Different Aspects of the Utilization of a Subsoiler equipped with an Horizontal Device for Soil Disruption

R. Fanigliulo, G. Colorio, L. Fornaciari, R. Grilli, G. Brannetti, C. Cervellini, G. Vassalini, D. Pochi
CRA – ING Agricultural Research Council, Agricultural Engineering Research Unit
Via della Pascolare, 16 – 00015 Monterotondo (Rome) Italy, Tel. +39 0690675233, e-mail: roberto.fanigliulo@entecra.it

ABSTRACT

Subsoiling is a very efficient tilling method for reducing soil compaction caused by repeated passages of agricultural equipment in orchard's rows. Soil compaction can restrict the passage of water in deep layers and cause excessive surface water stagnation. Subsoiling can restore the structure of compacted soils through a vertical cut and an elevation of the ground, without mixing the tilled layers. Consequently, stable soil porosity and better drainage are favoured, the plough sole is removed, altogether improving the growth of roots and the absorption of nutrients. In particular, vibrating subsoilers can reduce the high draft force required by common subsoilers, and consequently smaller power class tractors can be employed. In order to assess several aspects regarding the use of a single shank subsoiler with an innovative oscillating device, the CRA-ING carried out specific tillage tests. The oscillating device is an horizontal metal plate that, during its run along the drill horizon, is raised at regular intervals through a connecting rod driven by a crank mechanism, consequently moving a greater mass of the above soil. Such a subsoiler has been tested under typical operating conditions in order to investigate different aspects of its utilization such as the energy requirements, the quality of the tilled soil and the level of vibrations transmitted at the driver seat by the oscillating device (according to the ISO 2631-1:1997 standard). Two series of tests have been performed through the untilled rows of a fifteen years old poplar grove, using the subsoiler both with the oscillating device and as a traditional one, at the same forward speed, with the aim of comparing the observed results. The tillage was done at the maximum depth depending on the soil's workability conditions (0,45 m), using a 110 kW, 4WD tractor.

Keywords: Subsoiling, compacted soils, energy requirements, cone index, vibrations level, Italy

1. INTRODUCTION

Soil compaction can be naturally occurring but the main cause is the repeated passes of farm machinery, especially in orchard's rows. As well in orchards that are managed maintaining a natural grass cover for many years, the associated long-term no-tillage may cause the soil to

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R. Fanigliulo, G. Colorio, L. Fornaciari, R. Grilli, G. Brannetti, C. Cervellini, G. Vassalini, D. Pochi . "Different Aspects of the Utilization of a Subsoiler equipped with an Horizontal Device for Soil Disruption". International Commission of Agricultural and Biological Engineers, Section V. Conference "Technology and Management to Increase the Efficiency in Sustainable Agricultural Systems", Rosario, Argentina, 1-4 September 2009. The authors are solely responsible for the content of this technical presentation. The technical presentation does not necessarily reflect the official position of the International Commission of Agricultural and Biosystems Engineering (CIGR), and its printing and distribution does not constitute an endorsement of views which may be expressed. Technical presentations are not subject to the formal peer review process by CIGR editorial committees; therefore, they are not to be presented as refereed publications.

reconsolidate. Likewise a conventional approach to site management with ordinary surface tillage will create a hard pan layer over the years. Physical degradation of soil reduces porosity and permeability leading to lower water infiltration capacity, surface water stagnation and increasing erosion risk by accelerating run-off.
Conventional tillage within the orchard will break up and turn over surface soil to a depth above the pan layer and will affect mainly topsoil parameters. Deep tillage is necessary to penetrate the compacted layer. Subsoiling loosens soils through a vertical cut and an elevation in the ground, without mixing the tilled layers. Consequently a stable soil porosity and better drainage are favoured, improving the growth of roots and the absorption of nutrients. Subsoilers has been developed in many models. The performance of conventional rigid subsoiling equipment depends on many factors such as shank design and layout, the insertion of side wings on the foot, the use of coulters, all affect the working depth and the profile of the loosened soil (Fanigliulo and Pochi, 2008). An important limitation to deep tillage may be represented by the limited power available with the tractors commonly employed in the orchard industry. Among existing equipment, vibrating subsoilers can reduce the high draft force required for pulling through the soil in comparison to an equivalent rigid system operating at the same speed and depth, providing for a more effective use of the available tractor power. Consequently smaller power class tractors can be employed, otherwise a greater depth and disruption of soil may be achieved (Sakai, et al., 1993; Bandalan et al., 1999).
Different management strategies such as dual depth tillage, dual pass approach can be used for maximising the capacity of this machinery. In orchards, subsoiling is generally performed with a single pass in the middle of the row but the farmer may consider the need for a double pass strategy, always safeguarding the root systems of plants. Deeper tillage means a greater volume of loosened soil that roots can explore for better access to water and nutrients. Deeper root systems give direct benefits, decrease reliance on irrigation water and improve yield and quality.
In order to assess several aspects regarding the use of a single shank subsoiler with an oscillating device, the CRA-ING carried out specific tillage tests. The oscillating device is an horizontal metal plate that, during its run along the drill horizon, is raised at regular intervals through a connecting rod driven by a crank mechanism, consequently moving a greater mass of ground. Such a subsoiler has been tested under typical operating conditions in order to investigate different aspects of its utilization, such as the energy requirements, the quality of the tilled soil and the level of vibrations transmitted at the driver seat by the oscillating device.
Beyond the determination of soil cloddiness in the tilled layer, the quality of work can also be indirectly evaluated observing the different amounts of ground volume (and mass) interested by the action of the subsoiler in the different working modes. For this purpose, an electronic portable penetrometer can be helpful (Raper, 2005). Such an instrument usually provides the measurement of the Cone Index of undisturbed soil along the layer interested by the tillage. This parameter resumes the soil reactions to the penetration of the shank and represents an index of the difficulty of the tillage. Repeating the measurement on the soil disrupted by the shank pass, at different distances from the centre of the furrow, allows to evaluate the extension of its action (both in width and depth) and the comparison between the effects of the subsoiling executed with and without oscillating device.
As regards the workers' exposure to the risk from vibrations, the European legislation 2002/44/CE (CE, 2004) indicates the minimum prescriptions, in safety and health matter.

Vibrations are classified as whole-body vibrations and hand-arm system vibrations. The decree of above reports the “limit value” (1.0-1.5 m s^{-2}) and the “action value” (0.5 m s^{-2}) as reference values for the time of exposure to the whole-body vibrations, determining some obligations. If the daily exposure level is not constant, the maximum level must be taken into consideration.
The test procedures for the measurement and evaluation of whole-body vibrations are reported in the ISO 2631-1:1997 standard (ISO, 1997) that provides an estimation of the effects of the vibrations on health and comfort.
Two series of tests have been performed through the untilled rows of a fifteen years old poplar grove, using the subsoiler both with the oscillating device and as a traditional one, at the same forward speed, with the aim of comparing the observed results. The tillage was done at the maximum depth depending on the soil’s workability conditions (0,45 m), using a 110 kW, 4WD tractor. The dynamic-energetic parameters of the tractor-subsoiler system have been measured according to the ENAMA test protocol n° 03 (National Body for Agricultural Mechanization), executing three replications for the chose subsoiler regulation. The data of the effective accelerations, a_{wx}, a_{wy} and a_{wz}, in the frequency interval 0.5 Hz up to 80 Hz, have been collected by a for-seat, tri-axial accelerometer oriented according to the above standard, by a second tri-axial accelerometer positioned on the tractor’s main frame and a multi-channel system specific for real-time acquisition of noise and vibration. The time of sampling was 120 s, sufficing to characterize the level of vibrations produced by the subsoiling. Three replications have been made for each thesis.

2. MATERIALS AND METHODS

The tested subsoiler is a tractor mounted tool with a mass of 400 kg (fig. 1), that operates deep soil tillage (from 350 to 550 mm). The mainframe is built in a reinforced box-type steel structure having an arched shape that provides an ideal flow for disrupted soil, thus allowing proximity between the lower beam and the soil surface. Working depth is set via the tractor linkage and stabilizer side-wheels assure a consistent working depth.
The linkage frame allows the connection to different size tractors, but a hydraulic top link is necessary on small tractors to lift the shank completely out of the ground.
The working tool has a straight shank fitted with a sharpened wear shin on the leading edge. The shank’s point is fitted with a 0.10 m wide reversible share. The bottom metal has a triangular shape and has a central cut so that it can be inserted on the shank’s foot. The front end of the plate is hinged behind the share, the back end of the plate is connected to a quadrangular rod that shifts on a vertical axis. The rod is driven by a crank mechanism powered by the PTO. The plate oscillates at a 9 Hz frequency, with amplitudes of ±70 mm.
The main characteristics of the subsoiler are indicated in the table 1.

Fig. 1. The tested subsoiler.

Table 1. Main characteristics of the tested subsoiler

Overall width (mm)	1450
Shank thickness (mm)	30
Shank's penetration angle in the soil (°)	12
Under frame ground clearance (mm)	750
Chisel share width (mm)	10
Oscillating plate: length (mm) –width (mm)	360-400

The tests have been carried at CRA-ING, Monterotondo (Rome), Italy, by the CPMA (Agricultural Machinery Testing Centre). CPMA is entrusted with the task of conducting the performance and safety tests aimed to the ENAMA certification of soil tillage machines (Fanigliulo *et al*., 2003). Tests were performed in a fifteen years old grove that has not been cultivated deeply since the date it was planted, in which only flail mowing is done, several times a year, for the maintenance of the grass cover. The soil of the experimental plots was clay-silt, characterized by a flat layout. Before the tillage tests, the physical-mechanical characteristics of the soil have been determined, referring to the depth of working. They are synthesized in the table 2.

Table 2. Characteristics of the soil

Atterberg limits (%)	
Liquid limit	62.2
Plastic limit	40.3
Plasticy index	21.9
Moisture content (%)	10.7
Dry bulk density (g cm^{-3})	1.13
Average cone index (MPa)	2.37

The subsoiler was moved by a 110 kW, 4WD tractor, with a total mass of 6.000 kg, previously tested at the dynamometric brake in order to verify its efficiency and to draw the characteristic curves of the engine. The tractor worked with locked differential and under maximum fuel delivery conditions. Through preliminary tests the most suitable tractor regulations were chosen for the experiments (gear ratio, working speed, etc.).

The effect of the vertical motion of the plate was evaluated through two different treatments: the subsoiler was used with the oscillating metal plate in action (thesis A) in comparison to the subsoiler in which the metal plate wasn't in action (thesis B). The tests were carried out making only one pass through the rows in the middle, to reduce root pruning and damage. Only a forward speed was used.

The data of the operative parameters of the tractor-operating machine system have been collected by an integrated system based on two units, a field unit and a support unit (Fanigliulo *et al*., 2004). The field unit is represented by the tractor (equipped with sensors and a PC equipped with a PCI card for the acquisition of the data and a LCD monitor) and a photocell system indicating the start and stop of the tests. The support unit consists of a van equipped as a mobile laboratory: during the tests it is parked on the field border. Its PC is in communication with the field unit's PC by means of a radio-modem system, exchanging data and allowing to monitor the behaviour of critical parameters, the efficiency of the instruments, etc. The support unit has also the

function of lodging the equipment and instruments used in the evaluation of the quality of work as the laser microreliefmeter, the sieves etc.
The sensors on the tractor were represented by a 3000 Nm full scale torque-tachometer splined to the tractor PTO shaft measuring the torque at the p.t.o. and its speed; a suitably placed incremental encoders for the measurements of the peripheral velocity and slip of the rear wheels and a volumetric fuel consumption measurer. The force of traction has been measured by means of a load cell (measuring range: 98 kN) suitably lodged in a drawbar: the tractor-subsoiler system is pulled, by means of the drawbar, by a traction vehicle at the same speed measured during the work. The traction vehicle can be considered as a further element of the field unit. Its PC transmits the data to the support unit.
The dynamic-energetic parameters of the tractor-subsoiler system have been measured according to the ENAMA test protocol n° 03 (ENAMA, 2003), executing three replications for each subsoiler regulation. The measurements refer to a 100 m reference distance. They were: actual time, width and depth of work; working speed; power transmitted by the PTO, force of traction required by the subsoiler and corresponding power under the measured working speed conditions; tractor's slip and corresponding power losses; fuel consumption.
The quality of work has been evaluated through the determination of the following parameters before and after the tillage: the cone index (resistance to penetration of the soil), the clod size distribution and soil refinement index (Peruzzi *et al.*, 1999).
The average cone index (ASAE standard, 1999b) has been determined, by means of a portable penetrologger, measuring the force needed for the penetration in the soil of a cone tip having a 60° top angle and a base areas of 10 mm^2, with the speed of 30 mm s^{-1}. On purpose, in each thesis, 6 sample areas have been individuated along the furrows and, in each area, three measurements have been executed, with reference to the tilled layer, respectively at 10, 20 and 30 cm from the centre of the furrow.
The cloddiness of the tilled soil is determined on soil samples drawn from a square trench with a 0.5 m side reaching the tillage depth. The samples are sieved by means of sieves with different holes diameter and weighed on a balance. The soil aggregates found in this volume must be divided into six dimensional classes. A characteristic index I_{ri} (varying from 0 for the biggest class to 1 for the smallest class) is attributed to each class. The cloddiness classification of tilled soil is provide by values of the refinement index, I_r ,which varies from 0 to 1 and is calculated by means of the relation:

$$I_r = \sum_{i=1}^{6} \frac{M_i \cdot I_{ri}}{M_t}$$

where M_i is the mass of each dimensional class and M_t is the total mass of the sample of soil.
The working depth and the uniformity of the bottom of the tilled layer have been calculated, on the same soil section, after the passage of the subsoiler, as the standard deviations (σ) of the series of data provided by a laser microreliefmeter (Raper *et al*., 2004): the sensor, moving along an horizontal bar, measures its distance from the soil surface at steps of 5 mm.
The basic parameter in the evaluation of the level of vibrations is the acceleration, a (m s^{-2}). As the effects of the vibrations depend on the frequency of the accelerations, these must be weighted by means of weighting filters calculated as a function of the human body sensitiveness to the acceleration in the different sampling frequencies filters, according to the above standard. They provide the frequency-weighted acceleration, a_w:

$$a_W = \left[\frac{1}{T} \int_0^T a_w^2(t)dt \right]^{\frac{1}{2}}$$ [1]

where: $a_{w(t)}$ is the measured value of the acceleration; T is the acquisition time interval (s). Basing on the values of the three accelerations measured along the x, y and z axes, the resulting acceleration sum vector, a_v, is provided by means of the relation:

$$a_v = [(k_x^2\ a_{wx}^2 + k_y^2\ a_{wy}^2 + k_z^2\ a_{wz}^2\ ]^{1/2}$$ [2]

where: a_{wx}, a_{wy}, a_{wz} are the weighted r.m.s. accelerations along the x, y and z axes; k_x, k_y, k_z are indices based on the effects that the relative axial accelerations have on the health: for k_x *e* k_y a value of 1.4 is applied in the case of sitting position, as they are equal to 1 for the erect position; k_z is equal to 1 in both positions. The instrumentation consisted of: a tri-axial accelerometer for driver seat (Brüel & Kjær, type 4322); a second tri-axial accelerometer (Brüel & Kjær, type 4321) positioned on the tractor's main frame on the same z axis of the seat; an 8-channel multi-analyzer (Sound-Book) for real-time acquisition of vibration data; six converters (B&K type 2647); a calibrator for accelerometers (PCB, mod. 394C06). The time of sampling was 120 s, sufficing to characterize the level of vibrations produced by the subsoiling. For each thesis, three replications have been made.

3. RESULTS AND DISCUSSION

Tables 3 and 4 respectively show the results of the measurements referring to the dynamic-energetic performances of the tractor-subsoiler systems and the values of the most significant parameters referring to the interaction between soil and machine.

Table 3. Main dynamic and energetic parameters resulting from the tests

Parameters	**Theses**	
	A	**B**
Average actual working speed (km h^{-1})	2.21	2.12
Actual working time (h ha^{-1})	0.91	0.91
Operative working time (h ha^{-1})	1.01	1.01
Operative efficiency	0.90	0.90
Operative working capacity (ha h^{-1})	0.99	0.99
Fuel consumption per hour (kg h^{-1})	11.7	9.3
Fuel consumption per surface unit (kg ha^{-1})	10.6	8.4
Average torque at the p.t.o. (daNm)	8.8	-
Average p.t.o. speed (min^{-1})	526	-
Average power at the p.t.o. (kW)	4.9	-
Average force of traction (kN)	32.9	27.7
Traction power requirement (kW)	20.2	16.3
Specific force of traction (kN dm^{-2})	1.29	1.26
Average engine speed (min^{-1})	1893	1892
Total power provided by the engine (kW)	38.5	27,1
Energy requirement per surface unit (MJ ha^{-1})	125.7	88.5
Energy requirement per volume unit of soil (MJ 10^{-3} m^{-3})	29.9	20.8
Slip (%)	19.2	22.3

Table 4. Main parameters referring to the quality of the work

Parameters	Theses	
	A	B
Actual tillage width (m)	0.61	0.34
Operative tillage width[1] (m)	5.00	5.00
Thickness of the tilled layer (m)	0.65	0.66
Working depth (m)	0.42	0.43
Elevation in the ground (m)	0.23	0.23
Area of the tilled cross-section (dm^2)	25.6	22.0
Average cone index (MPa)	1.82	1.76
Soil refinement index after the tillage	0.43	0.49

[1]= corresponding to the spacing between the rows

The soil within the orchard was extremely compacted, this limited the working depth that was achievable in the tests to about 0.43 m. Traction power requirement, fuel consumption per hour and per surface unit, and energy requirement per surface unit and per volume unit resulted always greater in theses A when the oscillating plate is working, compared to theses B, in which the plate was steady. The power requirement at tractor's PTO, used for powering the swinging mechanism of the metal plate, is extremely small. Furthermore tractor slippage is very high when the oscillating device is not used during the trials. The analysis of working time indicates no significant differences between treatments performed. The cross-sectional area of the loosened profile and the actual tillage width are considerably greater when the vibrating plate is used.

As to the evaluation of the quality of work through the consistence of the disrupted soil, the diagrams of fig. 2 show the values of the Cone Index (C.I.) meanly observed in the six sample areas, before the tillage and after, at 10, 20, 30 cm from the furrow opened by the shank.

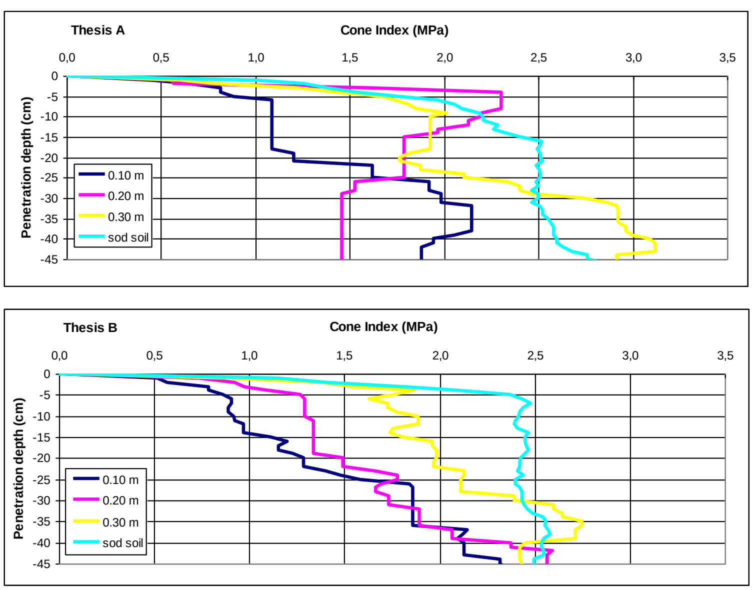

Figure 2. The average C.I., for each theses, in the three positions from the center of the furrow.

For the thesis A, the irregular trend of the C.I. values indicates the presence of fissures, even at high depth, determined by an extended soil disruption. In particular: at 0.10 m from the centre of the furrow, the C.I. has particularly low values in the layer 0-20 cm for the presence of fissures and gradually increase at higher depth; at 0.20 m from the centre it can be noticed a different behaviour, with C.I. values higher at 10 cm of depth and lower at 30 cm, revealing the presence of deep fissures created by the subsoiler; at 0.30 m from the centre, the C.I. has an increasing trend, reaching high values in the deeper layers. For the thesis B, the C.I. has a more regular trend, increasing with the distance from the centre, testifying that the ground underwent a less powerful action.

The soil clods produced by the deep soil tillage are gathered into six classes of size. The results confirm that the subsoiler performs a very effective loosening and shattering action. In fact in the trials in which the plate was working, almost 68% of total clods fit into the bigger dimension classes (> 25 mm) against a 60% with metal plate steady. As a consequence, it is evident that the oscillating plate produces, along the tillage profile, a better subsoil water drainage. The highest value of the refinement index was achieved in plot B. The elevation in the ground was not very big along the line operated by the shank and could be reduced still if the ripper is fitted with the cage roller that will level the tilled soil. This fact can induce high stability conditions for the tractor in all the following agricultural practices. The bottom of the tilled layer has been observed after cleaning the transversal trench. The scanning of the bottom, by means of the laser relief-meter, reveals the presence of crenations caused by the action of the shank. It is evident that the cross-section of tilled soil is clearly bigger in thesis A than those in thesis B with the metal plate steady. The results of the vibration levels tests are synthesized in the tables 5 and 6.

Table 5. Measured values of the axial accelerations at the driver seat and resulting acceleration sum vector

Replication	Thesis A				Thesis B			
	a_{wx}	a_{wy}	a_{wz}	$\mathbf{a_v}$	a_{wx}	a_{wy}	a_{wz}	$\mathbf{a_v}$
No.	m s^{-2}	m s^{-2}	m s^{-2}	m s^{-2}	m s^{-2}	m s^{-2}	m s^{-2}	m s^{-2}
1	0.527	0.180	0.289	**0.832**	0.540	0.185	0.257	**0.839**
2	0.420	0.198	0.255	**0.698**	0.510	0.175	0.254	**0.796**
3	0.507	0.196	0.298	**0.818**	0.416	0.185	0.266	**0.690**
Average	**0.485**	**0.192**	**0.281**	**0.783**	**0.488**	**0.182**	**0.259**	**0.775**
Stand. dev.	0.057	0.010	0.022	0.073	0.065	0.006	0.006	0.076

Table 6. Measured values of the axial accelerations at the tractor's main frame and resulting acceleration sum vector

Replication	Thesis A				Thesis B			
	a_{wx}	a_{wy}	a_{wz}	$\mathbf{a_v}$	a_{wx}	a_{wy}	a_{wz}	$\mathbf{a_v}$
No.	m s^{-2}	m s^{-2}	m s^{-2}	m s^{-2}	m s^{-2}	m s^{-2}	m s^{-2}	m s^{-2}
1	0.340	0.132	0.354	**0.622**	0.435	0.137	0.235	**0.680**
2	0.351	0.137	0.300	**0.607**	0.332	0.149	0.234	**0.561**
3	0.418	0.145	0.374	**0.724**	0.405	0.164	0.224	**0.651**
Average	**0.370**	**0.138**	**0.343**	**0.651**	**0.391**	**0.150**	**0.231**	**0.631**
Stand. dev.	0.042	0.006	0.031	0.064	0.053	0.014	0.006	0.062

It can be noticed that, for the thesis A, the accelerations at the driver seat and at the tractor's main frame, calculated with the relations [2] and [3], are lightly higher than for the thesis B. In all the considered cases, the main solicitations occurred on the X axis. The figures 3 to 4 show the frequency analysis made for the linear and weighed accelerations on the X and Z axes, directly involved in the oscillation of the metal plate of the subsoiler, with the aim of observing possible differences between the two theses. In the diagrams, the data of the frequency analysis referring to the driver seat tests with the a_v values nearer to the average are compared with the corresponding values observed at the same time on the tractor's main frame.

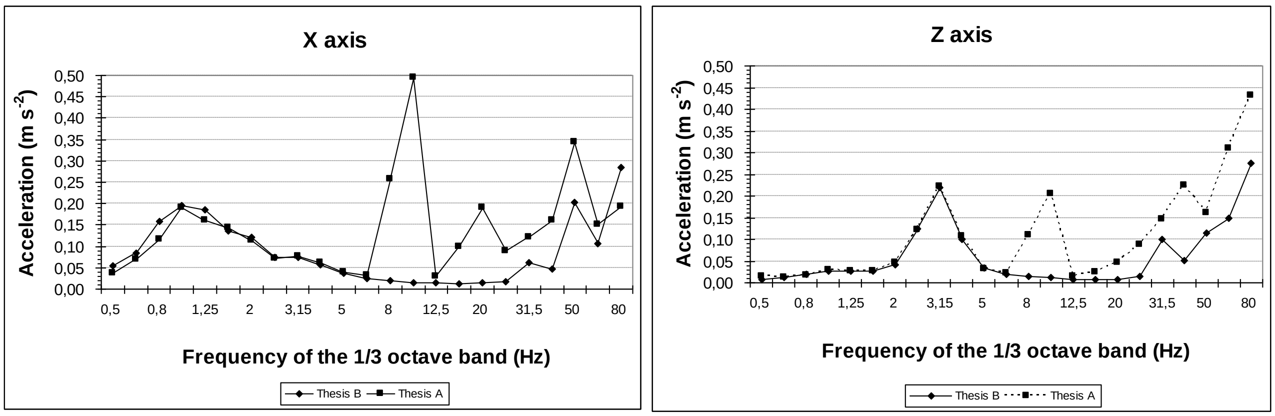

Figure 3. Values of linear accelerations found on the tractor's main frame with the oscillating metal plate in action (thesis A) and steady (thesis B).

In fig. 3, in the X axis, it can be noticed an increasing trend of the acceleration for the thesis A in the frequency interval 6.3 up to 80 Hz, with a series of peaks at 10, 20 and 50 Hz (10 Hz was the frequency of oscillation of the metal plate). The diagram of the Z axis shows a similar behaviour, with only one significant peak at 10 Hz.

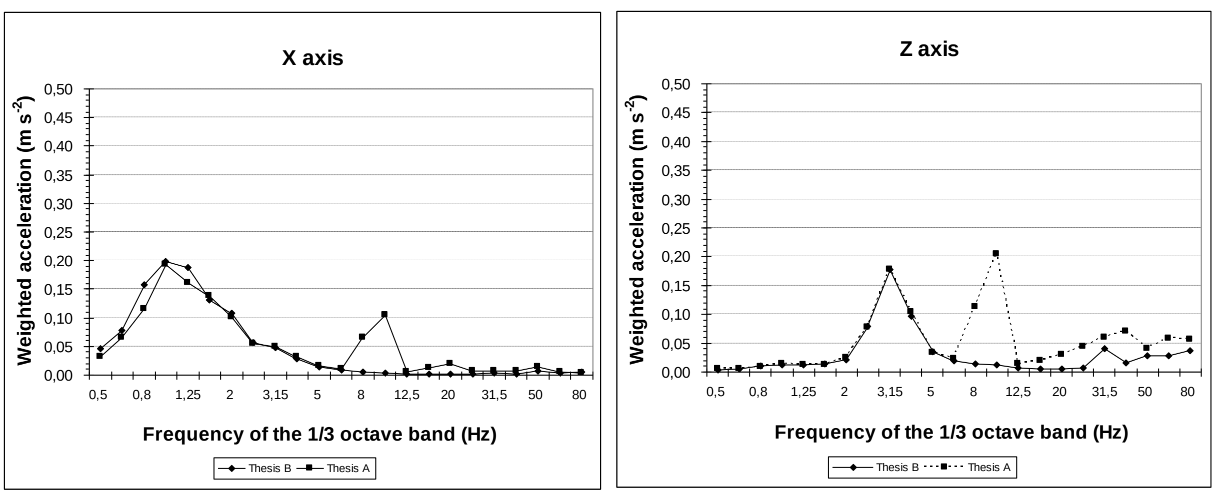

Figure 4. Values of the weighted accelerations found on the tractor's main frame with the oscillating metal plate in action (thesis A) and steady (thesis B).

Fig. 4 shows the same accelerations observed on the tractor's main frame reported in fig. 2 that underwent weighting by means of a suitable filter according to the standard ISO 2631:1997. In the X and Z axes, it can be observed the reduction of the values of a_w in the frequency interval 12.5 to 80 Hz; the presence of the peak at 10 Hz is confirmed and, in the Z axis, it has been not affected by the weighting filter.

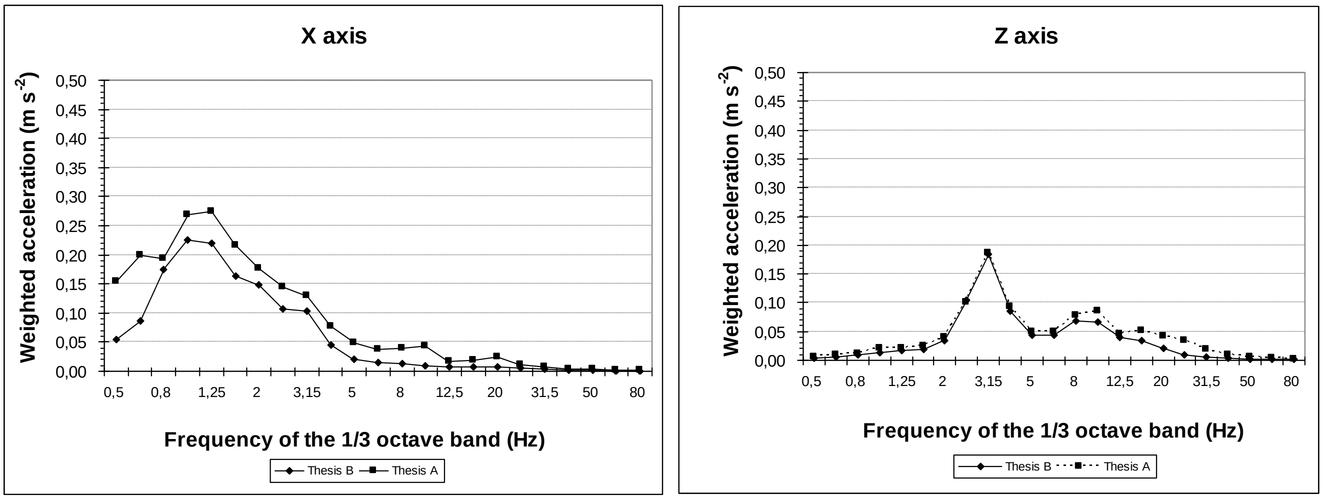

Figure 5. Values of the weighted accelerations found on the driver seat with the oscillating metal plate in action (thesis A) and steady (thesis B).

Finally, fig. 5 reports, for both the theses, the values of the weighted accelerations, a_w, observed at the driver seat. The frequency analysis shows, in the X axis, a light increase of a_w in the thesis A in the interval 0.5 to 25 Hz. As to the Z axis, it can be noticed an evident reduction of the peak at 10 Hz, with respect to the main frame (fig. 3), testifying the effective action of the shock absorbing system of the driver seat.

4. CONCLUSIONS

The success of the subsoil tillage in row crops is strongly influenced by soil conditions: in presence of an extremely compacted soil, tractor's slippage was too high and the working depth had to be reduced. The action of the oscillating metal plate moved a greater mass of soil and provided a better quality of work. As a result, the drainage action in the subsoil was favoured, due to the presence of bigger clods. The correct setting of the implement contribute to the reduction of power requirements and to improve overall operative performances.
As to the vibrations measured during the work, the comparison between the two theses shows that their level never reached conditions of risk for the driver. The presence of high vibration levels outside the frequency interval 0.5 to 80 Hz (considered as a reference for the health of the operator), could represent matter for further investigations, as they can cause discomfort conditions during the work.

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