

Inertia Tensor and Other Mass Properties Measurement for Automotive Applications

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ABSTRACT

A method for the measurement of the full mass properties of vehicles and subsystems is presented.

The knowledge of the center of gravity location and of the inertia tensor of vehicles and subsystems is fundamental for performing accurate dynamic simulations, ranging from handling to durability.

The accurate estimation of the inertia tensor can be achieved primarily via experimental tests.

Given a rigid body and its mass, the proposed method allows to measure the center of mass location and the inertia tensor during a single test.

The proposed technique is based on the analysis of the free motion of a multi-cable pendulum to which the vehicle or the subsystem is connected. The body under test is made rotating around three axes passing nearby the body center of mass with a highly non linear motion. The motion of the pendulum and the forces acting on the system are recorded and the mass properties are identified by means of a proper mathematical procedure based on a least square estimation. After the vehicle or the component is positioned on the test rig, the full measurement procedure takes a few minutes. The natural frequencies of the pendulum and the accelerations involved are quite low, making this method suitable for full vehicle testing.

In the paper, the proposed method is described and two test rigs are presented: the first has been developed for road vehicles (up to 3500 kg) and the second for vehicles components i.e. engines, gearboxes, ... (bodies up to 400 kg). A validation of the measurement method has been performed with satisfactory results. Both the center of gravity location and the inertia tensor components can be identified with very high accuracy. The test rigs hold a third part quality certificate according to ISO 9001 standard.

The system can be easily scaled up to measure the mass properties of large vehicles such as trucks, busses and even airplanes.

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INTRODUCTION

Dealing with the dynamic simulation of complex mechanical systems, such as vehicles, requires the accurate knowledge of the mass properties. The mass properties of a rigid body are a set of ten parameters, namely the mass, the location of the center of mass and the inertia tensor-3×3 matrix. Due to the difficulties in getting such data, very often, the mass properties are roughly estimated reducing very much the accuracy of simulation results.

A number of contributions has been given [1,2] on the problem of defining an acceptable level of uncertainty on the mass properties for getting reliable simulations. Referring to vehicle simulations, (both ground or aero-space vehicles), it has been proved that small errors in the mass properties produce non negligible errors in the computed dynamic responses [1],[2],[3],[4],[5],[6],[7]. This problem, with particular focus on ground vehicles, will be discussed in the first section of this paper.

A common practice for the estimation of mass properties is their computation by means of 3D CAD models. Such an estimation is prone to errors generated by the huge amount of data that must be entered especially when very complex systems such as vehicles are considered. Errors on the inertia tensor components of more than 5% (and sometimes, much more) are commonly experienced for complex systems composed by thousands of parts.

The most reliable way to get an estimation of the mass properties of complex mechanical systems is resorting to experimental tests. Many test rigs have been presented in the literature for the measurement of the mass properties of rigid bodies, some of them explicitly designed for measuring the mass properties of ground vehicles.

Among the mass properties, only the mass is indirectly measurable with very high accuracy [8],[9],[10]. The center of mass coordinates can be identified together with the inertia tensor components by dedicated test rigs [10,26]. For a ground vehicle, the measurement of the center of mass location is a straightforward operation only for the two coordinates in the horizontal plane [11],[12]. For the third coordinate, quite complicated approaches are needed and poor measurement accuracy has to be expected.

Referring to the measurement of the inertia tensor, only rigid bodies with a symmetry around one axis or along one plane can be processed in a relatively simple way (industrial applications can be found in [13]). For non symmetric and heavy bodies, (such as ground vehicles and their subsystems), many different approaches have been realized. These can be grouped in two main classes: the components of the inertia tensor are identified one at a time or they are identified all together.

In the first case, the body is made rotating around a defined axis and the moment of inertia with respect to that axis is measured [14],[15],[16],[17]. At least six different rotation axes have to be used to derive all of the components of the tensor. By this approach, the accuracy can be high but usually cumbersome hardware and long testing time are required to obtain all of the required rotation axes.

In the second case, the body is made moving in order to excite all of its rigid modes [18],[19],[20],[21],[22],[23] [24]. Even if the motion could be just a vibration ([18],[19]), for automotive applications complex non linear motion at low frequency ([20],[21],[22],[23] [24]) are used. The motion can be imposed by actuators [23],[24] (in this case the actuating forces are to be measured, for instance by means of six axis load cells [25],[26]) or it can be a free motion in the gravitational field [20],[21],[22]. The advantages are a shorter testing time and the possibility to identify the center of mass location along with the inertia tensor. However, in case the actuators are involved, the test rigs can be relatively complex.

The experimental measurement of the mass properties for ground vehicles and their subsystems is the main topic of this paper. After the definition of the required accuracy for the mass properties, two test rigs able to measure the mass properties of full vehicles and their subsystems are presented. These test rigs are based on the non-linear motion of a multi-cable pendulum from which all of the required mass properties are measured at the same time. By letting the pendulum freely swinging in the gravitational field there is no need for actuators, thus reducing the complexity and the cost of the test rigs.

1. INFLUENCE OF THE MASS PROPERTIES ON VEHICLE DYNAMICS

The influence of the mass properties (mass, center of gravity and inertia tensor) on the dynamic of the vehicle is important both referring to vehicle comfort and handling and to the noise vibration harshness (NVH) due to the vibrations of the engine-gearbox system.

1.1 Influence of the Inertia Tensor on Vehicle Comfort and Handling

The effect of the mass properties on vehicle comfort and handling can be estimated by means of mathematical models shown in figure 1 and 2 [2].

Fig. 1 shows a linear nine-degrees of freedom model of the vehicle able to simulate a vehicle running on a rough road and has been validated as shown in [2]. The degrees of freedom are the four vertical displacements of the unsprung masses, vertical and lateral displacements of the center of mass of the vehicle and the three rotations of the vehicle. The tires are described by a steady state Pacejka model plus a first order differential equation for the transient behavior. The resulting non linear equation of motion are linearized around the steady state condition [2].

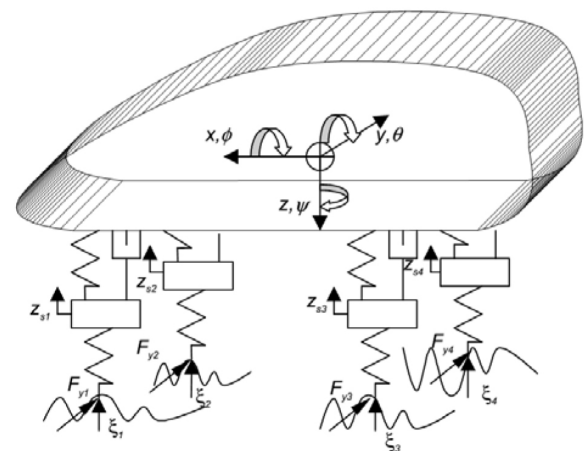


Figure 1. Nine degrees of freedom linear model for comfort performance evaluations, adapted from [2].

The model in Fig. 2 represents a non-linear full model of a vehicle. The model is composed by modules, each module represents a vehicle subsystem interacting with the other subsystems by means of input-output variables. The model can be easily adapted to different vehicles by simply modifying the different modules [2],[27]. The chassis is modeled as a rigid body, the suspensions are double wishbone type with non linear shock absorbers and bump stops, the brake distribution and the transmission are fully described. A Pacejka model plus a first order differential model are used to describe the steady state and transient behavior of the tires. The elasto-kinematics of the suspension and the combined longitudinal-lateral behavior of the tires are considered. This model is able to reproduce the handling performances of a vehicle and has been validated as shown in [2].

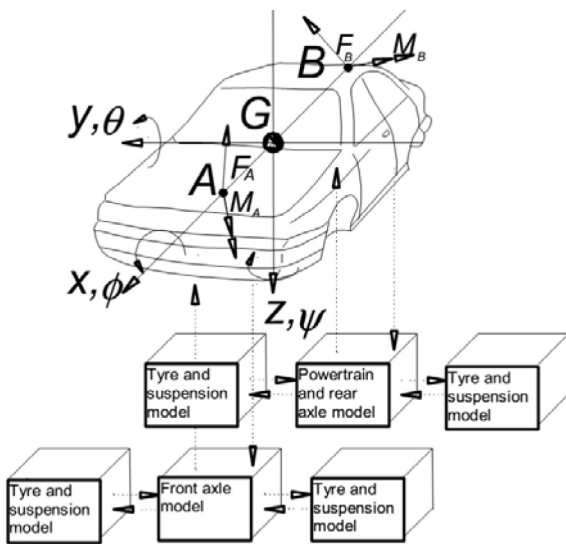


Figure 2. Fully non linear vehicle model for handling performances evaluation, adapted from [2].

By using the first model, the running over a rough road has been simulated at different speeds (ranging from 10 to 50 m/s). Different values of the components of the inertia tensor have been considered in the simulations. From the results of the simulations, it appears that

- the vertical acceleration on the driver seat is affected by the components J_{xx} and J_{xy} (J_{xx} affects the roll vibrations, while J_{xy} couples roll and pitch motions)
- the acceleration of the driver head is affected by the components J_{xx} and J_{xz}
- the driver longitudinal acceleration is affected by the component J_{yy}
- the road holding (standard deviation of the vertical forces on the tyres) is not affected by any component of the inertia tensor
- the vehicle on line centring behaviour (directional stability) is affected by the component J_{zz} .

The second model has been used to simulate the handling behavior of a racing car. Two maneuvers have been considered, namely a steering step input (speed 40 m/s, steer step 0.05 rad at wheels) and a passing over a kerb while steering (speed 40 m/s, steer step 0.05 rad at wheels, kerb height 50 mm). The simulations have shown that the steering maneuver is not influenced by any component of the inertia tensor. The passing over a kerb while steering maneuver has shown that in case $J_{xz} \neq 0$ the vehicle can unstable.

From the simulations performed by the two models, it appears that variations of about 3% in the diagonal components of the inertia tensor and of about $\pm 15 \text{ kgm}^2$ of the extra diagonal components can affect in a sensible way the handling behavior of the vehicle. Thus, the components of the inertia tensor of a vehicle should be known with a confidence interval not larger than such values.

1.2 Influence of the Mass Properties on NVH Performances

In Fig. 3 a six degrees of freedom multi-body model that can be used to assess the effects of the mass properties on the dynamic behavior of an engine-gearbox system [1] is shown. The engine-gearbox system is attached to the chassis, which works as ground, by means of three mounts and one connecting rod. The mounts are modeled by means of a seven parameters Maxwell model. This model is able to reproduce the viscoelastic behavior of the mounts and their frequency response. This model has been validated and used to compute the frequency response of the engine-gearbox system.

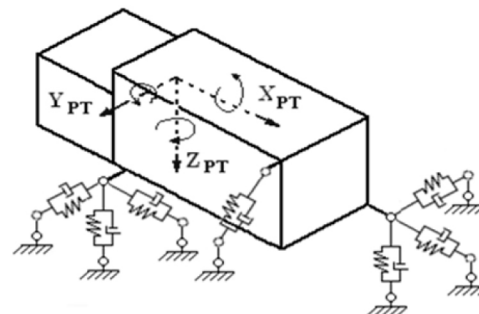


Figure 3. Engine-gearbox vibration model, adapted from [1].

The model has been used to simulate an excitation received from the road irregularity which causes an imposed vertical displacement of the car body. The validation is reported in [1]. The influence of the mass properties (mass, center of mass and inertia tensor) has been estimated by computing the working space (defined as maximum deformation of the mounts) and the root mean square of the force transmitted by the mounts to the chassis.

The results have shown that the effect of the mass properties on the working space is limited, while the transmitted forces are strongly affected by the mass and the location of the center of mass. The natural frequencies of the engine-gearbox vibrations are affected by the components of the inertia tensor. From the