Road profile excitation on a vehicle measurements and indoor testing using a four-post rig

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ABSTRACT
This paper has the purpose to show a procedure, used in the Dep. of Mechanical Engineering of the Brescia University, to esteem the excitation acting on a two or four wheeler vehicle due to the road profile and to reproduce, making use of these measured data, the acquired load spectrum in indoor testing sessions, conducted on the same vehicle. The paper explains the features of the testing device and the testing modalities. It also presents some results obtained from this procedure applied on a car, to test its behaviour.

This research project has potentially a great number of applications in the automotive and transportation industry, because it allows to test in indoor sessions the behaviour of vehicles, of their components and of the transported goods, when they are excited by actual road profiles, coming from an opportunely created database.

Different kink of road surface irregularity has been considered and indoor performed on the four-post rig. A comparison between the “measured/performèd” road irregularity and the “real” road surface can hardly made, wherever the correspondence between the effects of the two on the vehicle (indoor and outdoor vertical acceleration and wheels-body displacements) are good. For this reason it is not possible to give an uncertain of the “measure” made (road surface irregularity), but it is possible indicate that the estimation of the parameters are quite close to reality.

KEYWORDS
Vehicle, indoor testing, vibrations, road surface

1 INTRODUCTION
In all the industrial fields the chance to develop indoor tests on products, to be carried on them before their release on markets, offers great advantages in terms of quality and reliability. Most of all, these aspects have great importance in the transport industry, including the production of transportations (cars, trucks, trains, planes), components and also goods to be transported.

In consequence of this consideration it’s easy to explain why during the last years NVH (Noise, Vibration and Harshness) analysis has become more and more important particularly in the automotive field. In the immediate future new vehicles will have a success on markets only if they show great quality in terms of handling behaviour and vibration comfort.

Testing modes to be applied on different devices are described by a great number of specifications (usually concerning random vibration testing). Nevertheless it’s often impossible to prevent the load spectrum due to the roughness of roadbeds, acting directly onto the vehicle in some specific positions (interior compartment, dashboard, engine bay, trunk).

This paper concerns the developing of a testing methodology, used to file different kinds of actual roadbeds in a database, allowing to reproduce, on a dedicated testing rig, roadbed roughness effects on two or four wheels vehicles.
2 FOUR-POST RIG

Indoor testing sessions on two or four wheels vehicles can be carried on using a testing rig called four-poster, belonging to the Dep. Of Mechanical Engineering of Brescia University. It is constituted by four servohydraulic actuators simultaneously controlled in position, which support four vibrating boards. These can be driven by an opportune signal in the range of frequency 0-100 Hz. Different kinds of testing are possible: sine test (sweep in frequency); simple waveform on each actuator; open loop test (driven by an external tension signal); a particular testing method called ICS control, which allows to reproduce on a car an actual service environment, starting from those data coming from the outdoor acquisition sessions.

The four actuators are installed on a basement made of cast-iron. This is isolated from the ground by six pneumatic springs. The testing rig is completed by a power hydraulic central and a control console, including a computer based controller (DCS2000) and a data acquisition unit.

Each actuator is equipped with one displacement LVDT sensor, which is located in the rod. The displacement control loop is made possible by these transducers.

3 INSTRUMENTED VEHICLE

A commercial car of medium dimensions (a Citroen Xsara Break 2.0 HDI) has been used to be tested. This car has been opportune instrumented with some transducers, which allow to view and record directly on road some of the most important mechanical quantities, concerning the aspects of vibrations and comfort on the car itself.

In testing session the instrumentation installed on the car was constituted by:

- four capacitive accelerometers, placed in correspondence of the upright of each tyre;
- one accelerometer, of the same type, collocated in a position which is likely near centre of gravity of the car;
- four resistive displacement transducers, placed between upright (wheel) and body of each wheel;
- an acquisition system based on a mobile PC, allowing to acquire the desired signals.

In figure 1 instrumentation mounted on vehicle uprights have been shown.

Figure 1 – Accelerometer and displacement transducer mounted on vehicle
The accelerometers, as mentioned, are of capacitive type; they have a passband of 0-300 Hz. Preventively a verification on the dynamic properties of these transducers has been conducted; they have been tested on a vibrating board, comparing their output with the one coming from an ICP piezo-accelerometer, taken as reference transducer. The used capacitive accelerometers are equipped with an input tension regulator. This has allowed to feed them, during the outdoor sessions, in an almost simple way, using a series of commercial vehicle batteries.

Particular attention has been taken on the criterion used to fix each accelerometer on the correspondent upright, because there was the need to ensure to the transducers enough protection from the mechanical and environmental actions on them (pebbles, water sprays, etc.), avoiding introducing causes of uncertainty depending from the position and from the fixing modalities (fixing plates).

For the purpose to estimate the pitch movements of the vehicle also four position transducers, of resistive type, have been placed on the car to acquire in service conditions the real deflection of each spring-damper system. We observed that the possibility of evaluating (relative) displacement measures, in addition with the acceleration ones, guarantees a better convergence for the method used to recreate actual roadbeds on the ICS analysis system.

For this transducer and for the aim of the testing done the uncertain can be consider of the order of 2 %.

4 OUTDOOR TESTING

The instrumented vehicle has been used to acquire some acceleration time histories on the uprights for some different kinds of roadbeds: bitumen paved road, bad surface road, paved road with a series of irregularities (“3M” road humps and traps), cobblestone road
and off-road. This allows to create a wide database of road profile load spectrums, in terms of wheels displacement.

Figure 3 – “3M” road humps

In figure 3 one of the road surface irregularity has been shown. Signals have been sampled at a frequency of 512 samples/s. Figure 4 shows the front upright (left and right) vertical acceleration time history recorded on vehicle on a bitumen paving road with hump (3M speed limiter). In figures 5 the PSD of recorded vertical acceleration signal are reported.

Figure 4 – time history of acceleration recorded on vehicle

Figure 5a shows the PSD of the four upright (front-rear left-right) acceleration recorded on a bitumen paving road with hump (“3M” speed limiters). In all the cases the signals have a relevant amplitude only in the range 0-25 Hz. Figure 5b shows a comparison between two PSD (of the same rear left upright) on two different road paving. In term of PSD solicitation on vehicle wheels are the same.
5 INDOOR TESTING PROCESS (ICS)

The operative process applied during the testing is based on the ICS software. This software is a commercial software and it has been developed specifically to provide simulation control capabilities to test rigs that are required to reproduce accurately the dynamic response that is present when a test specimen is subjected to actual service conditions. Figure 6 shows the key elements in the simulation process and how ICS Analysis, along with DCS2000, serves the process.

As previously mentioned, the test system is given by four servohydraulic actuators, which provide the excitation to the test rig under closed loop control, using DCS2000; the control is displacement (given by LVDT transducers). The actuator control parameters are the same as the dynamic response measurements that need to be reproduced: the tested car is equipped with five accelerometers, which have a sensibility of 200 mV/g. The servocontroller receives its command inputs from the test rig controller; on the DCS2000, this last element is integrated in the servocontroller.

The test rig controller provides synchronised data acquisition and control signal generation capabilities, for up to 16 channels. The data acquisition section is used to measure the response from the transducers fitted to test specimen (accelerometer placed
on the car), while the control signal generation section is used to provide the command signals (concerning displacements) for the servocontroller, these are then played out to the rig in the form of a drive file. The reproduction of the test specimen response, from the same transducers used to measure the service conditions, is carried out by the simulation control software. ICS analysis employs an iterative process that creates a drive file for the test rig controller, that reproduces the desired test specimen response. ICS analysis uses the standard industry approach to simulation testing, but uses an advanced form of iterative de-convolution to produce test rig controller drive files. The basic elements of the process are shown in fig. 6.

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**Figure 7 – ICS Iteration loop**

The first step in the process is to create a mathematical model of the system, the system matrix. The model includes the test rig, the test specimen and all the control hardware and response transducers. To create the model, a white noise signal is used to excite the test rig and the resulting test specimen is collected. The white noise drive file and the test system response file are then used to create a general system model, or matrix. Finally an inverse form of the model, called the inverse system matrix is calculated; this can then be used to predict the test rig drive file needed to reproduce the desired response. Once the system matrix has been evaluated, it’s possible to proceed developing the test rig drive file.

Theoretically if a test system is perfectly linear, the test rig drive file could be generated in just a single pass through the loop shown in figure 7. However all test systems contain some non linearity and noise that require the test rig drive to be generated using more than one pass through the control loop. This process is known as iteration. The number of iterations required to generate the required drive file depends on the gain setting of the control loop and the accuracy of the system model. ICS analysis simplifies the process reducing the number of steps required to calculate the system model and generate drive files.

### 6 RESULTS

The testing instrumentation has been used to simulate the behaviour of the car in different service conditions. In this section the most important results are shown; in
particular, some actual roadbeds acquired during the outdoor sessions, are taken into consideration: road with 3M humps, cobblestone road. The graphs presented in figure 8 (a, b, c, d) show the results obtained in the first of the mentioned conditions: the four graphs refer to the accelerations acquired on the uprights of tested vehicle (FL stands for front left upright; FR stands for front right upright; RL stands for rear left upright; RR FL stands for rear right upright), which are represented in the time dominion. Each one of the graphs shown in figure 6 allows to notice a good accordance of the indoor acquired signal with the one taken in condition of actual service for the tested car (outdoor). For each case it is simple to calculate the RMS error between the two curves considered (indoor/outdoor).

The graph shown in fig. 9 concerns the acquisition about the FL upright; it is built on a different time section than the one considered in fig8 (a). The comparison between these
two diagrams witnesses the good accordance of the outdoor acquired data with the indoor ones on the entire time horizon.

Figure 9 – FL acceleration in a different time section

The same diagrams, concerning the case of the cobblestone road, are presented in fig. 10 (a, b, c, d).

Figure 10 – Uprights acceleration on cobblestone road

In this case the signal has a greater frequency, as it could be expected. Also in the present situation (cobblestone road), the diagrams show a good accordance between outdoor and indoor acquired data.

The graph shown in fig. 11 illustrates the acquisition about the FL upright evaluated in a different time section than the one considered in fig 10 (a): it can be noticed that a good
accordance between the two groups of data is maintained on the entire acquired time range.

Figure 11 – FL acceleration in a different time section

Figure 10a shows the drive file pointed out by the ICS analysis system (in the last of the considered iterations) using as response desired file the one acquired in the case of testing of the vehicle behaviour (in outdoor sessions) on a roadbed with 3M road humps on it’s surface. In this diagram FL stands for front left upright while FR stands for front right upright. The y axis shows the displacement given by the servontroller to the specific hydraulic actuator (FL or FR); the x axis reports time. As it should be expected the two curves are very similar, witnessing that the two front uprights are subjected, in the indoor test, to the same kind of load spectrum.

Figure 12 – (a) ICS Drive - (b) Road surface profile vs. actuator displacement

From the drive file it’s possible to point out a profile which describes the trajectory of the upright, corresponding to the envelope curve of the positions taken by the point of contact between the tyre of the car and the roadbed. If the car speed is known, it’s possible to give this curve in function of the horizontal displacement of the car (x) itself, obtaining these values by a simple abscissa transformation (multiplying time by speed). This curve, calculated for the front left upright is presented in fig. 12b, where it is compared with the profile of a 3M road humps 400mm wide and 30 mm high. The axis of the graph are vertical (y) and horizontal (x) displacement given in millimeters. The comparison between the two curves shows that the drive file follows almost closely the
actual profile of the considered roadbed, showing the reliability of the used acquiring and testing methods.

7 APPLICATION ON A TWO WHEELS VEHICLE

Indoor simulation on four wheels vehicle not allows to perform inertial solicitation due to frontal acceleration of the car. Wherever for many dynamic NVH analysis on vehicle this kink of solicitation do not give a great contribution in terms of comfort and active safety on car [4].

A different solution has been used for testing two wheels vehicle using the “bike-shake” developed by the Department of Mechanical Engineering of Brescia University, as shown in figure 13. The drive files created using procedure described in this paper have been used to study road surface solicitations on components mounted on a motorbike. Inertial load due to frontal acceleration of the bike can be reproduce using pneumatic actuator directly on the wheel as shown in [5].

Figure 13 shows the bike during a testing session.

8 CONCLUSION

A methodology to evaluate the road profile excitation on vehicles has been presented. Results obtained are quite satisfactory and the “synthetics road” can be used to test vehicle different by the ones used to esteem it.

Testing has shown that using only the vertical acceleration measured on vehicle on road it is not possible to reduce the gap between recorded and reproduced signal under a certain level. Wherever different testing sessions has be performed using the vehicle equipped with 7 acceleration transducers (4 on wheels and 3 on vehicle body) and 4 displacement (resistive) transducers to measure the relative displacement between body and wheels.
The use of displacement transducer allows to reduce the gap between real and reproduced signals thanks to the amplification (to the low frequency) of the frequency range of relevant measured quantities. Results obtained show a good correspondence between the observed (outdoor quantities) and reproduced (indoor simulation) vertical accelerations and wheel-body displacement. For this reason it is possible to used the road surface estimated to perform testing on vehicle.

Reference