XVII[th] World Congress of the International Commission of Agricultural and Biosystems Engineering (CIGR)

Hosted by the Canadian Society for Bioengineering (CSBE/SCGAB)
Québec City, Canada June 13-17, 2010

POWER SPECTRAL ANALYSIS OF AGRICULTURAL FIELD SURFACES

M. CUTINI[1], C. BISAGLIA, S. A. BERTINOTTI

[1]CRA-ING, via Milano 43, 24047, Treviglio (BG), Italy, maurizio.cutini@entecra.it

CSBE100948 – Section V: Management, Ergonomics and Systems Engineering Conference

ABSTRACT Agricultural vehicle operators are exposed to high levels of WBV related, specifically, to surface irregularities and forward speed, which are considered to be the most important sources. 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. Although most of the studies are directed to measure comfort, vibration dumping and developing models, one of the most important parameter, the surface profile, is not analyzed as expected both for the difficult of the measurement, and because it's deformable. This study aims to evaluate the possibility of defining the real and not the apparent profile acting vertically on the tractor. Three terrain test benches were prepared for the tests and one tractor was used driving at different forward speed. Acceleration at the hubs of the tractor was acquired and reproduced at a four plates test bench. The displacement of the plates defined the vertical input of the terrains and their spectrums were obtained. This first approach seems confirming the possibility of defining a common power spectral density for the solicitations on tractor on fields.

Keywords: Measurement method, four-post test bench, iterative deconvolution, mechanical soil analysis, comfort, power spectral analysis

INTRODUCTION

In the last years an increasing demand in power requirements, payloads and driving speeds of agricultural vehicles has been observed mainly due to the evolution of the tractor and of implements in agricultural environment. In particular, the transition towards increased forward speeds, both in road transport, both on fields in working condition introduces technical problems related to the exposure of tractor drivers to high levels of vibration.

The exposure to mechanical vibrations represents a relevant risk factor for the exposed workers. In particular, whole-body vibrations (WBV), like those which affects an operator driving an agricultural tractor, can produce different effects, depending on their intensity, duration and frequency. Vibrations with frequency lower than 2 Hz can cause minor and temporary effects like carsickness, 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 spinal column (Chiang et al., 2006; Seidel et al., 1986).

The growing importance of this risk, both in terms of health and economic damage, led, in the industrialized countries, to the drawing of specific regulations to reduce its impact (Directive 2002/44/EC, 2002; ISO standard 2631-1, 1997). Moreover, in 2008, Italy adopted a specific national regulation on safety (Decree no. 81/2008).

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., 2002), on tool oscillations and impact on work quality (Bisaglia et al., 2006).

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 (Ferhadbegovic et al., 2006; Brinkmann et al., 2006; Cutini et al., 2007). 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.) such that its analysis is a formidable task and it is almost impossible to reproduce testing conditions in fields. The main obstacle to reproduce field signals is technological, indeed as far as we know, it's impossible to measure the forces or displacement under the tires. Actually it's possible to measure forces at the hubs but it considers the contribute of the tires. Using measured soil profiles (obtained for example with optical technology) as system inputs is not sufficiently precise and repeatable because of soil deformations.

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 the test bench and the actuators of the bench are driven in order to create input signals such that the sensor readings match with the measurements obtained in the field.

The CRA-ING Laboratory of Treviglio used a deconvolution method on a electro-hydraulic four-post test bench to reproduce test condition.

This work has the goal of carrying out an analysis of the input signals representative for the considered conditions, in order to find out potential correlations between the soil parameters and the effects on vehicle dynamic and driver comfort and to identify worst-case or common scenarios.

MATERIAL AND METHODS

Tested vehicle

The tested agricultural vehicle was 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.

Table 1. Materials specifications.

Material	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.

Agricultural field surfaces

In this work three field surfaces, with different mechanical characteristics (penetration resistance and skeleton percentage of the upper layers), have been considered:

- a soft ground with low skeleton percentage (S1 – Figure 1);
- a compacted soil with low skeleton percentage (S2 – Figure 2);
- a soft ground with high skeleton percentage (S3 – Figure 3).

With reference to the classification made by the *European Soil Bureau Network* (ESBN) and with the *World Reference Base* for Soil Resources (WRB), the soil at the Laboratory of Treviglio can be classified as an *Haplic Luvisol*, which is a typical soil in the west-northern parts of Italy (European Commission, 2005). A mechanical analysis of the soil texture of the fields, made according with the *United States Department of Agriculture* (USDA) system of nomenclature (Brown, 2003), has shown that the topsoil and subsurface are constituted by the following fractions of separates (diameter limits < 2 mm): 68% of sand, 24% of silt and 8% of clay.

Figure 1. S1 test track.

Figure 2. S2 test track.

Figure 3. S3 test track.

The skeleton is composed of quartzite, granulite, marlstone and granite with Mohs hardness between 4-7. The soil structure analysis of S3 shows a skeleton percentage between 58-87%. A detailed analysis of the coarse fragments is reported in table 2.

Table 2. Detailed mean soil structure analysis

Diameter limit	Content		
	S1	S2	S3
(mm)	(%)	(%)	(%)
>150	-	-	1.1
50-150	-	-	21.6
20-50		-	24.8
2-20	-	-	21.2
<2	-	-	31.3

During the field tests, S1, S2 and S3 had a water content (in the upper layers) of 15%, 13.1% and 13.5% respectively. These percentages were obtained by taking five samples of terrain for each type of soil along the tracks. The penetration resistance of the three surfaces has been evaluated by using a standard soil cone penetrometer (figure 4). The normative references are reported in ASAE EP542 FEB99 and ASAE S313.3 FEB04.

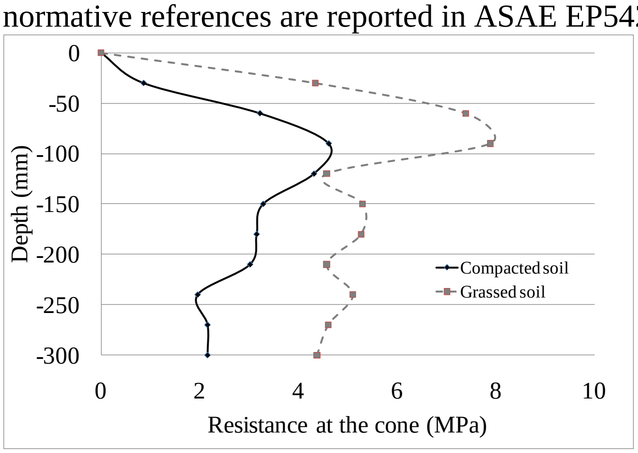

Figure 4. Resistance at the cone penetrometer of S1 and S2

S2 is characterized by an upper horizon of organic matter (grass).

Four poster test bench

The CRA-ING four-post test bench is specifically designed to test large and heavy vehicles up to 15 t in off-road low-medium range forward speed conditions.

The stand is composed of:

- a seismic mass of the weight of 408 t, isolated from the ground by means of pneumatic springs;
- four servo-hydraulic actuators articulated for wheel-base/track adjustment on the seismic mass and supporting four vibrating plates upon which the tires of the vehicle are placed;
- 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 has been instrumented with a set of four piezo-electric monoaxial accelerometers (range ±50 g, sensitivity 100 mV/g) to measure the wheel hubs vertical acceleration and a triaxial seat accelerometer (range ±50 g, sensitivity 100 mV/g) placed in correspondence of the seat surface to evaluate the operator comfort.

Field tests

For S1 and S2 five field tests at increasing speed with step of 0,55 ms^{-1} (1.39 ms^{-1}, 1.94 ms^{-1}, 2.5 ms^{-1}, 3.05 ms^{-1}, 3.61 ms^{-1}) have been performed and the time-histories at the axles have been recorded. For S3 the tests were performed only at the first three speeds because the value of discomfort were already too high. The step of 0,55 ms^{-1} is enough to excite the main resonance of the tractor (Cutini et al., 2007). These signals are called reference signals and have been used to evaluate the operator comfort and reproduced on the four-post.

Iterative deconvolution, theoretical considerations

The calculation of the control signals for the actuator of the test bench, called drive signals, is a multivariable tracking problem, currently solved by industry with the so-called iterative deconvolution (ID) procedure (Soderling, et al., 1999). ID is an off-line iterative feedforward procedure where the drive signals are updated based on 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 a good approximation of the real field surfaces subject to deformations.

RESULTS

Ride comfort

During the field tests the frequency-weighted vertical seat accelerations have been evaluated according to ISO standard 2631-1, 1997 (table 3).

Table 3. Frequency weighted acceleration during field tests

Surface	Speed (ms^{-1})	a_w (ms^{-2})
S1	1.38	0.639
S1	1.94	0.833
S1	2.5	0.985
S1	3.05	1.061
S1	3.61	1.069
S2	1.38	0.68
S2	1.94	0.903
S2	2.5	1.048
S2	3.05	1.047
S2	3.61	1.318
S3	1.38	1.054
S3	1.94	1.232
S3	2.5	1.771

It has been shown that:

- regardless of the speed and skeleton percentage, the comfort is better when the penetration resistance of soil is low (S1 vs. S2);
- regardless of the speed and penetration resistance, the comfort dramatically decrease when the skeleton percentage is high (S3 vs. S1);
- moving towards increasing forward speeds, the comfort decreases.

Emulation of the field-test time-histories

In order to evaluate the accuracy and performances of the data achieved during the laboratory tests, the reference signals collected during the field-tests have been compared with the emulated responses. For this purpose, a root mean square (RMS) analysis of the wheel hubs accelerations has been used. The RMS error shows how large is the difference between the actual and the achieved responses; the iterations are converging so the RMS error becomes smaller in a scale ranging from 100 to 0. The RMS errors achieved were always lower than 20, guaranteeing the desired simulation of the working situation recorded (figure 5).

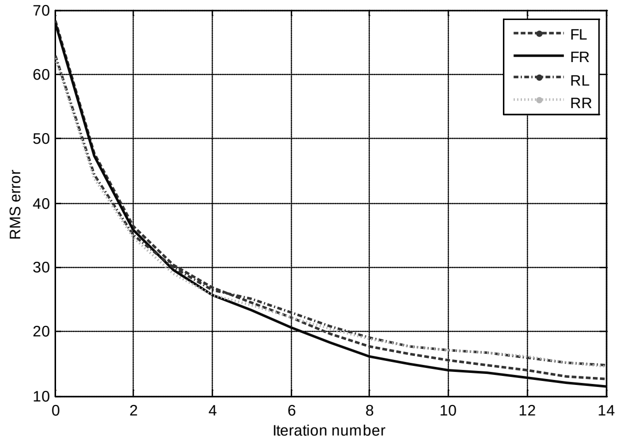

Figure 5. Trend of the RMS error during a test.

Power spectral analysis

Once the emulated responses have been validated, a frequency domain analysis of the correspondent input signals has been carried out. The frequency power spectra have been obtained by using the fast-fourier-transform (FFT) method on the drive signals.

The analysis of the power spectra shows that:

- in every test, regardless of the surface type and engine revolutions, there is an energy peak directly proportional to the forward tractor speed (at 5.6 Hz, 8 Hz and 10.2 Hz when the speed is 1.38 ms^{-1}, 1.94 $ms^{-1}$and 2.5 ms^{-1} respectively). It has been demonstrated that the frequency of the peak is correlated to the geometrical shape of the front tires, in particular to the number of treads. It can be noticed that the peaks are less marked by considering the S3 surface: it has been assumed that the higher energy level of this type of surface masks the peaks. These peaks must be considered as a side effect due to the specified tire models and not to the surface type;
- in every test, regardless of the surface type, forward speed and engine revolutions, there are three energy peaks around 2.2 Hz, 4.3 Hz and 8.1 Hz, respectively. These peaks are more pronounced in the time histories of the rear plates and correspond to the vibration modes of roll, pitch and heave of the cabin. It has been deduced that they are due to the different conditions under which the field-tests and the bench-tests have been performed. In fact during the field-tests the cabin was weighted down by two operators (150 kg) and this might have produced a stronger response of the cabin in respect to the bench-tests, during which the lack of the operators was compensated by an increase of the input energy at those frequencies. 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;

Data are reported in figures 6, 7, 8.

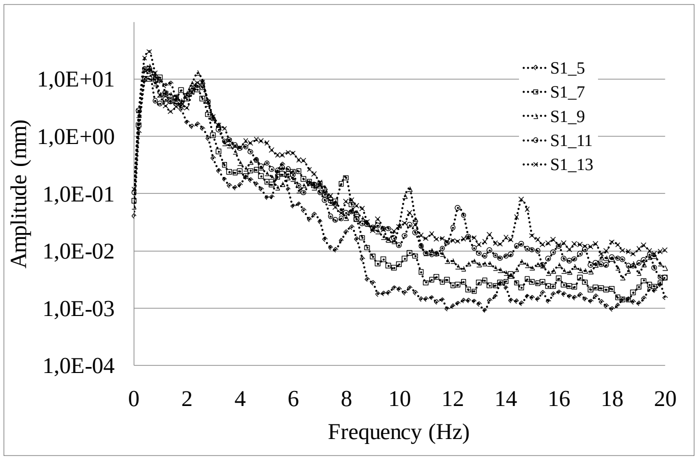

Figure 6. S1 surface frequency spectrum with respect to the forward speed.

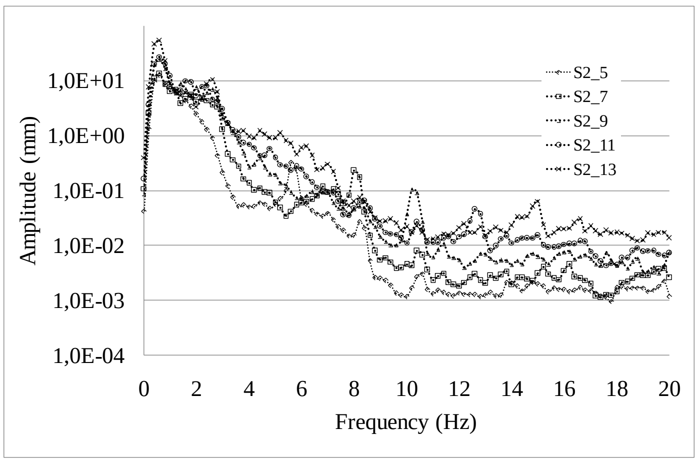

Figure 7. S2 surface frequency spectrum with respect to the forward speed.

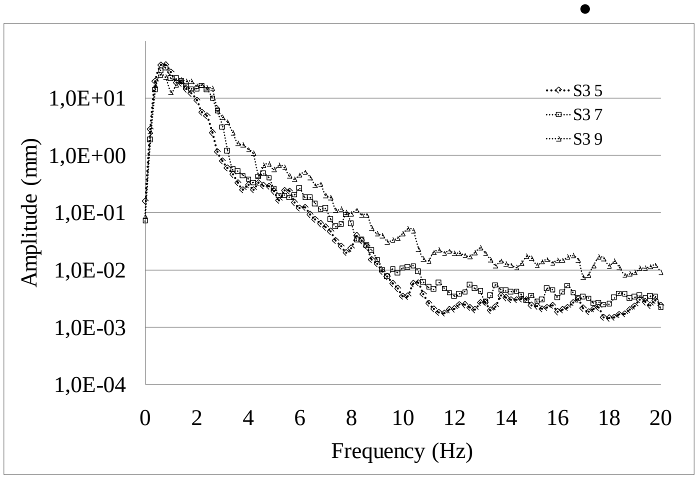

Figure 8. S3 surface frequency spectrum with respect to the forward speed.

The following conclusions are depicted by neglecting the previous side effects:

- it can be seen that, regardless of the surface type, moving towards increasing forward speeds there is a correspondent increase of the spectrum magnitude in the whole considered range of frequency;
- the considered surface types show similar frequency spectrum shapes, regardless of the forward speed: the power spectral density is most relevant at the lower frequencies (less than 4 Hz); in this bandwidth the spectrum magnitude rapidly decreases (approximately 100 dB/decade). Between 4 Hz and 10-12 Hz the spectral components are less relevant, while the decrease rate is approximately 25 dB/decade. Above 10-12 Hz the spectral components are negligible; over this frequency band the spectrum is flat and the signals can be considered “white”;
- the power spectral density of the S3 surface, in the considered bandwidth and regardless of the forward speed, is always higher in respect to the S1 and S2 surfaces. The spectra of the S1 and S2 surfaces are very close. The S3 surface can be considered as a worst-case scenario in respect to the other types of surfaces.

CONCLUSIONS The CRA-ING Laboratory of Treviglio has carried out a test for evaluating the power spectral density of the soil terrain acting on a tractor. Results have shown that changing soil profile and tractor speed the spectral trend of the soil profile is always similar. It‘s relevant at frequencies less than 4 Hz, at this bandwidth rapidly decreases and between 4 Hz and 10-12 Hz is less relevant. After 12 Hz the spectral components is flat and the signals can be considered “white”. This result has to be validated from further investigations considering different tractors and operations, but they confirm the possibility of defining a standard trend of soil solicitations.

Acknowledgements. The research has been carried out in the frame of the Vibramag Project (Evaluation and control of the vibrations of agricultural vehicles through analysis methods based on four-post test bench) funded by the Italian Ministry of Agriculture.

REFERENCES

Anthonis, J., et al. 2007. Feedback Approach for Reproduction of Field Measurements on a Hydraulic Four Poster. Biosystems Engineering. 2007. 96(4), pp. 435-445.

ASAE EP542 FEB99. Procedures for using and Reporting Data Obtained with the Soil Cone Penetrometer.

ASAE S313.3 FEB04. Soil Cone Penetrometer.

ASAE Standards, 36th ed. 1989. S352.1: Moisture measurement -- Grain and seeds. St. Joseph, Mich.: ASAE.

Bisaglia, C., Cutini, M. and Gruppo, G. 2006. Assessment of vibration reproducibility on agricultural tractors by a “four poster test stand”. Proceedings of the XVI CIGR, EurAgEng 2006, 64th VDI-MEG and FAO joint "World Congress - Agricultural Engineering for a Better World". Bonn, Germany : s.n., September 3-7, 2006. pp. 1-6.

Brinkmann Ch., St. Bottinger, H. D. Kutzbach, 2006, Investigation on high frequency vibration behaviour of agricultural tires, XVI CIGR World Congress, Ageng 03-07 September 2006, Bonn.

Brown, R. B. 2003. Soil Texture. Fact Sheet SL29 - Soil and Water Science Department, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida. 2003.

Bukta A. J., K. Sakai, A. Sasao, S. Shibusawa, 2002, “Free play as a source of non linearity in tractor-implement systems during transport”, Applied Engineering in

Agriculture; vol.45(3): 503-508
Chiang, C. F. and Liang, C. C. 2006. A study on byodinamic models of seating human subjects exposed to vertical vibration. International Journal of Industrial Ergonomics. 2006. Vol. 36, pp. 869-890.
Coombs, T. R., and F. C. Watson. 1997. Computational Fluid Dynamics. 3rd ed. Wageningen, The Netherlands: Elsevier Science.
Cutini M., Bisaglia C., Romano E., 2007, "Assessment of tractor's tires influence on operator's confort", Advances in Labour and Machinery Management for a Profitable Agriculture and Forestry, Nitra, Slovakia, Conference Proceedings pp.183-189
Directive 2002/44/EC. 2002. Minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (vibration). Official Journal. 2002. Vols. L 177 , 06/07/2002 P. 0013 - 0020.
EEC 2002. Directive of the European Parliament and of the Council of 25 June 2002 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (vibration). Directive 2002/44/EC, Official Journal of the European Communities (No L 177/13 6/7/2002)
European Commission. 2005. Soil Atlas of Europe, European Soil Bureau Network. Office for Official Publications of the European Communities. L-2995 Luxembourg : s.n., 2005. p. 128.
Ferhadbegovic B., Ch. Brinkmann, St. Bottinger, H. D. Kutzbach, 2006, Hohenheim Tyre Model – A Dynamic Model for Agricultural Tyres –- XVI CIGR World Congress, Ageng 03-07 September 2006, Bonn.
Health & Safety Commission. 2004. Proposals for new Control of Vibration at Work Regulations implementing the Physical Agents (Vibration) Directive (2002/44/EC) Whole-body Vibration
Hoppe U., H. Hoppe, J. Meyer. 2004. Vibration isolation in farm machines. State of the art. Landtechnick 59(1): 24-25.
Hostens I., J. Anthonis, P. Kennes, H. Ramon. 2000. Six-degrees-of-freedom test rig for simulation of mobile agricultural machinery vibration. Journal of Agricultural Engineering Research 77(2); 155-169
ISO standard 2631-1. 1997. Mechanical vibration ad shock - Evaluation of human exposure to whole-body vibration. 1997. Vol. Part. 1: General requirements.
NSC. 2001. Injury Facts Online. Itasca, Ill.: National Safety Council. Available at: www.nsc.org. Accessed 17 December 2001.
Seidel, Helmut and Heide, Renate. 1986. Long-term effects of whole-body vibration: a critical survey of the literature. International Archives of Occupational and Environmental Health. s.l. : Springer Berlin / Heidelberg, 1986. Vol. 58, 1, pp. 1-26.
Soderling, S., Sharp, M. and Leser, C. 1999. Servo Controller Compensation Methods Selection of the Correct Technique for Test Applications. VII International MobilityTechnology Conference & Exhibit. Sao Paulo, Brazil : s.n., 1999. pp. 30-35.
Waladi, W., B. Partek, and J. Manoosh. 1999. Regulating ammonia concentration in swine housing: Part II. Application examples. Trans. ASAE 43(4): 540-547.