

Spectral analysis of a standard test track profile during passage of an agricultural tractor

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Abstract

National statistics on work safety are pointing out a decreasing trend about related injuries and fatalities but an increasing number of reports about professional diseases. In this frame are also considered the mechanical vibrations, in particular whole-body vibrations (WBV). This study aims to reproduce and analyse the vertical displacement of the wheel of an agricultural tractor during the passage on a standard surface (ISO 5008) for defining potential correlations between the surface contour and the effects on vehicle dynamic and driver comfort by analysis of the signals acting under the tractor tires. An agricultural tractor, in four setting conditions and four different forward speeds, was tested on an ISO

5008 standard test track. The accelerations at the hubs of the tractor were acquired and subsequently reproduced on a four hydraulic actuators test bench, at CRA-ING laboratories, Treviglio, Italy. The analysis of the spectrums generated have shown that a roughness surface induces a transformation of the part of energy developed by the forward speed of the vehicle in vertical acceleration that excites the elastic parts (*i.e.* tires, suspensions). These phenomena seem to indicate that vehicle's vibration entity is due to the combination of surface roughness and forward speed as amplitude and to the elastic properties of the vehicle as frequency.

Introduction

National statistics on work safety are pointing out a decreasing trend about injuries and fatalities but an increasing number of reports about professional diseases. A mean value more has been observed of 36% in the last 5 years but data in agricultural environment are increased of 383% in the same period. It's difficult to associate these data specifically to some well identified causes but it is sure that the interest about the occupational diseases is increasing. In this frame are also considered the mechanical vibrations. In particular, whole-body vibrations (WBV) could affect an operator driving an agricultural tractor depending on intensity, duration and frequency.

European Parliament Directive 2002/44/EEC sets the minimum requirements for protection of workers from risks to their health and safety arising from exposure to mechanical vibrations; moreover, in 2008, Italy adopted a specific national regulation on safety (Decree Law n. 81/2008). Although most of the studies are directed to measure comfort (Deboli *et al.*, 2010), vibration dumping and developing models, one of the most important parameter as the surface profile, is not analyzed as expected, above all for the difficult its standardisation and measurement.

Vibrations with frequency lower than 2 Hz can cause smaller and temporary effects like motion sickness, which anyway interfere with the desired development of the work activity and produce a remarkable discomfort. A long-term exposure to vibrations with frequency ranging from 2 to 20 Hz can cause severe disease, like degenerative pathologies of the spine (Chiang *et al.*, 2006; Seidel and Heide, 1986).

The work has the goal to reproduce and analyse the vertical displacement of the wheel of an agricultural tractor during the passage on a standard surface (ISO 5008:2002) for defining potential correlations between the surface contour and the effects on vehicle dynamic and driver comfort.

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State of the art

For agricultural tractors, considering normal conditions of use,

irregularity of working terrains and forward speed are the most important causes of vibrations transmitted to the driver (Scarlett *et al.*, 2007), on tool oscillations and impact on work quality (Bisaglia *et al.*, 2006; Cutini *et al.*, 2011).

For several years, tires have been the main element for attenuation of mechanical vibrations on agricultural tractors. Their effectiveness depends on factors such as eccentricity, load, resonance frequency, and elasticity characteristics (Nguyen and Hinaba, 2011; Sherwin *et al.* 2004; Park *et al.*, 2004; Taylor *et al.*, 2000). So, most of the studies have been directed to the tires' properties, dumping systems and/or their interaction.

However, as aforementioned, in agricultural machines an important factor characterizing the amplitude and frequency of vibrations is represented by the environment, in particular by the soil unevenness.

Soil unevenness has a stochastic character; its deformation has a non-linear, visco-elastic-plastic behavior and its condition depends on a wide range of parameters (cultivation, cropping/tillage history, texture, organic residue, drainage conditions, etc.) so that it is almost impossible to standardize testing conditions in fields. For this reason, the experimental test has been carried out on the smoother ISO, 100 m track. To analyze the effect of surface outline on the vehicle body is necessary to obtain the displacement, or the accelerations, acting under the tires.

The most common existing approach (Anthonis, *et al.*, 2007; Bisaglia, *et al.*, 2006) consist in an iterative methodology. During the field test, the accelerations are measured at specific locations of the machine (usually at the hubs), then the machine is put on a test bench and the actuators (one for each tires) of the bench are driven in order to create, by a deconvolution method, input signals such that the sensor readings (one for each hubs) match with the measurements (accelerations) obtained in the field.

Theoretical considerations

An iterative deconvolution method is a computerized control technique that enables to duplicate, in the test laboratory, vehicle or component responses measured during field testing. The calculation of the control signals for the actuator of the test bench, called drive signals, is a multivariable tracking problem, currently solved with the so-called iterative deconvolution (ID) procedure (Soderling, *et al.*, 1999). ID is an off-line iterative feed forward procedure where the drive signals are updated by the measured frequency response function matrix (FRF) of the test arrangement and the tracking errors obtained in the previous iteration. Several commercial versions of the algorithm were developed. During the laboratory tests the Remote Parameter Control (RPC®) software from MTS Systems Corporation has been used. The drive signals obtained with this procedure can be considered an approximation of the real field surfaces subject to deformations.

Materials and methods

An agricultural tractor, in four setting conditions and four different forward speed, was tested on smoother ISO 5008 standard test track presents at CNR IMAMOTER testing facilities, located at Pratofiorito (Candiolo, TO). The tractor's hubs accelerations were acquired and subsequently reproduced on a four hydraulic actuators test bench, at CRA-ING laboratories of Treviglio (BG).

The vertical displacement of the hydraulic actuators were driven, by specific electronics, for reproducing the profiles defined as the vertical input of the surfaces.

The condition adopted and the relevant test code are reported.

Mass:

- With ballast (_Z)
- Without ballast (_N)

Tires inflation pressure

- 80 kPa (_08)
- 160 kPa (_16)

Forward speed

- 6 km/h (_6)
- 10 km/h (_10)
- 12 km/h (_12)
- 14 km/h (_14)

Three repetitions were carried out for each tests. The sampling frequency was 1250 Hz.

The accelerations at the hubs of the tractor were acquired and subsequently reproduced, as above reported, on the four hydraulic actuators test bench by the deconvolution method.

Tested vehicle

The tested agricultural vehicle is a medium-range tractor, with a four-wheel drive (4WD) transmission, engine with 89 kW rated power, a closed rubber-mounted cabin and a mechanical suspended seat. The most relevant data for the tests are reported in Table 1.

The test track

The ISO 5008 track (Figure 1) consists of two parallel strips suitably spaced for the wheel track of the tractor. The surface of each strip is formed of wooden slats 80 mm wide, each slat separated from the next by a gap of 80 mm. Slats are sited firmly in a base framework. The surface of each track strip has been defined by the ordinates of elevation, with respect to a level base, listed in Tables of ISO 5008.

Operative conditions

During the tests, the tractor ran at four forward speeds (6, 10, 12 and 14 km/h), with tires at two inflation pressures (80 and 160 kPa). All tests were performed in unballast and ballast conditions. In the ballast tests, an 800 kg ballast was connected at the rear three-point hitch and a 320 kg ballast at the front.

One experienced operator (70 kg mass, 180 cm height) carried out all the tests.

Table 1. Tractor characteristics.

Item	Parameter	Unit/type	Value/type
Tractor	Power	kW	89
	Wheelbase	mm	2467
	Front width track	mm	1700
	Rear width track	mm	1800
	Front mass	kg	2230
	Rear mass	kg	2960
	Cab suspension	type	Rubber mounts
	Front axle suspension	type	None
	Seat suspension	type	Mechanical
Front tires	Overall size	ETRTO 2005	420/85R24
	Treads	n.	22x2
	Treads height	mm	41*
Rear tires	Overall size	ETRTO 2005	460/85R38
	Treads	n.	22x2
	Treads height	mm	42,5*

*Measured at 160 kPa at the midpoint of two consecutive noses, medium value of three measurements. The value was the same between right and left.

Acquisition times ranged between 59 s at 6 km/h forward speed and 25 s at 14 km/h.

Each test was replicated three times.

Four poster test bench

The CRA-ING four-post test bench is specifically designed to test large and heavy vehicles up to 15 t (Figure 2).

The test rig is composed of a seismic mass of 408 t weight, isolated from the ground by means of pneumatic springs, supporting four servo-hydraulic actuators, articulated for wheel-base/track adjustment. On the top of actuators are fixed four plates 1000 mm diameter upon which the tires of the vehicle are placed. Are also present a power hydraulic and a control unit, including a computer-based controller and a data acquisition unit.

Each actuator is controlled in position (up to a frequency of 100 Hz and a peak-to-peak amplitude of 250 mm) and excites one tire of the vehicle in vertical direction.

The displacements of the actuators are measured through linear variable differential transformer (LVDT) transducers, whose output signals are acquired and recorded.

Measure instrumentation

The vehicle was instrumented with a set of four piezo-electric monoaxial accelerometers (range ± 50 g, sensitivity 100 mV/g) to measure the wheel hubs vertical acceleration. The output accelerometer signals were sent to a signal conditioner (Rogadaq 16) and then to a heavy-duty personal computer (Panasonic CF29).

Results

The acceleration registered on the standard track were reproduced at the four poster test bench.

A mean value of the root mean square error (RMSE) was 20.

Graphic example are reported in Figures 3 and 4.

Figure 3 shows the spectrum of both the desired ($_des$) and the reproduced signal ($_res$) in the test condition at 10 km/h, without ballast, tire pressure of 80 kPa, rear left hub (RL).

Figure 4 shows the spectrums of both the desired ($_des$) and the reproduced signal ($_res$) in the test condition at 10 km/h, without ballast, tire pressure of 160 kPa, front left hub (FL).

The analysis of the spectrums shows that, in each test, there is an energy peak proportional, as amplitude, to the forward tractor speed correlated to the elastic properties of the front tires. This peak must have been considered as an effect due to the specified tire models and not to the surface type.

In each test there are energy peaks corresponding to the vibration modes of the cabin. These peaks must be considered as a side effect correlated to the dynamics of the vehicle and to the test conditions and not to the surface type.

It can also be seen that, regardless of the surface type, moving towards and increasing forward speeds there is a correspondent increase of the spectrum magnitude in the whole range of frequency.

The surface types show similar frequency spectrum shapes, regardless of the forward speed: the power spectral density is most relevant at the lower frequencies (< 3 Hz); increasing frequency the spectrum magnitude rapidly decreases. Between 4 Hz and 10-12 Hz the spectral components are less relevant. Above 12 Hz the spectral components are negligible; over this frequency band the spectrum is flat and the signals can be considered "white".

Two auto spectral density spectrum (ASD) are reported as example

in the N₁₆ setting: Figure 5 shows the mean value of the displacement of the two front plates and Figure 6 of the rear.

In the frame of the comfort analysis it must be considered that two filters have been applied to the spectrums of the plates' acceleration:



Figure 1. The standard test track.



Figure 2. The four poster test bench.

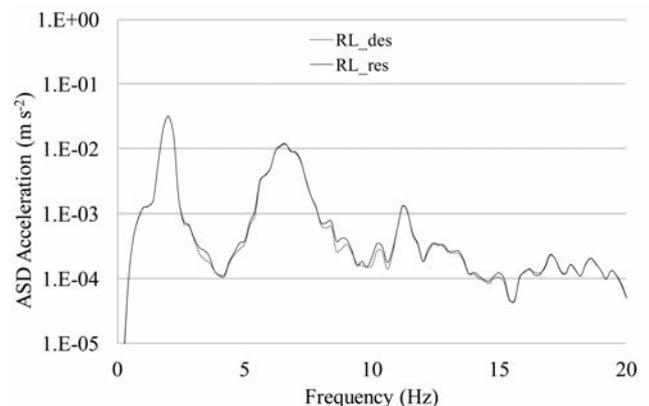


Figure 3. Example of reproducibility on the RL hub in R10_N08 condition.

the filter related to the vehicle (tire, cab, seat) and the filter related to the procedure (ISO 2631).

The outcome is that the frequency band of interest results 0.6-12 Hz with a major contribute between 1-4 Hz.

The interpretation of the results requires to consider the solicitation

of the elastic part of the vehicle, as the change in rolling radius of the tires, when passing over a cleat. The forces induced depend from the surface forward curvature such as road unevenness. In the effort to evaluate the effect of rolling over an obstacle it is important to consider the increment in normal slope as height, curvature and length.

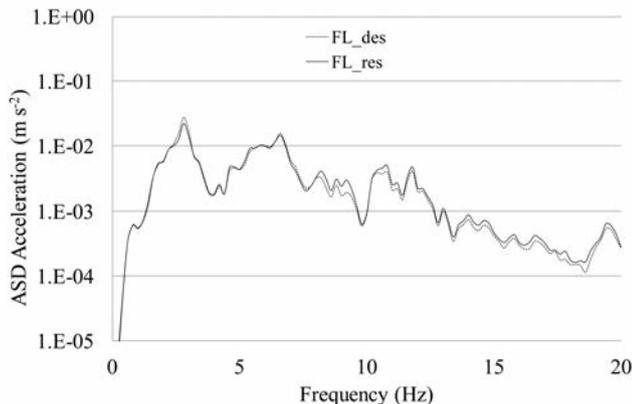


Figure 4. Example of reproducibility on the FL hub in R10_N16 condition.

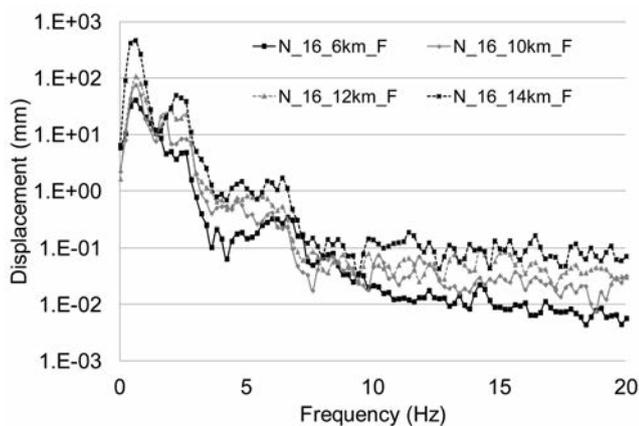


Figure 5. ASD Spectrum of the settings N_16 on the front plates.

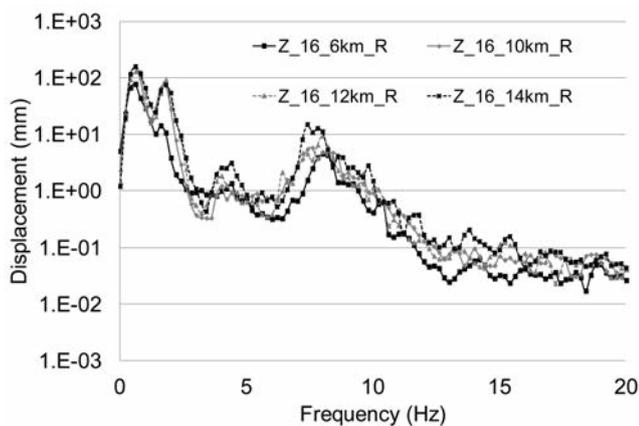


Figure 6. ASD Spectrum of the setting N_16 on the rear plates.

Conclusions

This first essay permitted to verify the functionality of the four hydraulic actuators test bench to reproduce vertical solicitations at the wheel hubs of a tractor when crossing the ISO 5008 track at different forward speeds, with different settings and different tires pressure.

The analysis of the spectrums of the data obtained both in the smooth track and in the test bench have shown that a roughness surface induces a transformation of the forward speed of the vehicle in vertical acceleration that excites the elastic parts (*i.e.* tires, suspensions, ...). These phenomena seem to indicate that vehicle's vibration entity is due to the combination of surface roughness and forward speed as amplitude and to the elastic properties of the elastic parts as frequency.

The comparison between the spectral power density of the accelerations of the wheel hubs achieved in the track with the same acquired in laboratory lead in new possibilities to redesign new artificial tracks to acquire vibration values over the tractor, which could convey to acceleration data at the operator seat.

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