EVALUATION OF VIBRATION LEVELS OF AN AGRICULTURAL TRACTOR ON HARROW OPERATION

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Abstract. *Excessive vibrations compromise the quality of agricultural field operations, contribute with mechanical components failures and submit the operator to deafness and disorders of the spinal column and stomach. These problems, when related to agricultural tractors, are due to inadequate operational conditions such as incorrect ballast addition, extreme forward travel speed and other factors. The objective of this work was to evaluate the vibration levels on the rear and front axles of an agricultural tractor working at different forward speeds and wheel drive conditions in plowing and harrowing operation. A front-wheel-assist (FWA) tractor (Valtra model 800), a reverse disc plow and an offset disc harrow were adopted in the field tests. The forward travel speeds of the tractor-implement set were 2.96, 3.36 and 4.50* $km \cdot h^{-1}$*, with FWA enabled and disabled. Field tests were carried out in a completely randomized design on factorial scheme 3 x 2, with three replications. Tractor vibration was measured using two single axis accelerometers fixed above the rear and front axles of the tractor. The actual forward speed of the tractor was obtained by means of ultrasonic radar and the angular velocity of the wheels was measured with magnetic sensors. The drawbar force necessary to pull the disc harrow was obtained by a load cell. The data acquisition system used was Spider 8 (HBM®). The results show that the vibration levels observed for the plowing operation were higher than the levels observed for the harrowing operation. When the front-wheel-assist was enabled there was a reduction in vertical vibration levels of the tractor axles. The highest vibration levels were observed in the frequency range of 2 to 4Hz for the performed soil tillage operations. The vibration levels acting on the tractor chassis during plowing and harrowing operations reinforce the need for seat design directed to operator comfort.*

Keywords: *acceleration; disc harrow, front-wheel assist*

1. INTRODUCTION

The expansion of agricultural activity is due, largely, to the improvement of field operations and the deployment of efficient mechanized sets. In 2010, the production of agricultural machinery in Brazil had an increase of 34% as compared to 2009. Approximately 83,000 agricultural machines were produced in 2010, of which wheel tractors represented 87% of the total production (ANFAVEA, 2011).

Among agricultural wheel tractors, those fitted with front-wheel assist (FWA) contribute to the improvement of several performance parameters. Spagnolo *et al.* (2010) verified that the use of FWA resulted in an increase of over 22% in tractive force while working in low gears. There is not much information about the influence of FWA on the vibration of tractors as compared to the global levels of vibration of agricultural tractors in general. Information about its association with other conditions, such as tractor forward speed, is not easily found.

In recent years, the mass of tractors decreased due to the use of new materials and improvement of design techniques. However, according to Gravalos *et al.* (2009), this mass reduction increased significantly the magnitude of vibration. Also, the increase of efficiency and forward speed of tractors contributes to raised levels of vibration, as well as creates new problems of vibration, mainly when operating agricultural tractors with high power sources (Servadio *et al.*, 2007).

The quality of agricultural field operations such as soil tillage, seeding and fertilization depends on the tractor-implement set characteristics. Excessive vibrations compromise quality, contribute to mechanical failures, and submit the operator to deafness and disorders of the spinal column and stomach. These excessive vibrations can be due to inadequate operational conditions of agricultural tractors such as irregular tire inflation pressure, incorrect ballast addition, extreme forward travel speed and others.

Of all field operations involved in farming, soil tillage is one of the most important tasks to be performed since it has great influence on all other operations. Conventional tillage operations are performed by one plowing and two harrowing tools, which generate great soil mobilization. Excessive soil mobilization can contribute to elevated levels of incident vibration on the tractor, which is transmitted to the operator through the seat. The seat is a component that affects the loads on the operator's body, and proper seat design is crucial to modify these load characteristics and reduce the discomfort of the operator (Mehta *et al.*, 2008).

The design of damping systems employed in agricultural tractor seats begins with the determination of the vibrations acting on the tractor. It is necessary to know the source of vibrations acting on the tractor and the systems that compose it in order to mitigate its effect on the operator's body (Cunha *et al.*, 2009). Vibrations due to the tire/soil interaction are largely transmitted by the axles of the tractor to the constituent components and machinery elements. Therefore, monitoring of vibration can be accomplished through the axles of the tractor.

Nguyen and Inaba (2011) determined vibration levels acting on an agricultural tractor, varying the inflation pressure of the tires and the forward speed, using a single triaxial accelerometer, placed on the rear axle of the machine. This study was carried out in order to determine the working conditions that reduce vibration on the axles, help reduce its transmissibility to the tractor seat and therefore to the operator.

The hypothesis that precedes this study is that the use front-wheel-assist (FWA) can reduce the vibration transmitted to the tractor's axles at any velocity of the tractor-implement set, during conventional soil tillage operations. The objective of this work was to evaluate the vibration levels on the rear and front axles of the agricultural tractor working at three different forward speeds, with additional front-wheel drive enabled and disabled, during plowing and harrowing operations.

2. MATERIAL AND METHODS

2.1. The tractor and implements

A Valtra make 800L model tractor with front-wheel-assist was adopted for all field tests. During all harrowing and plowing operations the tractor remained with 300 kg of front ballasts. The implements used to prepare the soil were a disc plow, Fonseca® make, and an offset disc harrow, manufactured by Baldan®, model SP. The main specifications of the tractor, tires, disc plow, and harrow are presented in Tab. 1.

Table 1. Main specifications of the tractor, tires, and implements used in field tests.

Characteristics of agricultural tractor and tires	
Engine model	420 DR, naturally-aspirated
Engine displacement (dm^3)	4.4
Number of engine cylinders	4
Engine power (kW)	59
Nominal speed of engine (rpm)	2270
Tractor mass without ballast (kg)	3225
Front tire (width – diameter, in)	14.9 – 24
Rear tire (width – diameter, in)	18.4 – 34
Characteristics of the disc plow	
Number of discs	3
Diameter of discs (m)	0.71
Work depth (m)	0.30
Characteristics of the offset disc harrow	
Disc types	Toothed (1st section) and plain (2nd section)
Number of discs	32
Diameter of discs (m)	0.46
Work length (m)	2.35

2.2. Experiment and instrumentation description

Acceleration acting on the tractor's rear and front axles was measured during soil plowing and harrowing operations. Vibration levels were determined for three different forward speeds of the tractor-implement set with additional front-wheel drive both enabled and disabled. In order to monitor the vibration of the tractor's rear and front axles two single-axis PCB® accelerometers were used, with operation range from 1 Hz to 4000 Hz. The accelerometers were installed under the rear and front axles of the tractor, close to their respective tires. The acceleration was measured along the vertical direction of the tractor.

Three work speeds for the field tests were pre-established for plowing and harrowing operations. Table 2 shows the transmission ratios used and the forward travel speeds of the unloaded tractor-implement set. For all tests the engine speed was kept at 1900 rpm. An ultrasonic radar, manufactured by Dickey John®, model Radar II, was used to measure the actual forward travel speeds of the tractor-implement set. The radar was installed on the tractor's chassis as shown in Fig. 2. Average travel reduction ratio observed during plowing operation was obtained, but during harrowing the travel reduction ratio was not measured.

Table 2. Transmission ratios and respective forward travel speeds of the tractor adopted during the tests.

Transmission ratio	Forward travel speed (km h^{-1})
2nd downshifted and torque converter in position I	$V_1 = 2.96$
2nd downshifted and torque converter in position II	$V_2 = 3.36$
3th downshifted and torque converter in position I	$V_3 = 4.50$

The drawbar force necessary to pull the disc harrow was measured using a load cell, manufactured by Kratos®, model KLC, with a nominal capacity of 5000 kgf. Ten samples were obtained for each experimental unit and the mean values were correlated with vibration amplitudes. All sensors, except the load cell that uses a proprietary display, were coupled to the data acquisition system Spider® 8 and configured using the software Catman 2.2, both supplied by HBM®. The sampling rate adopted for the vibration measurements was 1200 Hz. Figure 1 shows the sensors used in the field tests.

(a) (b) (c)

Figure 1. Sensors used to measure the actual forward speed of the tractor-implement set (a); acceleration of the rear axle of the tractor (b); and drawbar force in harrowing operation (c).

2.3. Parameters obtained in field tests

The root mean square (RMS) acceleration of the axles was used to characterize the vibration levels. The values were obtained during plowing and harrowing operations. The RMS value, according to Harris and Piersol (2002) is the measure of both the central tendency and dispersion of vibration.

The RMS acceleration values allow observing the vibration magnitude acting on the tractor and estimate the possible levels transmitted to the operator. The obtained values were confronted with the ISO 2631 standard (1997), which establishes exposure limits for maximum acceleration in order to provide ideal comfort to the machine's operator.

The frequency spectrum was obtained for the front and rear axles of the tractor during plowing and harrowing operations. The differences in the spectral signature were studied for both axles for the highest and lowest speed of the tractor with and without the use of additional front-wheel drive (FWA).

2.4. Statistical design and analysis

Field tests were carried out in a completely randomized design on a 3x2 factorial scheme; i.e. three forwards speeds of tractor-implement set and two traction conditions (additional front-wheel drive enabled and disabled). Three replications were done, totaling 18 treatments. Each experimental unit consisted of a 15 m long work line. The RMS acceleration value was calculated for the mean portion of the sampled period for each parcel. In other words, the data was trimmed at the beginning and end of acquisition in order to remove the regime of acceleration and deceleration of the tractor-implement set.

The data of RMS acceleration was treated with variance analysis in order to verify the significance of the use of FWA for different speeds. Quantitative factors were analyzed by linear regression and qualitative factors were analyzed by means of a statistical F-test. The t-test was used to compare the vibration levels between the rear and front axles of the tractor when the qualitative factor (FWA) showed a significant effect.

2.5. The experimental area

The experiments were conducted at the Agricultural Engineering Department of the Universidade Federal de Viçosa, Minas Gerais, Brazil. The experimental area, close to 700 m^2, has low slope. The main physical characteristics, such as water content, bulk density and penetration resistance of soil are shown in Tab. 3. The water content in soil was obtained by drying at 105 ± 5 ° C, for 24 hours and represented on dry basis. The density was measured by the volumetric ring method. Penetration resistance was represented by cone index, at 0.30 m of depth, measured using a penetrometer, model PNT-2000.

Table 3. Soil physical properties of the experimental area used for the tests.

Soil bulk density (kg m^{-3})	1798
Soil water content (%)	12.22
Cone index (MPa)	1.10

3. RESULTS AND DISCUSSION

Vibration levels in the front and rear axles of tractor were determined during the plowing and harrowing operation, with and without the use of front wheel assist drive. Forward speed of the tractor-implement set was varied and the resulting acceleration levels along the vertical axis of the tractor were measured during operation. Vibration levels transmitted from the soil through the tractor axles were represented by the root mean square (RMS) acceleration. The influence of forward speed and the use of wheel assist drive on vibration levels were also analyzed.

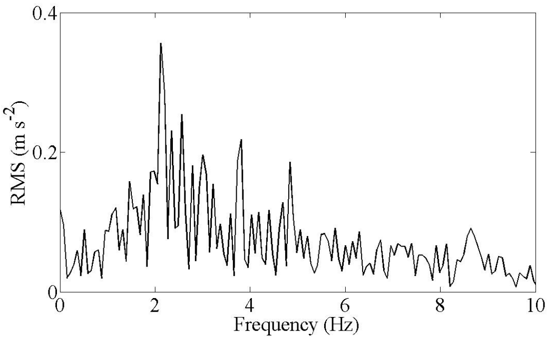
During plowing operation, the use of wheel assist drive had no significant effect on the transmittance levels at the tractor's axle; however, the forward speed of the tractor-plow set influenced the vibrations of the axle. Table 4 shows the main results of variance analysis for the RMS acceleration acting on the rear and front axles of the tractor. It was observed during the plowing operation an average travel reduction ratio of 15.49% on the rear wheel with the use of FWA. With FWA disabled, the average travel reduction ratio was 5.21% for the front wheel and 5.15% for the rear wheel.

Table 4. Main results of variance analysis of RMS acceleration determined for the rear and front axles of the agricultural tractor, in plowing operation.

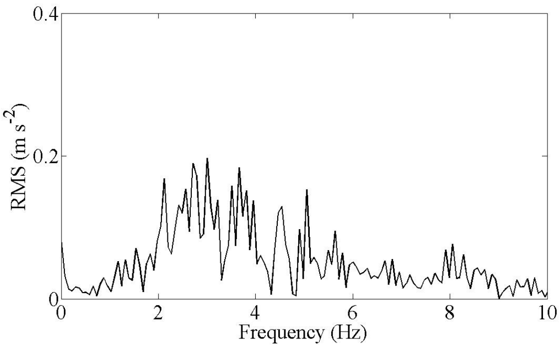
		Rear axle	Front axle
RMS acceleration	V	(F-test = 8.16; p = 0.0058)	(F-test = 19.46; p = 0.0002)

** Significance level used 5 % of probability.

In Figures 2 and 3 the frequency spectra are represented for the tractor's rear and front axles during plowing, respectively, at the V_1 and V_3 speeds.



(a)



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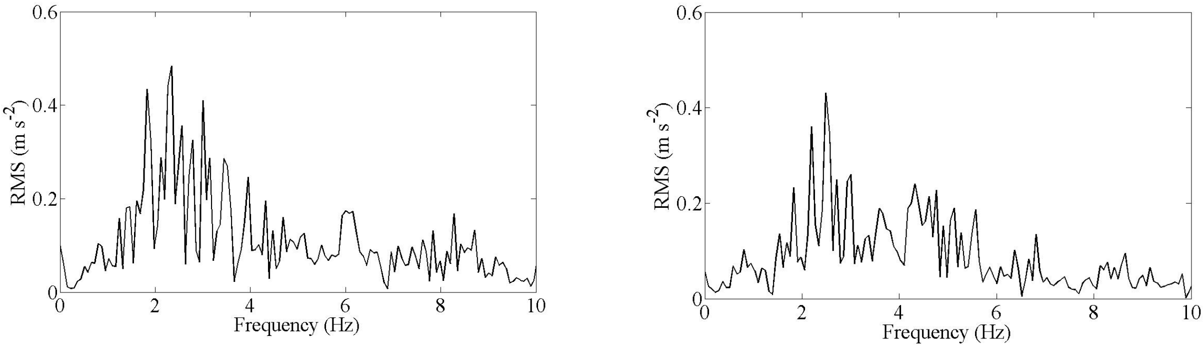
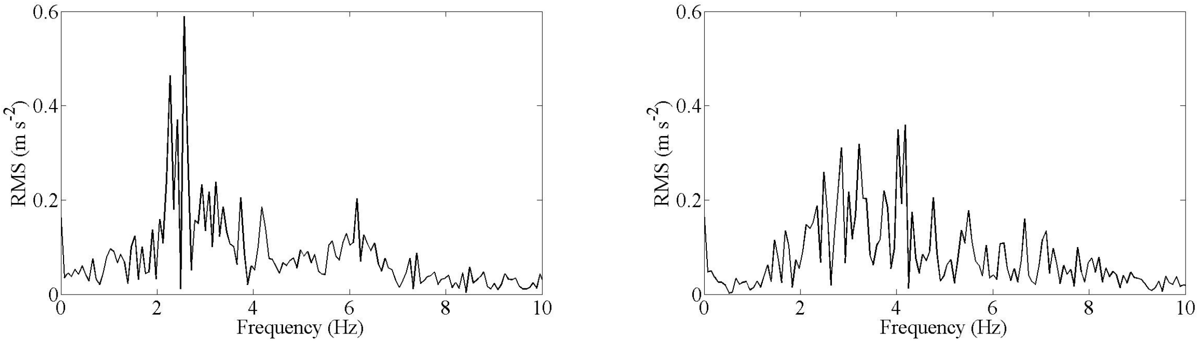
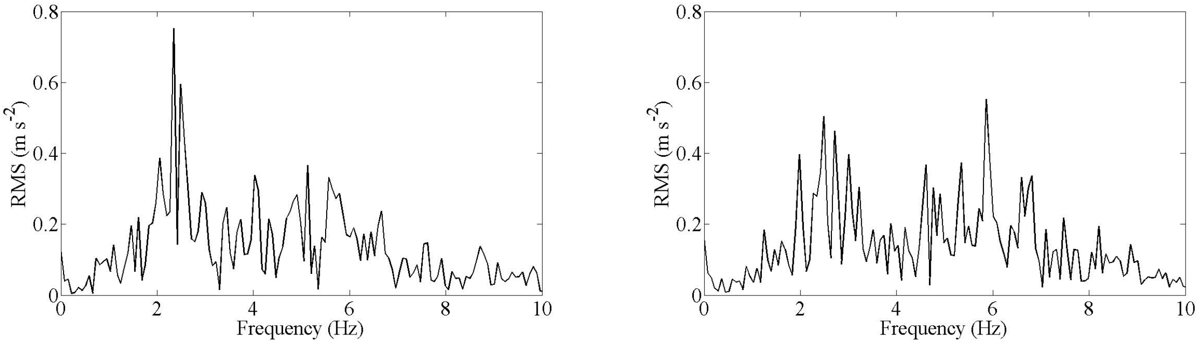


(c) (d)

Figure 2. Frequency spectra for the rear axle in plowing operation: (a) forward speed V_1 with FWA OFF, (b) forward speed V_1 with FWA ON, (c) forward speed V_3 with FWA OFF, and (d) forward speed V_3 with FWA ON.



(a) (b)



(c) (d)

Figure 3. Frequency spectra for the front axle during plowing operation: (a) forward speed V_1 with FWA OFF, (b) forward speed V_1 with FWA ON, (c) forward speed V_3 with FWA OFF, and (d) forward speed V_3 with FWA ON.

According to Prasad *et al.* (1995), main vibrations in tractors are sinusoidal and random. Sinusoidal vibrations are deterministic and can be predicted. Random vibrations are irregular and thus cannot be predicted. The undamped natural frequencies of a tractor during its displacement are in the range of 3 to 5Hz (Goering *et al.*, 2006). From the frequency spectra (Fig. 2 and Fig. 3), it can be observed that the vibration on the tractor's axles for the plowing operation is random and that the highest vibration peaks were in the range of 2-4Hz. Only for the V_3 forward speed with FWA enabled a peak out of this range was observed, at about 6 Hz. However, with the FWA enabled, there was an average reduction of vibration levels in this range, of about 33%.

Equations 1 and 2 show the fitted models for studying the effect of tractor forward speed as related to the levels of vertical vibration in the rear and front axles. The models were chosen based on the coefficient of determination, on the significance of the chosen parameters, and on the lack-of-fit.

$$RMS_{pr} = -0.35191 + 0.38824\,V \qquad r^2 = 98.08\ \% \tag{1}$$

$$RMS_{pf} = 0.16076 + 0.33051V \qquad r^2 = 98.63\% \tag{2}$$

where,
RMS_{pr} and RMS_{pf} = RMS acceleration on rear and front axles in plowing operation, m s^{-2};
V = tractor forward speed, km h^{-1}.

Figure 4 represents the forward speed effect over vibration levels on the tractor axles. It was verified that acceleration levels vary linearly with speed, i.e., as the forward speed increases, so does the vibration on the rear and front axles.

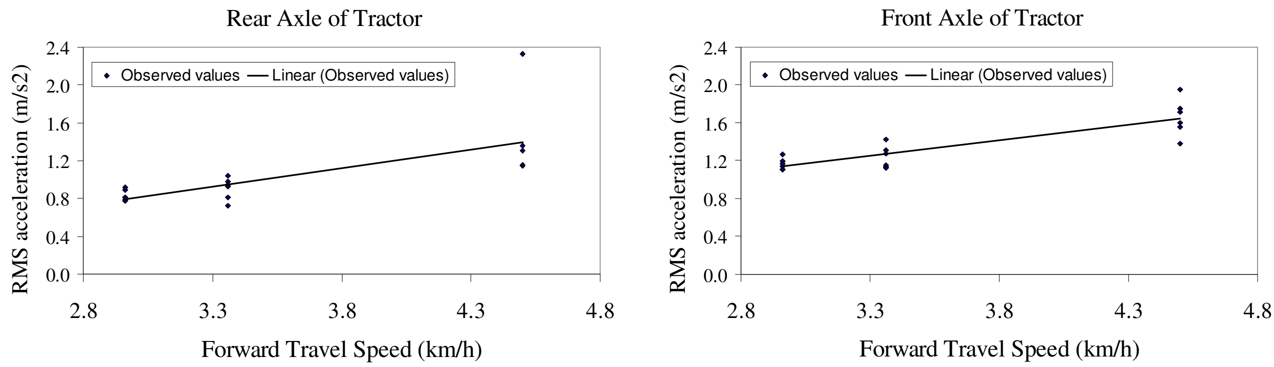


Figure 4. Fitted curves of RMS acceleration for the rear and front axles as a function of forward travel speeds in plowing operation.

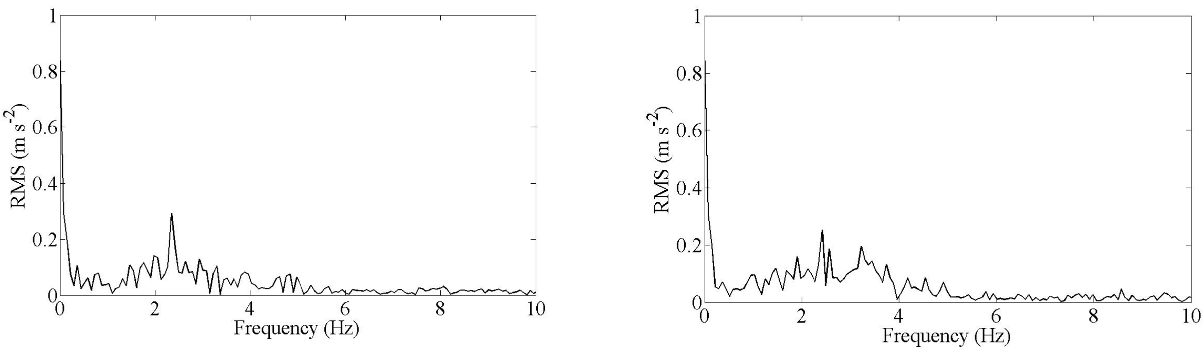
Table 5 shows the results of variance analysis for the vibration on the tractor's axles during harrowing operation. It can be verified that the use of front wheel assist and the forward speed of the tractor-implement set influenced significantly the RMS acceleration acting on the tractor's rear and front axles. RMS acceleration on both axles was not affected by the interaction of forward speed and the use of front wheel assist. The required force to pull the harrow was not influenced by the forward speed of the tractor-implement set and by the use of the front wheel assist, as well as the interaction between them. The mean force acting on the drawbar of the tractor was 5210 N.

Table 5. Summary of results of variance analysis for RMS acceleration determined for the rear and front axles of the tractor in harrowing operation.

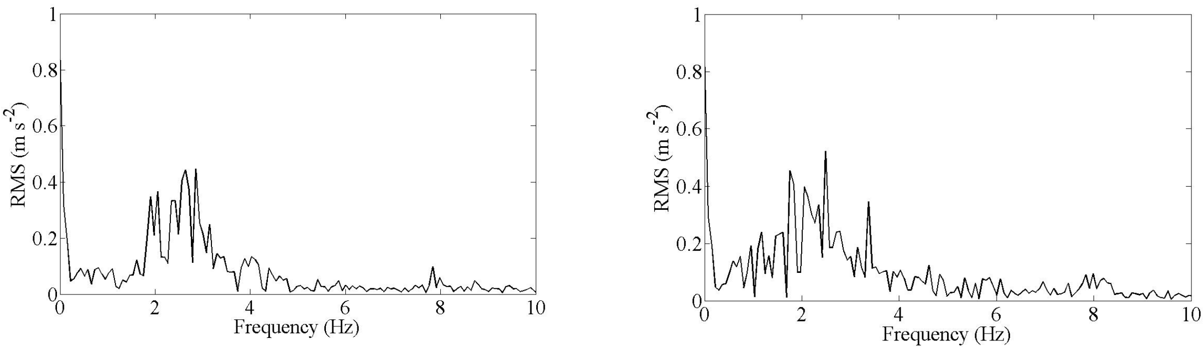
		Rear axle	Front axle
RMS	FWA	(F-test = 91.30; p = 0.0001)	(F-test = 25.44; p = 0.0001)
acceleration	V	(F-test = 14.51; p = 0.0025)	(F-test = 13.41; p = 0.0033)

** Significance level used 5 % of probability.

Figures 5 and 6 show the frequency spectra for the harrowing operation at forward speeds V_1 and V_3 for the tractor's rear and front axles, respectively.

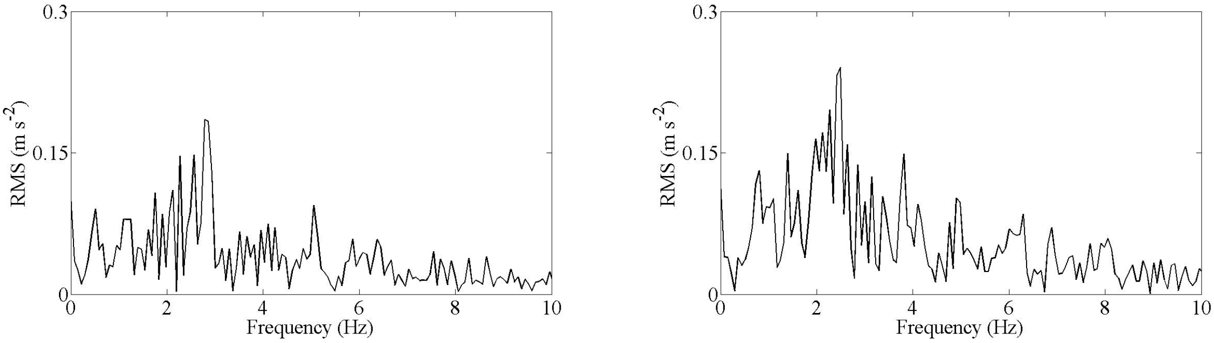


(a) (b)

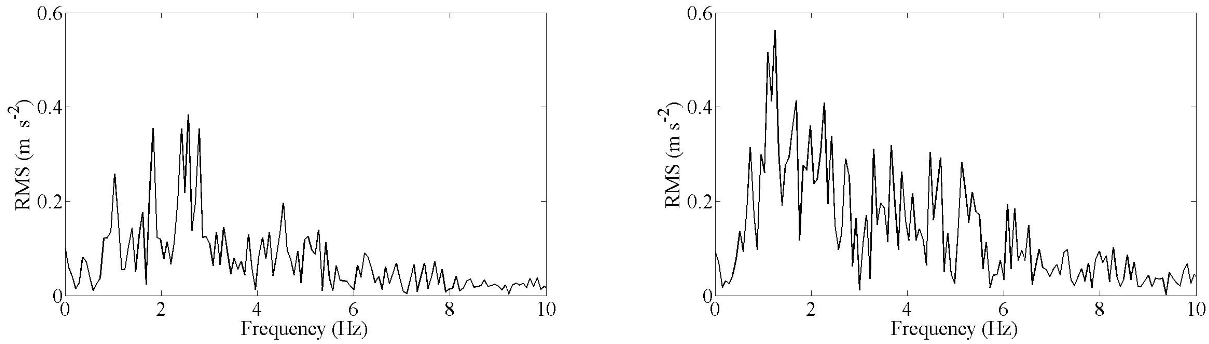


(c) (d)

Figure 5. Frequency spectra for the rear axle in harrowing operation: (a) forward speed V_1 with FWA OFF, (b) forward speed V_1 with FWA ON, (c) forward speed V_3 with FWA OFF, and (d) forward speed V_3 with FWA ON.



(a) (b)



(c) (d)

Figure 6. Frequency Spectra for the front axle of the harrowing operation: (a) forward speed V_1 with FWA OFF, (b) forward speed V_1 with FWA ON, (c) forward speed V_3 with FWA OFF, and (d) forward speed V_3 with FWA ON.

According to Figures 5 and 6, it was observed that vibration on the tractor's axles for harrowing operations is random and that the highest vibration levels are in the range of 2-4 Hz. Only for the V_3 forward speed with FWA enabled a global peak out of this range could be observed, at 2 Hz. Similar results were found by Fernandes *et al.* (2003), who verified that the highest levels of vertical vibration on the seat of the tractor occurred in the frequency range of 2-4 Hz, while executing the same operation.

On the front axle, with FWA enabled, there was an increase of 26% in the RMS acceleration levels for the V_1 speed, whereas a 16% reduction was observed at the V_3 speed with FWA disabled. For the rear axle, an increase of 14% was observed for the V_1 speed and an increase of 16% for V_3.

Equations 3 and 4 represent the fitted models used for studying the effect of tractor forward speed in regards to the levels of vertical vibration on the rear and front axles of the tractor in harrowing operation. Figure 7 shows the forward speed effect over vibration levels on the tractor's axles. Similarly, for the plowing operation, it was verified that the acceleration levels vary linearly with speed, i.e., as forward speed increases, so does the vibration on the rear and front axles of the tractor.

$$RMS_{hr} = 0.17722 + 0.23533\,V \qquad r^2 = 98.18\,\% \tag{3}$$

$$RMS_{hf} = 0.28019 + 0.24831\,V \qquad r^2 = 96.86\% \tag{4}$$

where,
RMS_{hr} and RMS_{hf} = RMS acceleration on rear and front axles in harrowing operation, m s^{-2}.

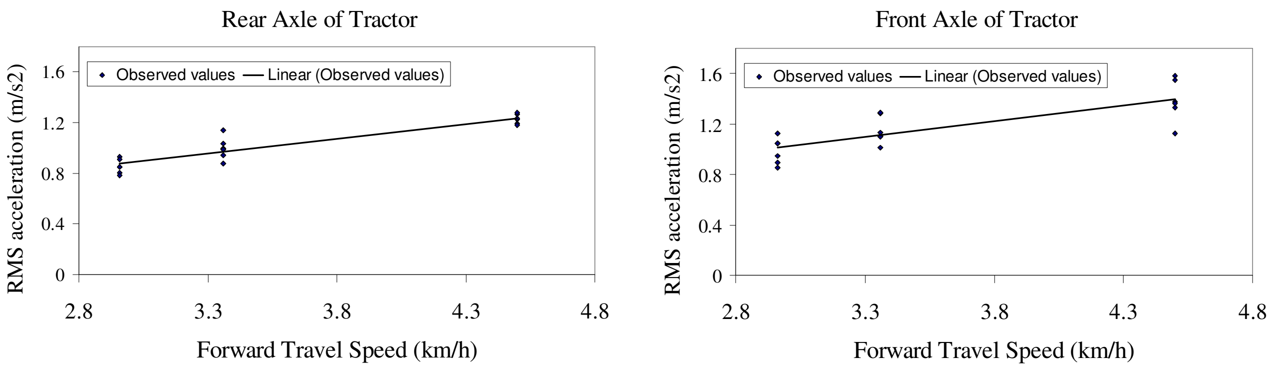


Figure 7. Fitted curves of RMS acceleration for the rear and front axles as a function of forward travel speed in harrowing operation.

The RMS acceleration values observed during the plowing and harrowing operations depends on the use of front wheel assist as shown in Table 4. The RMS acceleration observed on the front axle was 22% higher than on the rear axle with FWA enabled for the harrowing operation and 28% higher for the plowing operation. The vibration transmitted from the soil through the rear axle is reduced by enabling FWA in both operations; however the front axle suffered an increase in vibration levels during the harrowing operation.

Table 4. RMS acceleration (m s^{-2}) observed for the rear and front axles of the tractor in harrowing operation with FWA ON and OFF.

	Harrowing RMS acceleration	Plowing RMS acceleration	Front-wheel assist
Rear axle	1.07	1.14	OFF
	0.98	0.96	ON
Front axle	1.10	1.36	OFF
	1.26	1.34	ON

The results for RMS acceleration shown in Table 4 indicate the importance of developing an adequate seat design, since a large portion of the vibrations acting on the chassis of the tractor is transmitted to the operator through the seat. According to ISO 2631-1 (1997), despite the use of FWA, the vibration observed for the rear axle would be classified as uncomfortable for both tillage operations, considering that the vibrations on the axle were effectively transmitted to the operator. As for the front axle, vibration levels are classified as very uncomfortable during the execution of operations, except for the harrowing operation with FWA disabled.

4. CONCLUSIONS

Based on the results it was concluded that:

- Vibration levels observed for the plowing operation were higher than the levels observed for the harrowing operation;

- When front wheel assist was enabled there was a reduction in vertical vibration levels of both axles;

- The highest vibration levels were observed in the frequency range of 2 to 4 Hz for the performed soil tillage operations;

- The vibration levels acting on the tractor chassis during plowing and harrowing operations reinforce the need for seat design directed to operator comfort.

5. ACKNOWLEDGEMENTS

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