



Vibration levels on rear and front axles of a tractor in agricultural operations

Geice Paula Villibor¹, Fábio Lúcio Santos^{2*}, Daniel Marçal de Queiroz² and Denis Medina Guedes²

¹Departamento de Engenharia de Produção e Mecânica, Universidade Federal de Viçosa, Campus Universitário, Viçosa, Minas Gerais, Brazil.

²Departamento de Engenharia Agrícola, Universidade Federal de Viçosa, Av. Peter Henry Rolfs, s/n, 36570-000, Viçosa, Minas Gerais, Brazil.

*Author for correspondence. E-mail: fabio.ls@ufv.br

ABSTRACT. Excessive vibrations in agricultural tractors can contribute with mechanical failures and subject the operator to discomfort. This work evaluated the vibration levels on rear and front axles of an agricultural tractor working at different forward speeds and wheel drive conditions in plowing and harrowing operations. Field tests were carried out in a completely randomized design in a factorial arrangement 3 x 2 (forward travel speeds x front-wheel-assist enable or disable), with three replications. Tractor vibration was measured using two single axis accelerometers fixed above the rear and front axles. 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 transducers. The drawbar force to pull the disc harrow was obtained by a load cell. The results showed that the vibration levels observed for the plowing operation were higher than observed for the harrowing operation. When the front-wheel-assist (FWA) 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 both soil tillage operations evaluated.

Keywords: tillage operations, mechanical vibrations, forward speed.

Níveis de vibração nos eixos dianteiro e traseiro de um trator em operações agrícolas

RESUMO. Vibrações excessivas em tratores agrícolas podem contribuir para falhas mecânicas e provocar desconforto ao operador. Objetivou-se avaliar os níveis de vibração nos eixos dianteiro e traseiro de um trator agrícola em diferentes velocidades de operação e condições de tração durante as operações de aração e gradagem. Os ensaios de campo foram realizados segundo delineamento inteiramente casualizado em esquema fatorial 3 x 2 (velocidade de deslocamento x tração dianteira auxiliar acionada ou não acionada), com três repetições. A vibração no trator foi determinada por meio de acelerômetros uniaxiais posicionados na parte superior dos eixos dianteiro e traseiro. A velocidade real de deslocamento foi obtida por radar ultrassônico e as velocidades angulares das rodas foram determinadas por meio de transdutores magnéticos. A força na barra de tração para tracionar a grade foi obtida por uma célula de carga. Os resultados mostram que os níveis de vibração observados para a operação de aração foram superiores aos da operação de gradagem. Quando a tração dianteira auxiliar (TDA) foi acionada houve uma redução nos níveis de vibração vertical nos eixos dos tratores. Os maiores níveis de vibração foram observados na faixa de 2 a 4 Hz para ambas as operações de preparo de solo avaliadas.

Palavras-chave: preparo de solo, vibrações mecânicas, velocidade operacional.

Introduction

The expansion of agricultural activities 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. Yanai et al. (1999) evaluated the influence of the FWA in agricultural tractors performance. The authors verified that the use of FWA resulted in significant advantages in operational performance, such as split, forward velocity and drawbar power. However, there is scarce 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 owing the use of new materials and improvement of design techniques. This mass reduction increased significantly the magnitude of vibration. Also, the increase of efficiency and forward speed of tractors contributes to raise 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 subject the operator to deafness and disorders of the spinal column and stomach (PRASAD et al., 1995; SCARLETT et al., 2007; ZEHSAZ et al., 2011). These excessive vibrations can be due to inadequate operating 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 high 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 to the operator (MEHTA et al., 2000).

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 vibration can be accomplished through the axles of the tractor.

Nguyen and Inaba (2011) determined vibration levels acting on an agricultural tractor, by 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, and that help reducing its transmissibility to the tractor seat and therefore to the operator.

The hypothesis of this study is that the use of a 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 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.

Material and methods

Experimental area

Experiments were conducted at the Agricultural Engineering Department of the Universidade Federal de Viçosa, Minas Gerais State, Brazil. The experimental area about 700 m² has low slope. The main physical characteristics, such as water content, bulk density and penetration resistance of the soil were determined to characterize the experimental area; it was considered eighteen replications along the experimental area to perform this characterization. The water content in soil was obtained by drying at 105 ± 5°C, for 24 hours and represented on a dry basis. The density was measured by the volumetric ring method. Penetration resistance was represented by cone index, at 0.30 m depth, measured using a penetrometer, model PNT-2000.

Tractor and implements

A Valtra 800L 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, made by Fonseca®, and an offset disc harrow, manufactured by Baldan®, model SP. The main specifications of the tractor, tires, disc plow, and harrow are listed in Table 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 the 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 (1 st section) and plain (2 nd section)
Number of discs	32
Diameter of discs (m)	0.46
Work length (m)	2.35

Experiment and instrumentation description

The 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-assist 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 over 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 Figure 2. Average travel reduction ratio observed during plowing operation was obtained, but during harrowing the travel reduction ratio was not measured.

Table 2. Transmission ratio and respective forward travel speed of the tractor during the tests.

Transmission ratio	Forward travel speed (km h ⁻¹)
2 nd downshifted and torque converter in position I	V ₁ = 2.96
2 nd downshifted and torque converter in position II	V ₂ = 3.36
3 th 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 50 kN. 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.

Parameters obtained in field tests

The root mean square (RMS) acceleration of the axles was used to characterize the vibration levels. Values were obtained during plowing and harrowing operations. The RMS value, according to Harris and Piersol (2002) is a 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 2631-1 (ISO, 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 using additional front-wheel-assist (FWA).

Statistical design and analysis

Field tests were carried out in a completely randomized design in a 3 x 2 factorial arrangement; i.e. three forwards speeds of the tractor-implement set and two traction conditions (front-wheel-assist 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, data were trimmed at the beginning and end of acquisition in order to remove the regime of acceleration and deceleration of the tractor-implement set.

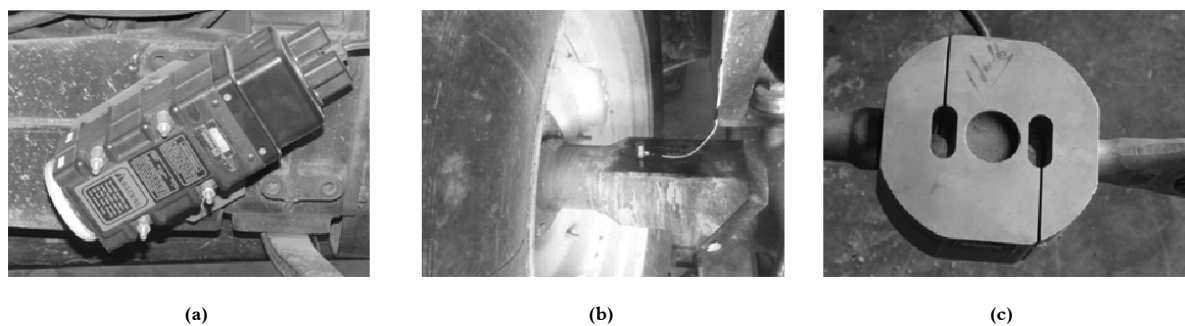


Figure 1. Transducers used to measure the actual forward speed of the tractor-implement set (a); acceleration of the rear axle of the tractor (b); and drawbar force in harrowing operation (c).

The data of RMS acceleration were treated with analysis of variance 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.

Results and discussion

The main physical characteristics of the experimental area, water content, bulk density and penetration resistance of the soil, are presented in Table 3. These soil physical properties were obtained along the experimental area, considering one sample for each treatment.

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

Vibration levels in the front and rear axles of tractor were determined during the plowing and harrowing operations, 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 the FWA on vibration levels were also analyzed.

During plowing operation, the use of the FWA had no significant effect on the transmittance levels in 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 the analysis of variance 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 the analysis of variance of RMS acceleration determined for the rear and front axles of the agricultural tractor, at plowing.

RMS Acceleration	Forward Velocity (V)	Rear axle	Front axle
		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 (lowest) and V_3 (highest) speeds.

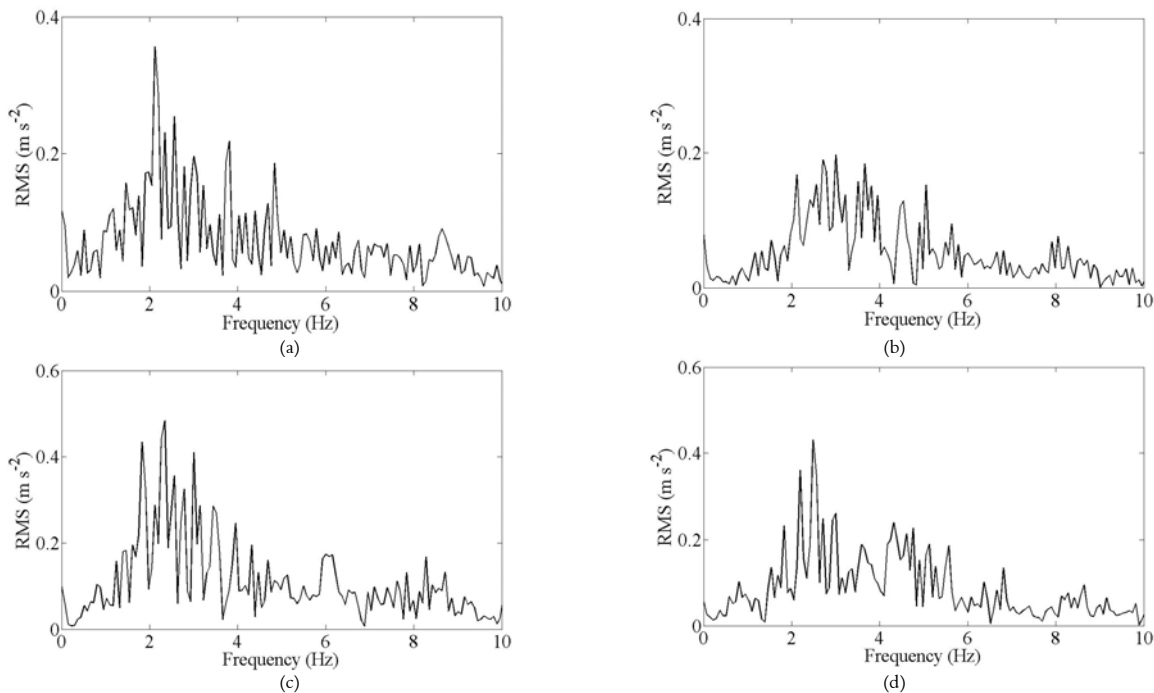


Figure 2. Frequency spectra for the rear axle during plowing operation: (a) forward speed V_1 with FWA OFF, (b) forward speed V_1 with FWA ON, (c) forward speed V_3 with FWA OFF, and (d) forward speed V_3 with FWA ON.

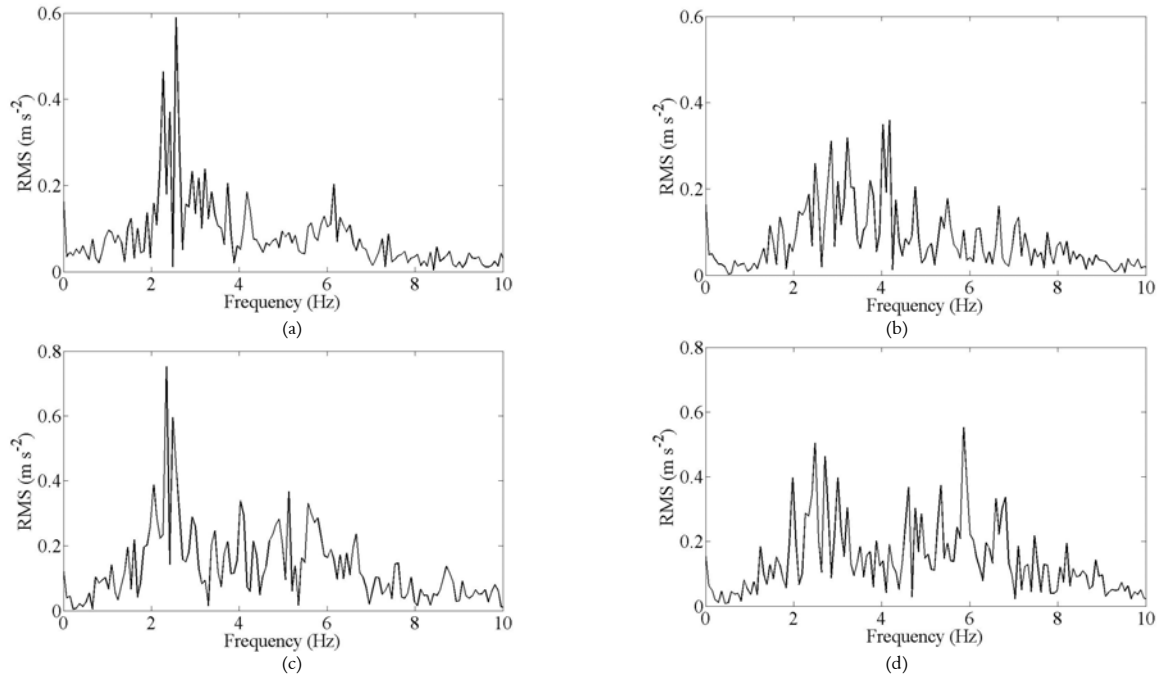


Figure 3. Frequency spectra for the front axle during plowing operation: (a) forward speed V_1 with FWA OFF, (b) forward speed V_1 with FWA ON, (c) forward speed V_3 with FWA OFF, and (d) forward speed V_3 with FWA ON.

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 - 5Hz (GOERING et al., 2006). From the frequency spectra (Figure 2 and 3), it can be observed that the vibration on the tractor's axles for the plowing operation is random and 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, around 33%.

Equations 1 and 2 show the fitted models for studying the effect of the 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.

$$RMS_{pr} = -0.35191 + 0.38824 V \quad (1)$$

$$r^2 = 0.98$$

$$RMS_{pf} = 0.16076 + 0.33051 V \quad (2)$$

$$r^2 = 0.99$$

where:

RMS_{pr} and RMS_{pf} = RMS acceleration on rear and front axles during plowing operation, $m\ s^{-2}$;

V = tractor-forward speed, $km\ h^{-1}$.

Figure 4 depicts 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.

Table 5 shows the results of the analysis of variance for the vibration on the tractor's axles during harrowing operation. The use of front wheel assist and the forward speed of the tractor-implement set had significant influence on 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 thereof. The mean force acting on the drawbar of the tractor was 5.21 kN.

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

According to Figures 5 and 6, the vibration on the tractor's axles for the harrowing operation is random and the highest vibration levels are in the range of 2-4 Hz. Only for the V_3 forward speed with FWA enabled a 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 the tractor-forward speed with regard to the levels of vertical vibration on the rear and front axles of the tractor during 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.

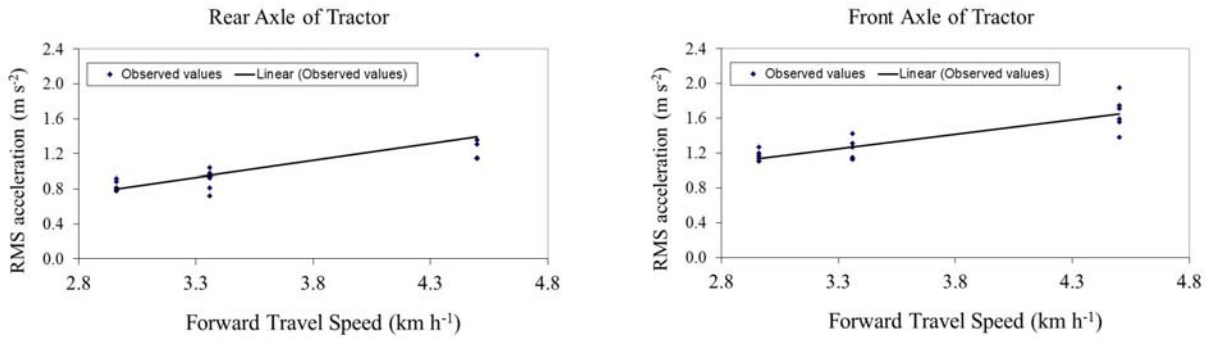


Figure 4. Fitted curves of RMS acceleration for the rear and front axles according to the forward travel speeds during plowing operation.

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

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

**Significance level used 5 % of probability.

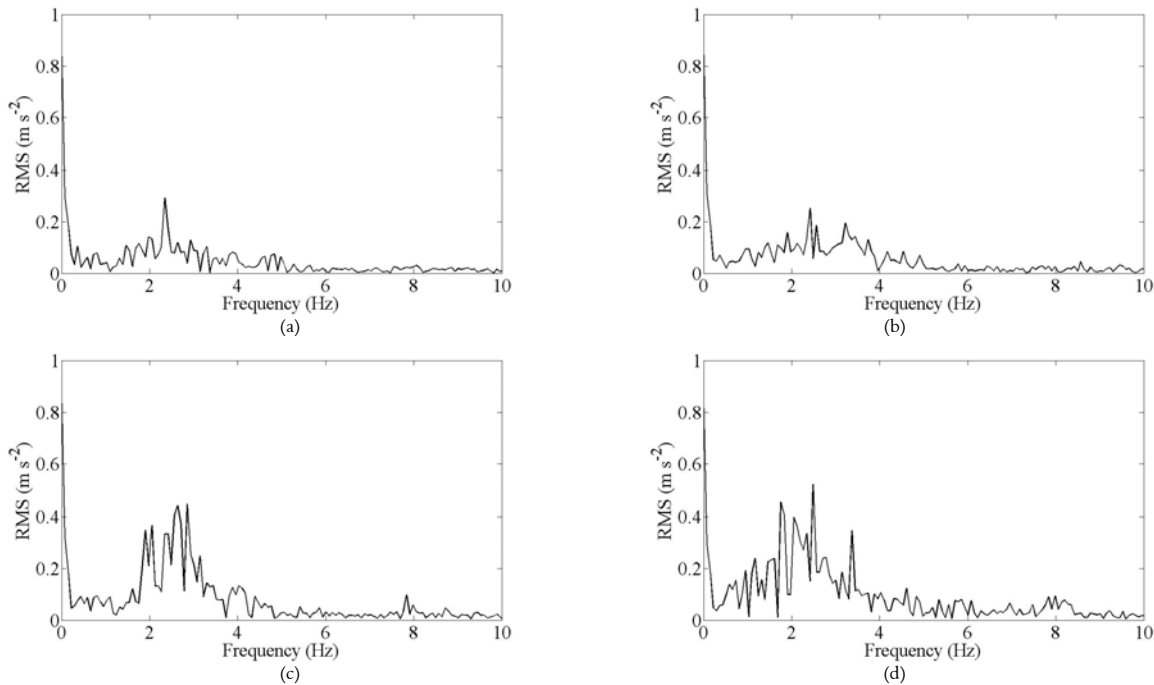


Figure 5. Frequency spectra for the rear axle during harrowing operation: (a) forward speed V_1 with FWA OFF, (b) forward speed V_1 with FWA ON, (c) forward speed V_3 with FWA OFF, and (d) forward speed V_3 with FWA ON.

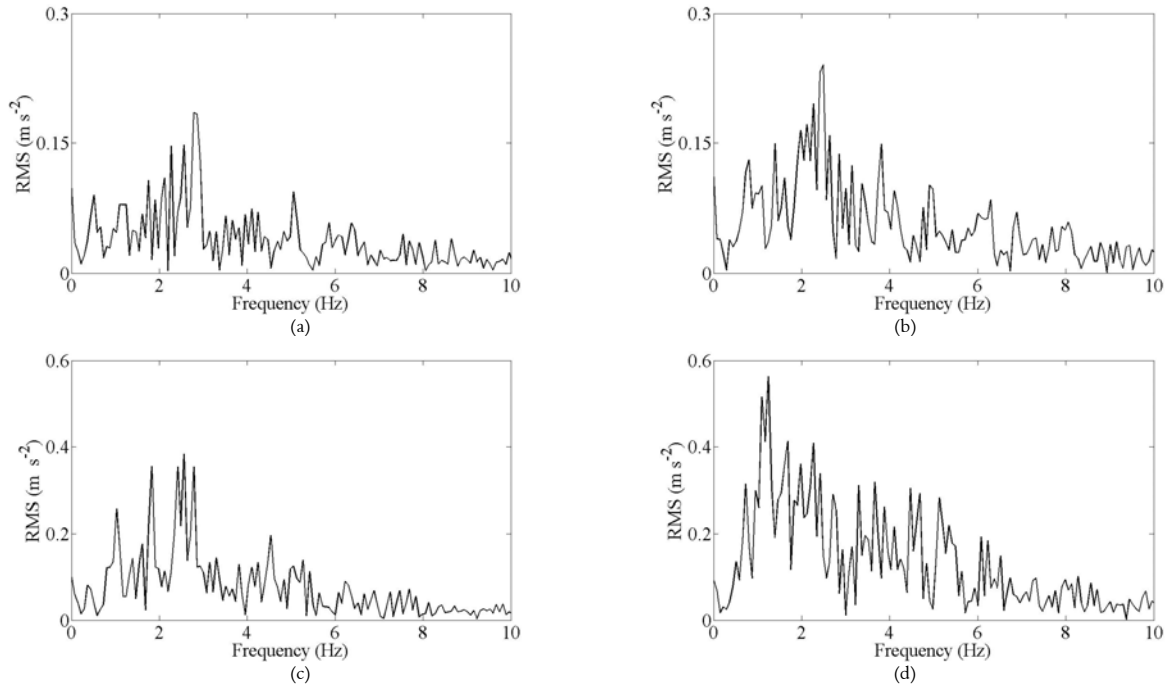


Figure 6. Frequency spectra for the front axle during harrowing operation: (a) forward speed V_1 with FWA OFF, (b) forward speed V_1 with FWA ON, (c) forward speed V_3 with FWA OFF, and (d) forward speed V_3 with FWA ON.

$$RMS_{hr} = 0.17722 + 0.23533 V \quad (3)$$

$$r^2 = 0.98$$

$$RMS_{hf} = 0.28019 + 0.24831 V \quad (4)$$

$$r^2 = 0.97$$

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

The RMS acceleration values observed during the plowing and harrowing operations depended 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 was reduced by enabling FWA in both operations; however the front axle suffered an increase in vibration levels during the harrowing operation.

The results for RMS acceleration shown in Table 4 indicated the importance of developing an adequate seat design, since a large portion of vibrations acting on the chassis of the tractor is transmitted to the operator through the seat. The vibration levels during plowing were higher than harrowing, and similar results were observed by Mehta et al. (2000).

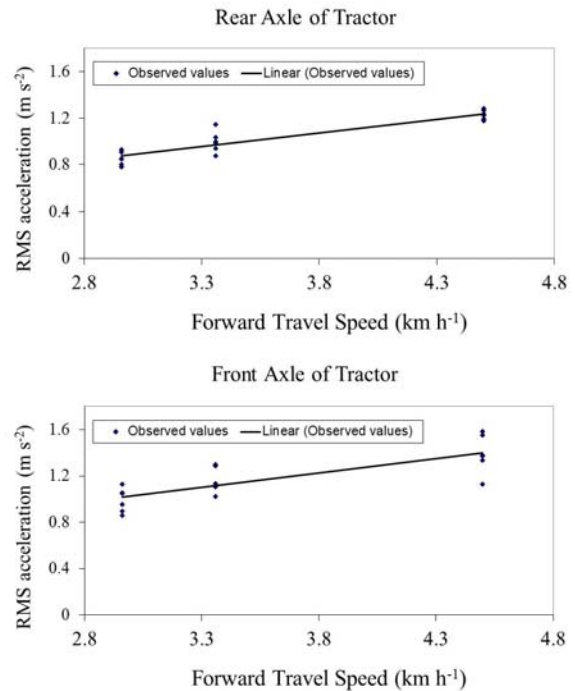


Figure 7. Fitted curves of RMS acceleration for the rear and front axles according to the forward travel speeds during harrowing operation.

According to ISO 2631-1 (ISO, 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.

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

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

Conclusion

Vibration levels observed for the plowing operation were higher than the levels observed for the harrowing operation. The highest vibration levels were observed at highest operating speeds for the evaluated operations. 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 soil tillage operations. The vibration levels acting on the tractor chassis during plowing and harrowing operations reinforced the need for a seat design directed to operator comfort.

Acknowledgements

The authors thank FAPEMIG – Fundação de Amparo à Pesquisa do Estado de Minas Gerais.

References

- ANFAVEA-Associação Nacional dos Fabricantes de Veículos Automotores. **Autoveículos**. Produção em 2010. São Paulo: Anfavea, 2011.
- CUNHA, J. P. A. R.; DUARTE, M. A. V.; RODRIGUES, J. C. Avaliação dos níveis de vibração e ruído emitidos por um trator agrícola em preparo de solo. **Pesquisa Agropecuária Tropical**, v. 39, n. 4, p. 348-355, 2009.
- FERNANDES, H. C.; SANTOS FILHO, P. F.; QUEIROZ, D. M.; CAMILO, A. J.; REIS, E. F. Vibração em tratores agrícolas: caracterização das faixas de

frequência no assento do operador. **Engenharia na Agricultura**, v. 11, n. 1, p. 23-31, 2003.

GOERING, C. E.; STONE, M. L.; SMITH, D. W.; TURNQUIST, P. K. **Off-road vehicle engineering principles**. St. Joseph: ASAE, 2006.

HARRIS, C. M.; PIERSOL, A. G. **Harris' shock and vibration handbook**. New York: McGraw-Hill, 2002.

ISO-International Organization for Standardization. **2631-1**. Mechanical vibration and shock: evaluation of human exposure to whole-body vibration. Part I: general requirements. Switzerland: International Standard, 1997.

MEHTA, C. R.; SHYAM, M.; SINGH, P.; VERMA, R. N. Ride vibration on tractor-implement system. **Applied Ergonomics**, v. 31, n. 1, p. 323-328, 2000.

NGUYEN, V. N.; INABA, S. Effects of tire inflation pressure and tractor velocity on dynamic wheel load and rear axle vibrations. **Journal of Terramechanics**, v. 48, n. 1, p. 3-16, 2011.

PRASAD, N.; TEWARI, V. K.; YADAV, R. Tractor ride vibration – a review. **Journal of Terramechanics**, v. 32, n. 4, p. 205-219, 1995.

SCARLETT, A. J.; PRICE, J. S.; STAYNER, R. M. Whole-body vibration: evaluation of emission and exposure levels arising from agricultural tractors. **Journal of Terramechanics**, v. 44, n. 1, p. 65-73, 2007.

SERVADIO, P.; MARSILI, A.; BELFIORE, N. P. Analysis of driving seat vibrations in high forward speed tractors. **Biosystems Engineering**, v. 97, n. 1, p. 171-180, 2007.

YANAI, K. L.; SILVEIRA, G. M.; LANÇAS, K. P.; CORRÊA, I. M.; MAZIERO, J. V. G. Desempenho operacional de trator com e sem o acionamento da tração dianteira auxiliar. **Pesquisa Agropecuária Brasileira**, v. 34, n. 8, p. 1427-1434, 1999.

ZEHSAN, M.; SADEGHI, M. H.; ETTEFAGH, M. M.; SHAMS, F. Tractors cabin's passive suspension parameters optimization via experimental and numeral methods. **Journal of Terramechanics**, v. 48, n. 6, p. 439-450, 2011.

Received on August 7, 2012.

Accepted on April 10, 2013.

License information: This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.