Experimental apparatus to determine the power applied in vibrating vertical tillage

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Abstract: The aim of this work was to evaluate an alternative to reduce energy consumption applied to primary soil tillage. To do this an experimental apparatus was developed to evaluate the operation of vibration induced tillage. The components that integrated the system for field valuation were: frame tool carrier that includes a system of three-point hitch and depth control mechanism; three sensors were included to measure tillage force, torque and the frequency of the subsoiler oscillation. Oscillatory impact force was applied through a rod and crank mechanism through a subsoiler tine whose movement is provided by a hydraulic motor. The apparatus evaluation was complemented by a system of data acquisition and signal conditioner that allows the registration of the variables of interests such as draft power, penetration force, applied torque and speed of oscillation of the system. The results of the calibration of the sensors showed a system correlation higher than 95%. The results obtained during field system verification at different speed, amplitude and depth of tillage showed a reduction of the draft force up to 50% using the oscillated induced tillage compared to the non-vibrating tine condition. The study shows a significant increase in the magnitude of the draft force and torque applied by 33% when the working depth increased from 0.30 to 0.40 m and an increase of 21% of draft force was produced when the amplitude of oscillation was reduced from 0.070 to 0.060 m. No significant difference was found when the tractor speed was increased from 1.5 to 2.5 km h^{-1}. For future work the developed apparatus will allow to determine how the amplitude and the working depth and oscillation frequency of the tine could affect the draft force in tillage work.

Keywords: oscillatory subsoiler, draft force, energy consumption, amplitude of oscillations

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1 Introduction

Vertical conventional tillage implements have soil-working tools, which do not move relative to the implement frame. Their draft requirements are comparatively high as they are always in contact with the soil and the power for operating these implements is transmitted through traction with tractive efficiency varying between 40 to 75% (Witney, 1995). To improve the tractive efficiency, the tractor drive wheels are ballasted with additional weights. However, this practice causes soil compaction, which is detrimental crop efficiency. Several researchers have reported that oscillating soil-working tools have lower draft requirements and break up the soil better than do their non-oscillating tine implements when working under identical conditions. Therefore, an oscillating soil-working tool may reduce the number of operations to prepare an acceptable seedbed and minimize soil compaction, thus providing a better physical environment for plant growth. In addition, oscillatory tillage uses more efficient tractor power-take-off by 90% to 95% to mechanically oscillate tines (Hendrick, 1980). Lower

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draft requirement of oscillatory tillage reduces the reliance on less efficient drawbar power; leading to a lower overall demand on engine power may occur (Slattery and Desbiolles, 2003), also is generally recognized that the draft force of a vibratory tillage implement can be reduced by 30% to 80%.

Bandalan et al., (1999) performed an experimental study on the tillage performance of an oscillatory subsoiler, determining the optimum combination of operating parameters of the subsoiler such as frequency of oscillation, amplitude and working speed the pull-force and the total power consumed were measured.

Sahay et al., (2009) developed an equipment induced vibration tillage that change the transmission frequency of vibration from 9 to 13 Hz and from 15 to 35 Hz. Experiments showed that the real depth of the oscillatory system work was 0.153 m while the same equipment without vibration was 0.074 m.

Shahgoli et al., (2009) in their study reported the evaluation of the effect of the angle of swing of the tine in the performance of the subsoiler. The objective of this study was to quantify the optimal angle of oscillation for the reduction of the strength of pull, low requirement of power, low specific draft-force, maximum disturbed area and minimum vibration transmitted to the operator's seat. In terms of performance, –22.5° was the optimum angle of oscillation for the reduction of the draft force and power.

Shahgoli et al., (2010a, 2010b) claimed in his study on the optimization of the oscillatory frequency of vibratory tillage, the tines were oscillated with an amplitude of ±69 mm at an angle of 27° using a working speed of 3 km h^{-1}. The frequency of oscillation was varied from 1.9 to 8.8 Hz. There was an optimal frequency near 3.3 Hz (1.5 speed ratio), which minimized the total engine power required to operate a subsoiler. It was estimated a decrement of engine power demand above 26% compared to a rigid tillage equipment.

Studies of oscillatory tillage cited by (Shahgoli et al., 2009 and 2010a) reported that the induced oscillation of a longitudinal or vertical tillage in directions tool can significantly reduce by 50% the draft-force requirements. They also mentioned that the oscillatory frequency, amplitude of swing, swing angle, speed of the tractor, tool design and soil properties those are important factors affecting the functioning of a vibrating tool.

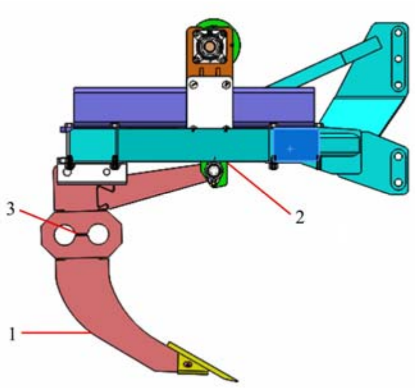
Campos-Magaña, Cadena-Zapata, et al., (2015) modified a vertical tillage implement call multicultivador and conducting a series of investigations by applying the theory of critical depth in tillage equipment. The modifications that were made by the researchers team, basically consist of place shallow tines on the front; and greater length at the rear tines. In the tines of the rear, wings of different sizes were evaluated to increase the disturbed cross sectional area. Field tests were conducted with this arrangement and experimentally was demonstrated that there is a decrease in the specific soil resistance by more than 20% in comparison with primary tillage using tines at the same working depth.

The purpose of the present research work was to develop an apparatus that allows determining the effect that has the variation of the most important parameters in vibration induced tillage such as amplitude and frequency of oscillation, as well as the effect of this vibration on the reduction of the draft force on the vertical tillage.

2 Materials and methods

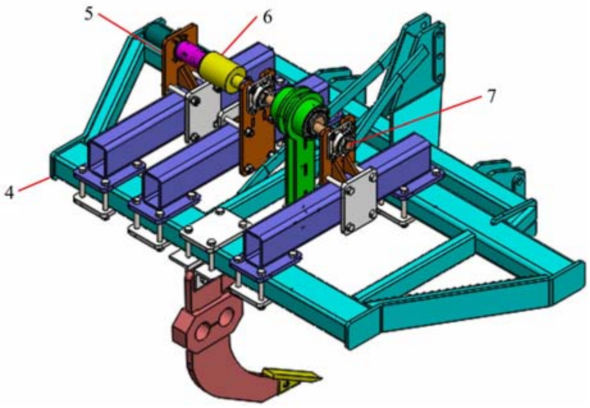
The experimental apparatus was design to be mounted to a tractor category II with three points hitch system, and the oscillatory system was powered by the hydraulic system of the tractor. This device allow adjustment of the frequency of oscillation from 3.3 to 4.9 Hz and amplitudes from 0.060 and 0.070 m. Figures 1 and 2 show the main components of the device designed and built by the Tecnomec Agricola S. A. de C. V. Company. The apparatus is integrated by an oscillation tine (1), an oscillatory mechanism connecting rod crank (2), an extended octagonal transducer (3), structure or chassis (4), a hydraulic motor (5), a torque transducer (6) and an oscillation frequency sensor (7).

The chassis corresponds to the structure of the apparatus in which all the components including the three-point hitch system are mounted. A crank connecting rod mechanism provides the swing of the tine as shown in Figures 1 and 2. This mechanism is operated by means of a hydraulic motor for high torque and low speed of rotation. The frequency of rotation is controlled by a flow regulator valve. A torque transducer with a capacity of 25 kW at a frequency of 9 Hz was coupled between the hydraulic motor and oscillating mechanism to measure the torque that is generated at the time of soil tillage.



1. Oscillating tine 2. Oscillatory mechanism 3. Extended octagonal ring transducer

Figure 1 Side view of the vibrating tillage equipment



4. Chassis 5. Hydraulic motor 6. Torque transducer 7. Frequency sensor

Figure 2 Isometric view of the vibrating tillage equipment

To measure horizontal and vertical forces applied to the soil an extended octagonal ring transducer (OAE) with capacity of 40 k N was built which dimensions are shown in Figure 3.

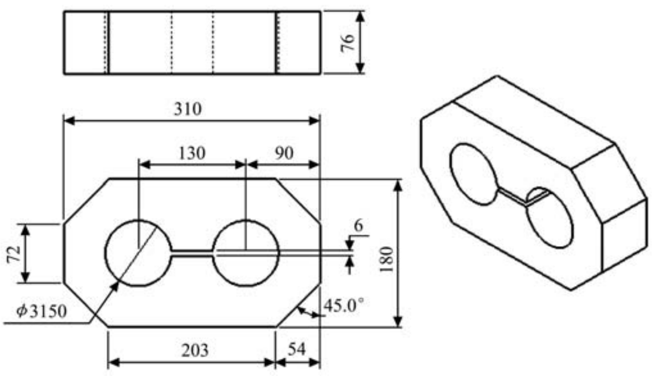


Figure 3 Dimensions and characteristics in the extended octagonal ring transducer in mm

An electronic card was developed to determine the frequency of oscillation in real time of the vibrating apparatus, using an infrared optoelectronic sensor H21A1 (Fairchild Semiconductors, USA) and a microcontroller PIC 16f84 (Microchip company, USA) to eliminate rebounds produced by the effect of magnetic noise.

The construction of the apparatus and mounting of sensors were built at Tecnomec Agricola S. A. de C. V, Aguascalientes State, Mexico, during the period from February to December 2014. Laboratory research and field test was carried out from January to October 2015 in the Agricultural Engineering Department and the experimental Station “El Bajío” at the Universidad Autónoma Agraria Antonio Narro. Located at the State of Coahuila, Mexico, at 25°21.52"N, 101°50"W and at altitude of 1740.5 m over the sea level in a clay soil with resistance to penetration of 2.45 kPa, and average soil moisture of 18%.

A John Deere tractor JD6403, single traction with 105 HP at the engine, was used for the field test. Instrumented tractor include the following equipment: analog to digital converter Logbook360 (Iotech Company, USA), calibrated at a frequency of 20 Hz sampling rate and signal conditioner model DBK43A from the same made, calibrated to a gain of 2500 micro strain (μδ).

In order to measure forces in the horizontal and vertical direction (Figures 4 and 5), it was necessary to make a static calibration of the transducer (OAE) using known loads of (470.8, 470.8, 716.13, 343.35, 343.35, 294.30, and 294.30 N). To run the calibration a loading and unloading of the weights were carried out, each operation was carried out 5 replicates.

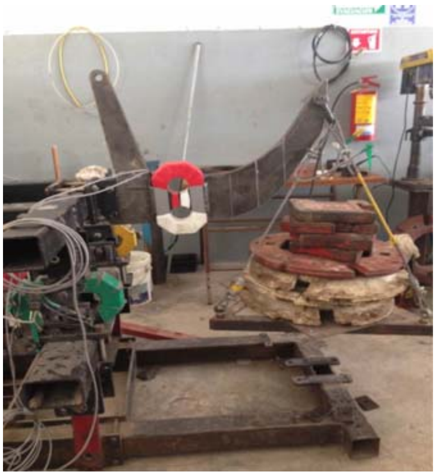


Figure 4 Calibration of transducer OAE for horizontal force

Figure 5 Calibration of the transducer OAE to determine vertical force constant

In order to measure the torque applied to the tine from the hydraulic system of the tractor was necessary a torque transducer calibration, the same Logbook360 data acquisition system was used. Calibration was performed with two-arm lever (0.65 and 0.85 m) and four loading and unloading weights: 294, 294, 343 and 343.5 N, each position was replicated 5 times (Figure 6).

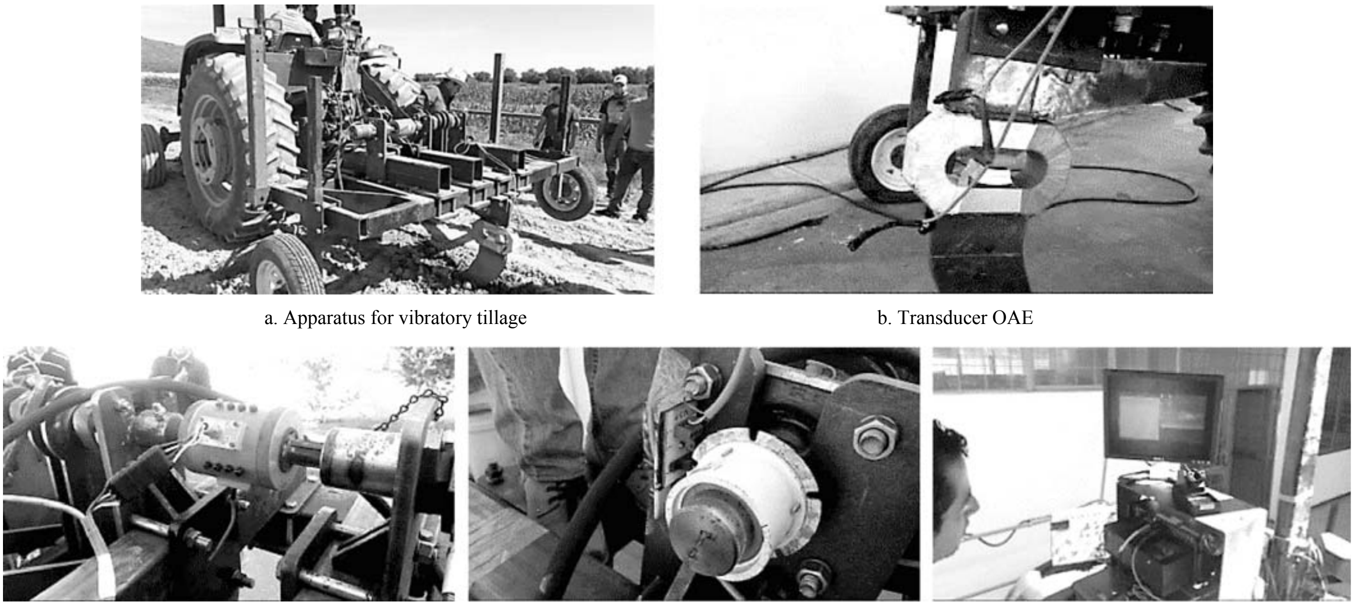
Data analysis was performed with the method of spectral analysis described by Campos-Magaña and Wills, (1995) using Matlab V2010a and Fast Fourier Transform algorithm to obtain the mean values, curves and calibration constants, using a linear regression of the data analysis. Analysis of variance was performed using Minitab V15 statistical analysis software. The field Treatments performed for two depths of 0.30 and 0.40 m, two working speed at 1.5 and 2.5 km h^{-1} and two amplitudes of 0.060 and 0.070 m for a single oscillatory speed of 3 Hz. A control test with not vibrating tine at two working depths of 0.30 and 0.40 m at a speed of 1.5 km h^{-1} was also performed. A total of 10 treatments were conducted and four replications were carried out by each arrangement; each trial was carried out on plots of 50 m long by 2.5 m wide.

Figure 6 Calibration of torque transducer

3 Results and discussion

3.1 Construction of the apparatus

Figure 7 shows instrumented apparatus for vibrating tillage (a), a transducer OAE (b) that was employed to measure required draft and vertical force, the torque transducer (c), an infrared optoelectronic sensor (d) to measure the frequency of the oscillating mechanism and a data acquisition system (e) for collecting all data information from the transducers in real-time to be subsequently analysed.



a. Apparatus for vibratory tillage

b. Transducer OAE

c. Torque transducer

d. Sensor optoelectronic

e. Data acquisition system

Figure 7 Instrumented Apparatus for field evaluation

To obtain the same reliability of measurement in the two transducers, it was necessary to standardize the coefficient of constant by means of the calibration adjustment on 3 channels of the amplifier that correspond to each sensor and adjust the input gain, the compensator and the excitation voltage. Figure 8, shows an example of a step graph of OAE corresponding to the vertical force transducer calibration. Figure 9 shows the equation of regression with a constant of 75.00 mV N^{-1}, with a correlation coefficient of 99.8%.

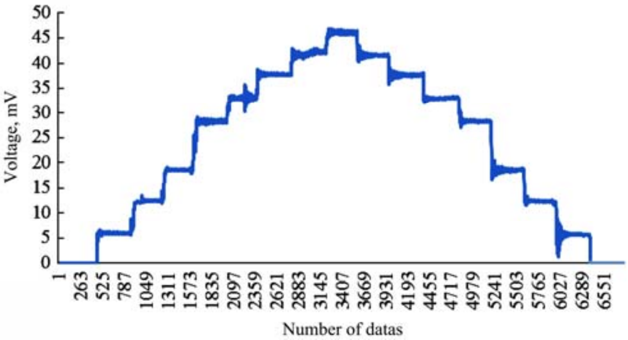
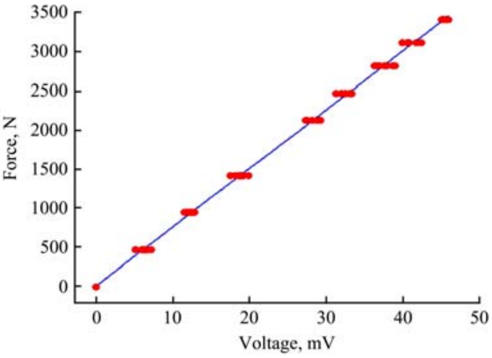


Figure 8 Cycles of loading and unloading of the OAE transducer during calibration with different weights for the vertical force



Note: The obtained equation was: Force (N) = 8.073+75.00* Voltage (mV).

Figure 9 Graph showing the linearity of calibration of OAE transducer for vertical force

Figure 10 shows an example Graph corresponding to the horizontal force of OAE transducer calibration and Figure 11 the linear calibration of horizontal force. In addition, shows the equation of regression with a constant of 47.74 mV N^{-1} with a correlation coefficient of 99.7%.

Figure 12 shows an example of the graph of the deformation in mV generated from the ascent and descent of four loads with a lever arm of 0.85 m and Figure 13 shows the equation of regression with constant 0.4538 mV N m^{-1} with a correlation coefficient of the 98.8%. Similar results were obtained by (Campos-Magaña, López-López, et al., 2015) for the calibration of sensors of the type of OAE.

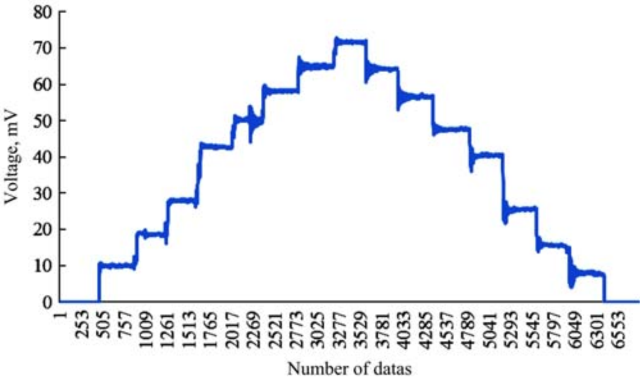
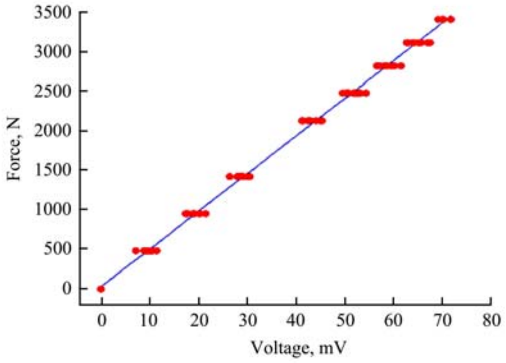


Figure 10 Cycles of loading and unloading of the OAE transducer during calibration with different weights for the horizontal force



Note: The obtained equation was: Force (N) = 21.97 + 47.74 Voltage (mV).

Figure 11 Shows the Linearity of calibration of horizontal force

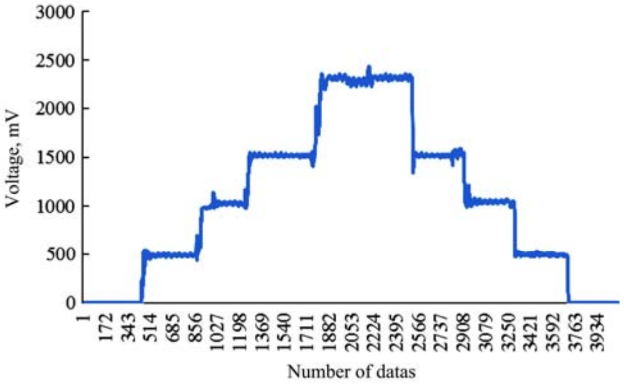
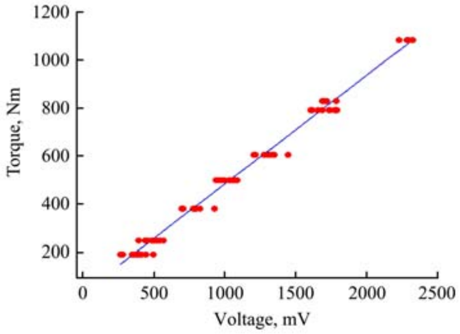


Figure 12 An example graph of cycles of loading and unloading during calibration the torque transducer with different loads and arm lever

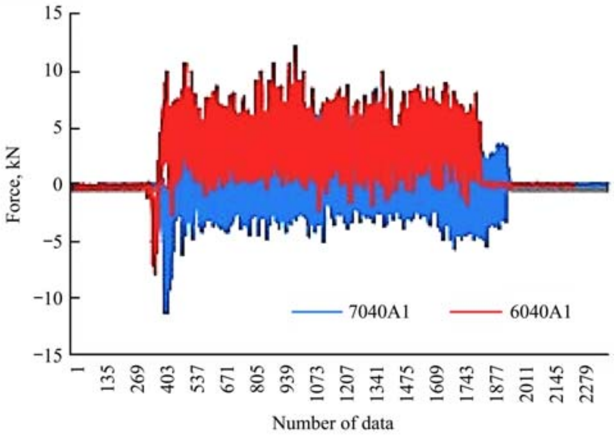


Note: Torque (Nm) = 29.34 + 0.4538 Voltage (mV).

Figure 13 Graph showing the linearity and constant of calibration for torque transducer

3.2 Tests under field conditions

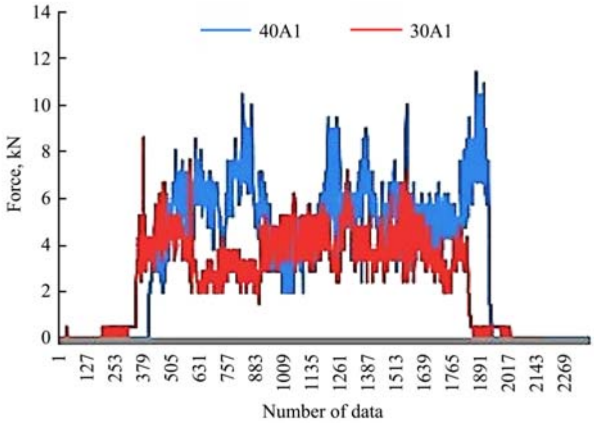
Figure 14 shows the forces obtained in field for the vertical force by comparing the amplitudes of 0.060 and 0.070 m, both working at a depth of 0.40 m and a speed of 1.5 km h^{-1}. It can be seen that the applied forces for higher oscillation amplitude (7040A1) are charged towards the positive part of the graph, while in the lower oscillation amplitude forces (6040A1) are distributed both in the positive as negative zone.



Note: The graph (7040A1) is for an amplitude of 70 mm and first replicate. The graph (6040A1) is for an amplitude of 70 mm and first replicate

Figure 14 Comparison of vertical forces to different amplitudes for a depth of 0.40 m

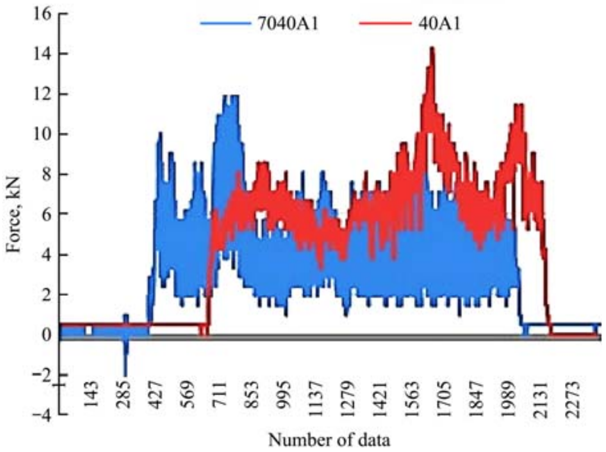
Figure 15 shows an example of the behaviour of horizontal force generated by the rigid tine subsoiler, where it can see the difference between two depths of tillage (0.30 and 0.40 m) at a speed of work of 1.5 km h^{-1}.



Note: Graph (40A1) shows the tine working at 0.40 m depth for the first replicate. Graph (30A1) shows the tine working at 0.30 m depth for the first replicate.

Figure 15 Comparison of the horizontal force at rigid tine at two depths

Figure 16 compares the draft-force obtained in field with the rigid and vibration tine for a forward speed (1.5 km h^{-1}), at the same depth of 0.40 m, which shows a lower draft-force demand when applying an induced vibrations to 0.070 m amplitude.



Note: Graph (7040A1) shows the draft force for vibrating tine working at 0.40 m depth. Graph (40A1) shows the draft force for rigid tine working at 0.40 m depth.

Figure 16 Comparative force demand at rigid tine and vibration (amplitude of 0.070 m) to the same depth of 0.40 m and speed of 1.5 km h^{-1}

From Figure 17 can be appreciated the magnitude of the torque obtained in field. Where shows that exist two directions of registered torque magnitude applied to the soil one for the forward working condition into compacted soil and the another magnitudes for the reverse when the tine is acting in loose soil. The results of this analysis are shown in Table 4.

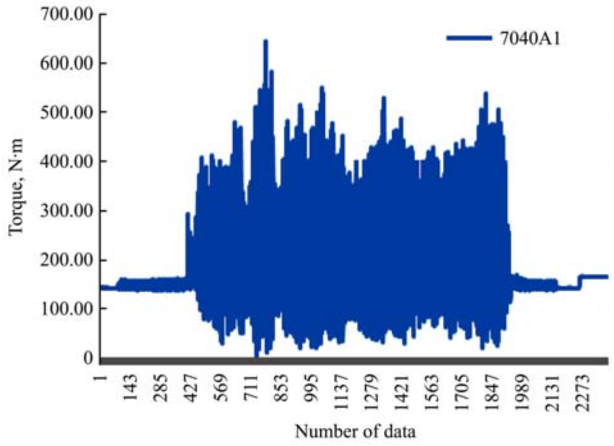


Figure 17 Graph showing the applied torque for the oscillating amplitude of 0.070 m and a working depth of 0.40 m

In Table 1, the variance analysis of the effect of depth of tillage of 0.30 to 0.40 m shows a highly significant difference on the magnitude of the draft force, as well as the force applied for tillage with oscillation chisel to three different magnitudes of swing (0.01, 0.06 to 0.07 m).

For the oscillatory tine, the mean values showed a decrease of 50.1% in the force of pulling, compared with the rigid tine. Similar results were reported by Shahgoli et al. (2010 b). The significant reduction in the magnitude of the draft force by change of depth of tillage, from 0.40 to 0.30 m, was also reported by (Spoor and Godwin, 1978; Campos-Magaña, Cadena-Zapata, et al., 2015).

Table 1 Analysis of variance of the effect depth (0.30 and 0.40 m) and swing (0.00, 0.06 to 0.07 m) on the magnitude of the pulling force

FV	GL	SC	CM	FC	F05	F01
Blocks	3	4.313	1.438	0.725		
Oscillation factor (O)	2	167.267	84.633	42.670**	5.14	10.92
Oscillation inaccuracy	6	11.901	1.983			
Depth factor (P)	1	2.8380	2.8380	221.21**	5.12	10.56
O×P	2	25.065	12.532	9.768**	4.26	8.02
Depth inaccuracy	9	11.546	1.283			
Total	23	505.892				

Note: (FV) Factors. (GL) degree of freedom. (CM)Mean square. (FC) F factor. (FC) F factor. (F05) F for ($P<0.05$). (F01) F for ($P<0.01$) (**) exist a significant difference between variable levels.

An analysis of variance was performed as shown in Table 2, whereas only the magnitudes of the draft force to the two assessed oscillation amplitudes of 0.060 and 0.070 m finding significant difference. Variance analysis shows the effect is also at two-tillage speed, 1.5 and 2.5 km h^{-1} on the draft force, finding not significant difference in force for the effect of change of speed. In this analysis was corroborated the significant effect that produces the depth of tillage on draft-force (Campos-Magaña, Reynolds-Chávez, et al., 2015).

Table 2 The variance analysis of the effect of working speed and depth, oscillating frequency and amplitude over the magnitude of the draft force

FV	GL	SC	CM	FC	F_{05}	F_{01}
Blocks	3	1.598	0.533	1.251		
Speed factor (V)	1	0.001	0.001	0.002	10.13	
Speed error	3	1.51	0.350			
Oscillation factor(O)	1	14.005	14.005	44.691**	5.99	13.75
V × O	1	1.129	1.129	3.602	5.99	
Oscillation error	6	1.88	0.313			
Depth factor (P)	1	118.157	118.157	186.240**	4.26	7.82
V × P	1	24.939	1.129	39.310**		
O × P	1	2.571	24.939	4.052		
V × O × P	1	3.194	2.571	5.035*		
Total error	24	7.613	3.194			
Total	31	176.138	0.634			

Note: (FV) Factors. (GL) degree of freedom. (CM)Mean square. (FC) F factor. (F05) F for ($P<0.05$). (F01) F for ($P<0.01$). (**) exist a significant difference between variable levels.

In comparison to the change of amplitude of oscillation, Table 3 shows a significant difference in the measurement of the draft force in the order of 21.0% when increases the oscillation amplitude from 0.060 to 0.070 m. Similar results were obtained by (Shahgoli et al., 2010 a).

Table 3 Comparison of means values of the magnitude of the draft forces at different frequencies of oscillation and depths of the tine work

Oscillation amplitude, mm	Average force, kN	Depth, m	Average force, kN
060	7.929a	030	5.153b
070	6.236b	0.40	8.96a

Note: Means in the same column followed by the same letter do not differ significantly ($P<0.\ 05$) by DUNCAN test.

From Table 4, the oscillation of the tine increases the magnitude of the vertical force to a 47.0% between the vibrating and the rigid tine when tillage speed increases from 1.5 to 2.5 km h^{-1}. Likewise, the magnitude of the torque is increased up to 33.0% when tillage depth is increased from 0.30 m to 0.40 m unless this increase has to do with the increased speed of 1.5 to 2.5 km h^{-1}. Similar magnitudes were reported by (Xin et al., 2013).

Table 4 Comparisons of means values of the vertical forces and torque for the evaluated treatments

Treatment	Vertical force, kN	Applied torque, N m
60 mm swing tine + 0.40 m Depth +2.5 km h^{-1}	8.93a	304.3a
70 mm swing tine + 0.40 m Depth +2.5 km h^{-1}	7.85a	303.1a
Rigid tine to 0.40 m Depth + 1.5 km h^{-1}	4.13bc	---
70 mm swing tine + 0.40 m Depth +1.5 km h^{-1}	4.04bc	318.1a
60 mm swing tine + 0.40 m Depth +1.5 km h^{-1}	3.96bc	310.2a
60 mm swing tine + 0.30 m Depth +2.5 km h^{-1}	3.28cd	186.5b
60 mm swing tine + 0.30 m Depth +1.5 km h^{-1}	3.62cd	203.8b
70 mm swing tine + 0.30 m Depth +2.5 km h^{-1}	2.39de	169.7bc
70 mm swing tine + 0.30 m Depth +1.5 km h^{-1}	2.14e	108.78c
Rigid tine to 0.30 m Depth+ 1.5 km h^{-1}	1.84e	---

Note: Means in the same column followed by the same letter do not differ significantly ($P<0.05$) by DUNCAN test.

4 Conclusions

The device designed and built by Tecnomec Agricola S. A. de C. V. allowed mounting of sensors for the on-field measurement of horizontal and vertical forces acting on the tine tool as well as frequency of oscillation and torque of impact of the tine in a satisfactory manner.

In the field-testing for verification of the system functions, data recorded at different amplitudes of swing revealed that the apparatus could reduce the draft force up to 50% using the oscillated induced tillage compared to the non-vibrating condition. There was a significant increase in the magnitude of the draft force and torque applied by 33% when the working depth increased from 0.30 to 0.40 m. Besides, an increase of 21% draft force was produced when the amplitude of oscillation was reduced from 0.070 to 0.060 m.

No significant difference was found when the tractor speed was increased from 1.5 to 2.5 km h^{-1}. Then, based on the above results, it was confirmed that there is a significant reduction in the draft-force between a rigid tines versus one vibrating at lower oscillation amplitude.

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