties in the measurement of the inertia properties of the engine-gearbox system of a front wheel drive car.

SOURCE OF ENGINE-GEARBOX VIBRATIONS

During the normal operation of a car, the passengers perceive vibrations and noise. The engine-gearbox system is one of the main sources of these dynamical excitations. In order to understand its dynamic behaviour, the engine-gearbox system can be modelled as a rigid body attached to the chassis by some viscoelastic elements.

Under normal operation, there are two main sources of excitation of the engine-gearbox [6]. The first excitation

source is the road irregularity. The frequency range for this excitation is 0 – 25 Hz. The second excitation source is the engine operation: both the unbalanced dynamic forces and internal combustion pressures generate such an excitation in the 25 – 200 Hz frequency range. Figure 1 presents schematically the two excitations, acting on a simple model of the engine-gearbox.

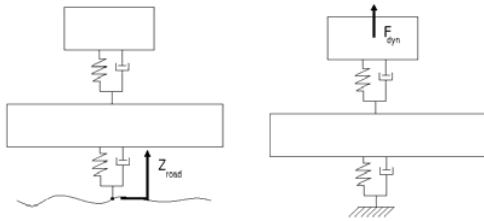


Figure 1. Main excitations acting on the engine-gearbox. Left, road irregularity excitation. Right, excitation from the engine operation.

EXCITATION CAUSED BY THE ROAD UNEVENNESS

Road irregularity generates a random excitation of the vehicle car body. In the literature, there are several papers studying the dynamic response of road vehicles subjected to random excitation [17-20]. The power spectral density of road irregularity is usually very simple, with the form $1/\omega^2$ [21,22]. Associating a driving speed with a road characteristic, a frequency description of the stochastic vertical input given to each one of the wheels (corresponding with z_{road} in Fig. 1) is obtained. The higher driving speed, the wider frequency band. Considering a typical power spectral distribution of a road and a realistic speed, the excitation from the road results practically bounded in the 0-25Hz frequency range (it is always unbounded, but the power content of the frequencies over 25 Hz is negligible). When the unevenness corresponds to an isolated bump the input can be modelled as a step of the vertical displacement of the wheels. The frequency (25 Hz) at which the car body is excited is bounded due to the response of the suspensions subsystem.

EXCITATION CAUSED BY THE ENGINE OPERATION

During the operation of a classical internal combustion engine, there are three main sources of excitation, namely dynamical forces, dynamical moments and actions due to fuel combustion [6, 23]. The frequency of the excitation is governed by the frequency of rotation of the crankshaft, and higher order harmonics. For the particular case under study, with a four cylinder in line engine, the harmonics of first order are equilibrated. This configuration is characterized by an excitation of harmonics of the second order.

The excitation originated by the combustion is generated by the change in the internal pressure of the cylinders, which also generates an oscillation on the delivered torque. This oscillation is minimized in the multi-cylinder

engines. For the four times engines, the second order is the most important, but due to the irregularity on the consecutive combustions there are also small components in the half-orders (for each piston, the excitation corresponds to one explosion every two turns of the crankshaft)

Considering the 900-6000 RPM operative range for the engine, the frequency range associated to the second order harmonics is 30-200 Hz. If the irregularities on the combustion are considered, the associated frequency range is 7.5-50 Hz, overlapping the road unevenness range.

SYSTEM DESCRIPTION

TESTING VEHICLE

The research was developed by using as testing vehicle a five doors saloon front wheel drive car. The engine-gearbox system of the testing car is formed by a 1900 cc four cylinders turbo diesel engine and a six gears manual transmission. The mounting system of the engine-gearbox of the testing car uses three mounts under the system and a reaction rod.

For both the experimental and the numerical activities, two main reference systems were used for the representation of the vehicle and its engine-gearbox system. The first reference system, named *Car Body Reference System (CBRS)*, is fixed to the chassis. The second reference system, named *Engine Reference System (ERS)*, is fixed to the engine-gearbox system. Both reference systems are shown in Fig. 2. The orientation of the ERS referred to the CBRS in the static condition is defined by a ZXY relative rotation, with $[\rho \ \beta \ \sigma] = [162^\circ \ 0 \ 90^\circ]$.

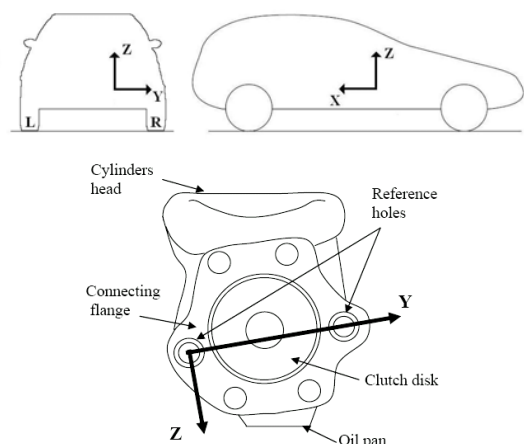


Figure 2. Reference systems (Top, CBRS; Bottom, ERS)

The inertia properties for the engine-gearbox system were measured by using the *InTensino* test rig, designed and built at the *Politecnico di Milano*. The inertia properties of the vehicle engine and gearbox were measured without internal fluids. The *InTensino* test rig

is shown in Fig. 3. The values for the inertia properties of the engine and of the gearbox are reported in Appendix A.

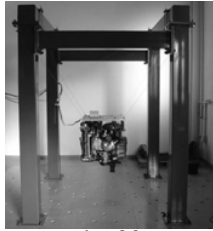


Figure 3. InTensino test rig. Measurement of the inertia properties of the engine.

EXPERIMENTAL SETUP

The engine + gearbox were instrumented with a set of single axis accelerometers fixed to the engine. The accelerometers were positioned properly to acquire the dynamic behaviour of the engine-gearbox system (six degrees of freedom). The locations of the accelerometers are reported in Appendix B.

The accelerometers were fixed to the engine through a frame. The frame served also as the support for the excitation system used during the tests and for some additional masses used in order to modify artificially the inertia properties of the engine-gearbox system. The frame used to fix the additional mass was designed with its first vibration mode higher enough (first vibration mode corresponds to 817 Hz, see Fig. 4) not to influence the tests.



Figure 4. FEM output describing the modal shape of the first natural frequency of the frame (817 Hz).

Excitation system

For the experimental characterization of the engine-gearbox vibration behaviour, the system was excited by the system in Fig. 5.

The excitation system was composed by an eccentric mass, a DC motor and a fixing base. The excitation system was attached rigidly to the engine (the first natural frequency of the fixture was well above 200 Hz in all the configurations). Three different orientations of the excitation system were tested. The configurations were defined by the alignment of the rotation axle of the motor with the three axes of the ERS. Fig. 5 shows the three configurations for the engine-gearbox excitation during the experimental tests. The rotation frequency of the eccentric mass varied from 4 Hz up to 100 Hz. The selected excitation generated a force rotating in a plane, and provided an excitation to all the vibration modes. The excitation was characterised by measuring the angular position of the input with a sensor that generates a sequence of pulses.

The experimental tests were performed with the engine turned off (the only source of dynamic forces was the excitation system) and the car body was fixed rigidly to the ground (this allowed avoiding to measure the response of the suspensions, as well as the non-rigid response of the car body).



Figure 5. Orientations of the forcing system. Left, vertical. Centre, transversal. Right, longitudinal.

Testing conditions

There are two main conditions of the engine-gearbox system, namely the *operative condition* and the *only mounts condition* (i.e. the condition in which the engine-gearbox system is supported only on its mounts, without any additional connection to the car body, and without internal fluids). The *operative condition* is the actual condition of the engine-gearbox when the vehicle is working. The *only mounts condition* corresponds to the simplification typically used for the engine-gearbox models.

The testing started with the *only mounts condition*, and then the pipes (air conditioning, fuel, oil, refrigerant and air) were connected to the car body. After that, the exhaust system was connected, and then the half axles were connected. Finally the *operative condition* was reached. The complete list of testing conditions is

1. *Only mounts condition*.
2. *Mounts & pipes condition*.
3. *Mounts, pipes & exhaust system condition*.
4. *Mounts, pipes, exhaust system and half-axles condition*.
5. *Operative condition* (as the previous, plus internal fluids).

EXPERIMENTAL RESULTS

The excited motion of the engine-gearbox was detected by six accelerometers whose spatial locations are reported in Appendix B.

For each testing condition, the normalized frequency response of every single accelerometer is reported. The normalization uses the magnitude of the input force as reference. The characterization was performed in the 4-95 Hz frequency range.

ENGINE-GEARBOX DYNAMIC BEHAVIOUR

Figure 6 shows the results in the complete frequency range for the *only mounts* testing condition; those data

are used both for the validation of the mathematical models and the comparisons between the different testing conditions. The same results are zoomed in figure 7, where the frequency range considered is 5-20 Hz. The results for the operative condition, zoomed between 5-20 Hz are shown in figure 8.

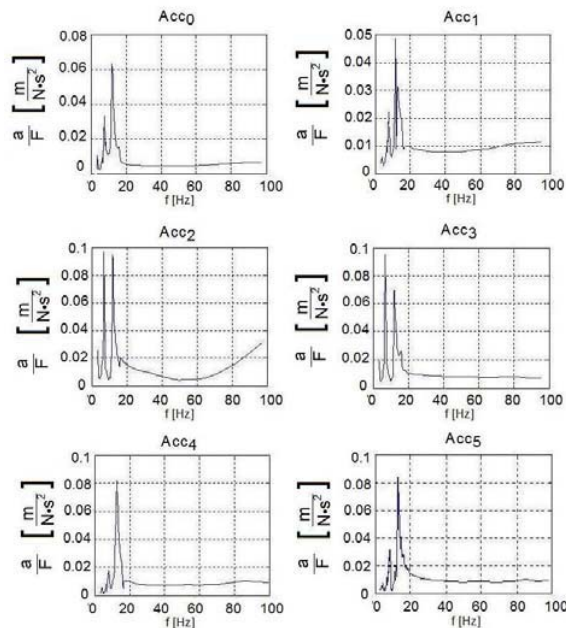


Figure 6. Results from the experimental tests; *only mounts* condition. Frequency range 4-95 Hz. Accelerations in normalized form (see Appendix B).

EFFECT OF THE OTHER ELEMENTS ATTACHED TO THE ENGINE-GEARBOX AND THE INTERNAL FLUIDS

The comparison between the only mounts condition and the operative condition in the 9-18 Hz frequency range is shown in Fig. 9. A change on the resonance frequencies and the resonance amplitudes is highlighted.

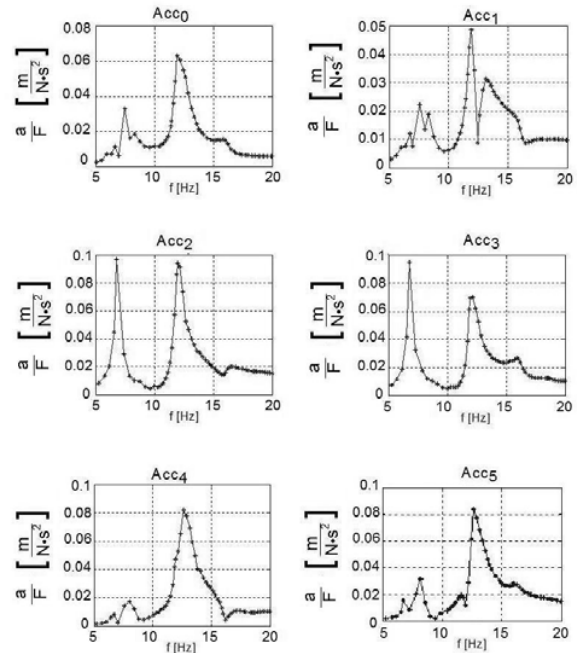


Figure 7. Results for the experimental tests; *only mounts* condition. Frequency range 5-20 Hz.

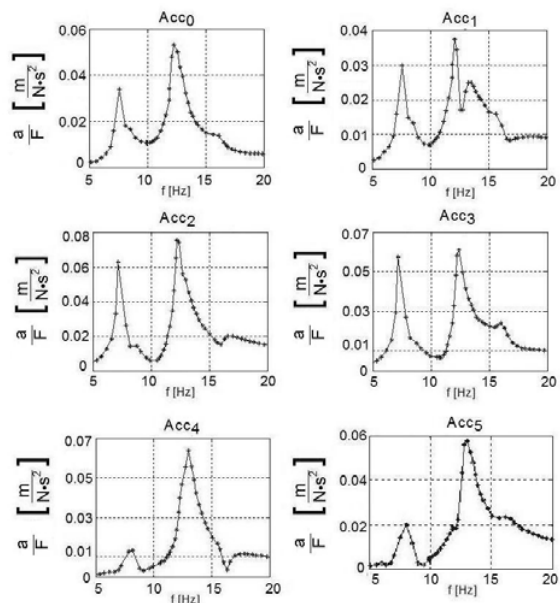


Figure 8. Results for the experimental tests; *operative* condition. Frequency range 5-20 Hz.