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Mechanical vibrations at the seat base of a tractor during the subsoiling operation

Vibrações mecânicas na base do assento de um trator agrícola durante a operação de subsolagem

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Abstract. Mechanical vibrations on tractors are influenced by different factors, such as the field operations, the operational speed of the tractor-implement set, the ballast conditions and the tires pressure of the tractor, among others. The aim of this work was to determine the vibration levels on vertical and longitudinal directions at the seat base of the tractor considering the influence of inflation pressure of the tires and operational speed of the tractor-subsoiler set. The acceleration at the seat base of the tractor was measured during the subsoiling operation considering three operational speeds and three inflation pressures of the tires. The field tests were carried out in a completely randomized design on factorial scheme 3 x 3, with three replications. Frequency spectrums were generated and compared with ISO 2631. The highest estimated values for the RMS acceleration were observed in the combination of the higher operational speed and the lower inflation pressure of the tires, 0.79 and 0.71 m s^{-2} for the vertical and longitudinal directions, respectively. The vibrations at the seat base during the subsoiling operation presented levels out of comfort range which reinforces the seek for designs that improve the comfort of the operator.

Keywords: whole body vibration, mechanization, instrumentation

Resumo. Vibrações mecânicas em um trator agrícola são influenciadas por diferentes fatores como o tipo de operação de campo realizada, a velocidade de trabalho do conjunto trator-implemento, as condições de lastros e a pressão nos pneus do trator, entre outros. No presente trabalho, objetivou-se determinar os níveis de vibração vertical e longitudinal no assento do tratorista verificando a influência da pressão de insuflação nos pneus e da velocidade de deslocamento do conjunto trator-subsolador sobre as acelerações atuantes. A aceleração atuando na base do assento do tratorista foi medida durante a operação de subsolagem em três velocidades de deslocamento do conjunto trator-implemento e três pressões de insuflação nos pneus. Os testes de campo foram conduzidos segundo delineamento inteiramente casualizado em esquema fatorial 3 x 3, com três repetições. As acelerações resultantes foram medidas nas direções vertical e longitudinal ao deslocamento do trator. Foram obtidos espectros de frequências que permitiram a identificação das frequências com maiores picos de aceleração incidente, os quais foram confrontados com a norma ISO 2631. Os maiores valores estimados para a aceleração RMS foi verificado na combinação entre a maior velocidade de deslocamento e a menor pressão de insuflação dos pneus, sendo de 0,79 e 0,71 m s^{-2}, para as direções vertical e longitudinal, respectivamente. As vibrações na base do assento do tratorista durante a operação de subsolagem apresentaram nívies fora da faixa de conforto, o que reforça a necessidade de projetos de assentos direcionados para a melhoria do conforto do operador.

Palavras-chave: vibração de corpo inteiro, mecanização, instrumentação

Introduction

Nowadays, the agriculture is characterized by high insertion of mechanized processes along of its production chain, which improve the efficiency and the quality of the tasks performed. The tractor appears, historically, as the main source of power in agricultural, being used in many operations. Along decades, the development of agricultural tractors was focused on mechanical improvement over the ergonomic and security aspects. The majority of the tractors sold in Brazil is unprovided of suspension in any of its axes, so the damping of vibrations is carried out only by the tires and the operator's seat.

The high efficiency and the operational speed of tractors have contributed to increase the vibration levels during the agricultural operations, this scenery has also created new problems associated with vibration, especially when the agriculture operation requires high power (Servadio et al., 2007). Among the agricultural operations, subsoiling is characterized by high power demand, which can result in instability during the execution of the operation by the tractor, due to the high travel reduction ratios or by the power hop phenomenon.

The effect of the generated mechanical vibrations during the execution of the agricultural operations can cause many injuries in workers, such as vision problems, lumbar deformations, irritability, digestive problems, among others (Santos Filho et al., 2003). According Loutridis et al. (2011) excessive vibrations in agricultural tractors are responsible for reducing the comfort and by causing injuries to the operator, besides to promote premature wear and failure of the machine components.

The seat is a component that transmits the loads to the body of the operators during the execution of the agriculture operations. In this context, a suitable design is crucial to modify the characteristics of the transmission of these loads and to reduce the discomfort of the operator during the work (Mehta et al., 2008). The vibrations transmitted to the operator seat and its relationship with the whole body vibration have been studied by many authors for different types of machines (Basri & Griffin, 2013; Cutini et al., 2012; Milosavljevic et al., 2012; Coggins et al., 2010).

According to Milosavljevic et al. (2011) the generated vibrations in vehicles used in agricultural activities depend on many characteristics, such as operator's experience, systems of damping, operational speed, soil properties and conditions of the field of work. The authors suggest a combination of engineering design and operational behavior to reduce the generation and the exposition to mechanical vibrations and shocks.

Mechanical vibrations in a agricultural tractors can be transmitted in different directions and depend directly of type of the operations performed. Scarlett et al. (2007) verified a dominance of horizontal vibrations in different field operations when the authors studied the whole body vibration levels on tractors. However, for transport operations, it was observed higher levels of vertical vibrations, which can be attributed to the inability of the seat suspension system of the tractor to attenuate vibrations.

The hypothesis of this study is that higher operational speeds of the tractor-subsoiler set increase the incident vibration levels in agricultural tractor and that unsuitable inflation pressure of the tires can also contribute to the generation of excessive mechanical vibrations. Thus, the aim of this work was to determine the levels of vertical and longitudinal (horizontal direction in relation to tractor displacement) vibrations at the seat base of an agricultural tractor and the influence of the inflation pressure of the tires and operational speed of the tractor-subsoiler set on the generated accelerations.

Material and Methods

The tests were conducted in an experimental field of 1200 m^2 with low slope. The main soil physical properties of the experimental field, such as water content of soil, bulk density and penetration resistance are presented in Table 1. The soil water content was obtained by drying at 105 ± 5 °C during 24 hours and presented on dry basis. The bulk density was obtained using the method of the volumetric ring. The penetration resistance of the soil was determined by cone index at 0.30 m depth, measured by a penetrometer, PNT-2000 model.

Table 1. Soil physical properties of the experimental field

Bulk density (kg m^{-3})	1060
Water content (%)	18.30
Cone index (MPa)	0.12

The vibration levels were determined at the seat base of the tractor during the subsoiling operation. For the tests, it was used an agricultural tractor John Deere with front-wheel-assist (FWA), model 5705. The tractor was configured with 300 kg in front ballast and 75 kg in each rear wheel ballast. The FWA was enabled during all tests. It was used a subsoiler manufactured by Baldan, composed by three rods, which worked in constant operational depth of 0.35 m and an operational width of 1.5 m. The main specifications of the agricultural tractor and its tires are summarized in Table 2.

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Table 2. Main specifications of the tractor and tires employed on the field tests

Characteristics of the agricultural tractor and tires	
Engine model	Jonh Deere/4045T 350 Series
Engine displacement (L)	4,5
Number of cylinders	4
Engine Power (kW)	63
Engine nominal rotation (rpm)	2400
Tractor mass without ballast (kg)	2700
Front tire (width – diameter, in)	7.5-18 F2
Rear tire (width – diameter, in)	18.4-30 R1

During the subsoiling operation, the accelerations at the seat base of the tractor were acquired in vertical direction and longitudinal direction in relation to tractor displacement. The vibrations were monitored by two uniaxial accelerometers manufactured by PCB, with operational range of 1-4000 Hz. The accelerometers were installed lagged 90° to each other at the seat base of the tractor (Figure 1), one of these accelerometers was used to monitoring the accelerations generated on the direction of tractor-subsoiler displacement (longitudinal vibration) and the other was employed to determine the vibrations on vertical direction (vertical vibration). The determination of the accelerations at seat base of the tractors allows the quantification of the vibration levels that can be transmitted to the operator through the seat.

The tests were performed considering three operational speeds which were combined to three inflation pressures of the tires. In Table 3 are presented the transmission gear ratios used, the operational speeds of the tractor-subsoiler set and the inflation pressure of the tires used on the subsoiling operation. For all tests, the engine speed was remained at 2150 rpm.

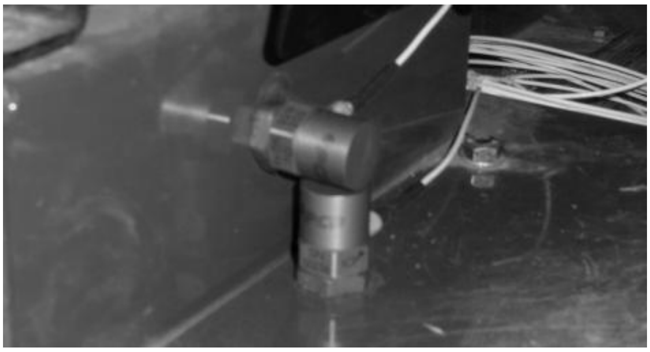

Figure 1. Uniaxial accelerometers at the seat base of the tractor.

Table 3. Transmission gear ratios, operational speed of tractor-subsoiler set and inflation pressures of the tires used during field tests

Transmission gear ratio	Operational Speed (km h^{-1})	Inflation Pressure (lbf pol^{-2})
Gear A2	$V_1 = 3.8$	P_1=12
Gear B1	$V_2 = 4.6$	P_2=15
Gear B2	$V_3 = 6.6$	P_3=18

During the subsoiling operation, besides the monitoring of the acceleration at the seat base of the tractor, the following variables were monitored: actual operation speed of the tractor-implement set, inflation pressure of the four tires and the travel reduction ratio of the front and rear wheels.

The vibration levels were measured by piezoelectric accelerometers, manufactured by PCB. The actual operational speed was determined by an ultrasonic radar, manufactured by John Dickey, model Radar II, which was installed at tractor chassis. The inflation pressure of the tires was monitored by an absolute pressure transducer manufactured by Sensata Technologies, 100CP-1 model, with operating range from 0 to 689.48 kPa (100 psi). The travel reduction ratio, during the subsoiling operation, was obtained by magnetic sensors, manufactured by Autonics ® brand, PRCM18 model, it was used a reference system installed in the front and rear wheels of the tractor.

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All sensors 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 50 Hz.

Frequency spectrum analyses were performed considering the combination between the highest and lowest operational speed of the tractor-subsoiler set and the highest and lowest inflation pressure of the tires of the tractor. The Fast Fourier Transform (FFT) was applied to the acceleration data in the time domain to obtain the frequency spectrum that allowed to determine the frequency bands with larger generated amplitudes of vibration.

The tests were carried out in a completely randomized design in a 3x3 factorial scheme; i.e. three operational speeds of the tractor-subsoiler set and three inflation pressures of the tires (Table 3). Three replications were done, totaling 27 treatments. Each experimental unit was composed by 30 m work line. The vibrational parameters were determined for the mean portion of the sampled period for each parcel. Thus, the data were trimmed at the beginning and end of acquisition in order to remove the regime of acceleration and deceleration of the tractor-subsoiler set.

The data composed by Root Mean Square (RMS) accelerations, in vertical and longitudinal directions, were submitted to analysis of variance in order to verify the significance of the operational speed and the inflation pressure of the tires over the accelerations at the seat base of the tractor. The influence of factors over the vibration levels at the seat base of the tractor were analyzed by linear regression using t-test.

Results and Discussion

Vibration levels at the seat base of the tractor were determined in the vertical direction and longitudinal direction of the displacement of the tractor along the subsoiling operations. The tractor-subsoiler operational speed and the inflation pressure of the tires were varied during the field tests. The vibrations transmitted by the tractor chassis to the seat base were represented by the Root Mean Square accelerations (RMS), which allowed the analisys of the influence of the operational speed and inflation pressure over the vibration levels generated (Basri & Griffin, 2013; Milosavljevic et al., 2012).

The analysis of variance performed for the RMS acceleration for the both directions, vertical and longitudinal, showed significant effect of the iteration between the tractor-subsoiler operational speed and the inflation pressure of the tires over the vibration levels generated at the seat base of the tractor. Thus, a linear model was fitted in order to explain the effect of interaction of these factors over the RMS acceleration generated.

In Table 4 are presented the results of analysis of variance of the fitted model for RMS acceleration, in the vertical direction, observed at the seat base of the tractor. The t-test results for estimated parameters of the model are presented in Table 5 shows. It can be verified that the significance of the regression and the no significance of the lack of fit of the model indicate that the fitted model is suitable to describe the behavior of RMS acceleration in the vertical direction at the seat base of the tractor. The coefficient of determination (R^2) of the model was 68.33%.

Table 4. Analysis of variance of the fitted model for RMS acceleration in vertical direction (VD) at the seat base of the tractor

Sources of Variation	Degree of Freedom	Sum of squares	Mean Square	F
Regression	3	0.33172	0.11057	5.89^{**}
Lack of fit	5	0.15370	0.03074	1.99^{ns}
(Treatment)	8	0.48542	0.06068	
Residue	18	0.27798	0.01544	
Total	26	0.76340		

** Significative on level of p<0.01; ns – no significative; VC (%) = 26.02%; β_i – estimated parameters; V – operational speed; P – inflation pressure.

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Table 5. Results of t-test to estimated parameters of the fitted model used to represent the RMS acceleration in vertical direction at the seat base of the tractor

Variable	Degree of Freedom	Estimated parameters	Standard error	t-values
Intercept	1	-1.48344	-	-
V	1	0.44080	0.12630	3.49**
P	1	0.11189	0.04271	2.62**
V x P	1	-0.02497	0.00832	3.00**

** Significative on level of $p<0.01$; ns – no significative; V – Operational Speed; P – Inflation pressure.

Equation (1) represents the selected model according to the regression analyses for acceleration in vertical direction at the seat base of the tractor (Table 5). In Figure 2 is presented the response surface of the RMS acceleration. It was observed that the highest estimated value for RMS acceleration, 0.79 m s^{-2}, is related with the combination between the higher operacional speed and the lower inflation pressure of tires. This value, according to ISO 2631-1 (1997) standard, is the near to the range considered uncomfortable to the operator, if all generated vibration was transmitted to his body. The inflation pressures of 18 psi (124.11 kPa) when associated with lower operational speed come out in a generated vibration level around 0.52 m s^{-2}, this level is in range considered slightly uncomfortable, if all vibration was transmitted directly to the operator.

$$A_{cv} = -1.48 + 0.44 \cdot V + 1.11 \cdot 10^{-1} \cdot P - 2.50 \cdot 10^{-2} \cdot V \cdot P \quad (1)$$

where,
A_{cv} = RMS acceleration in vertical direction, m s^{-2};
V = operational speed, km h^{-1};
P = inflation pressure of the tires, psi.

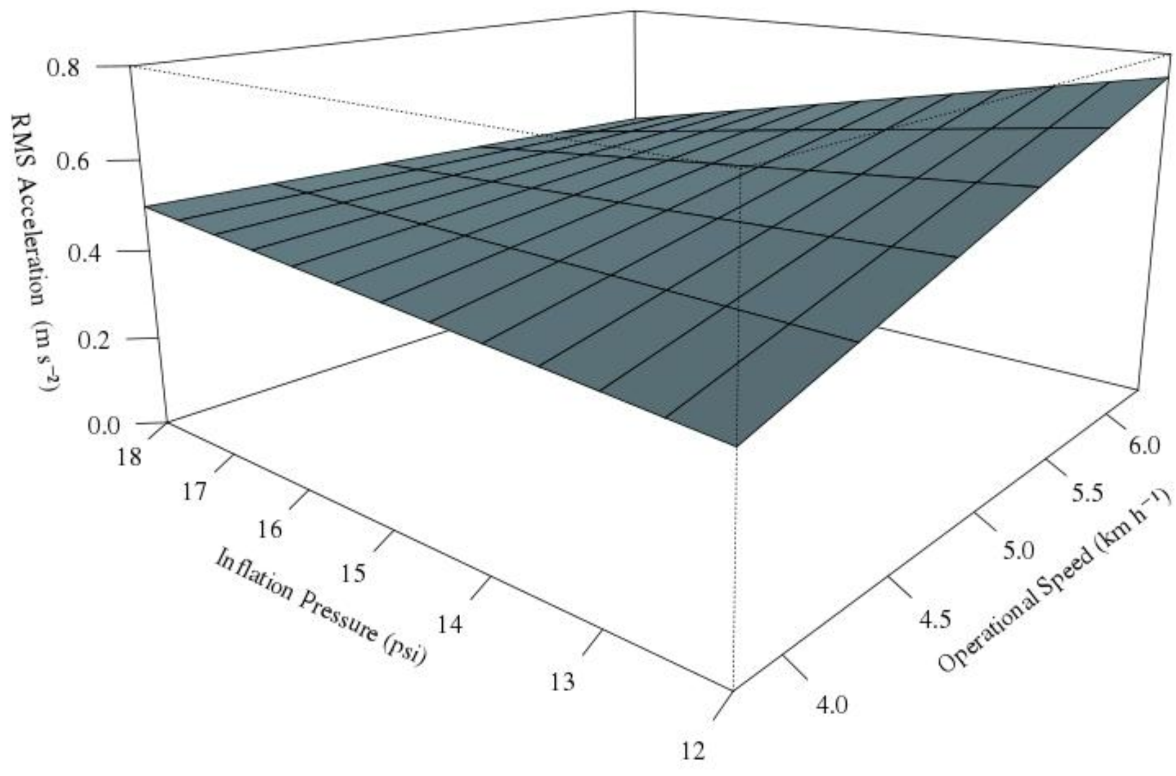

Figure 2. Response surface fitted to RMS acceleration in vertical direction at the seat base of the tractor.

For vertical vibration was observed that the increase of the inflation pressure allows a greater transmission of vibrations along chassis to the seat base of the tractor. The increase of the operational

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speed influences directly on vibration levels generated during the execution of the subsoiling operation (Figure 2).

Analysis of variance of the fitted model to the RMS acceleration, in longitudinal direction, at the seat base of the tractor is presented in Table 6. The results were similar to the RMS acceleration in vertical direction and the fitted model can be considered suitable due the significance of the regression and the no significance of the lack of fit of the model. In Table 7 are presented the t-test results to fitted model. The coefficient of determination for the model was 67.75%.

Table 6. Analysis of variance of the fitted model for RMS acceleration in longitudinal direction (LD) at the seat base of the tractor

Sources of variation	Degree of Freedom	Sum of Square	Mean Square	F
Regression	3	0.31055	0.10352	8.27^{**}
Lack of fit	5	0.14784	0.02957	3.82^{ns}
(Treatment)	8	0.45839	0.05730	
Residue	18	0.13922	0.00773	
Total	26	0.59761		

** Significative on level of p<0.01; ns – no significative; VC (%) = 24.55%; β_i – estimated parameters; V – operational speed; P – inflation pressure.

Table 7. Results of t-test to estimated parameters of the fitted model used to represent the RMS acceleration in longitudinal direction at the seat base of the tractor

Variable	Degrees of freedom	Estimated parameters	Standard error	t-values
Intercept	1	-0.77039	-	-
V	1	0.33387	0.08700	3.82^{**}
P	1	0.06566	0.02958	2.22^{**}
V x *P*	1	0.01905	0.00574	3.32^{**}

** Significative on level of p<0.01; ns – no significative; V – operational speed; P – inflation pressure.

Equation (2) represents the selected model according to the regression analyses for acceleration in longitudinal direction at the seat base of the tractor (Table 7). Figure 3 represents the response surface for the RMS acceleration, in longitudinal direction, at the seat base of the tractor. A similar behavior to the RMS acceleration in vertical direction was observed. This way, the highest RMS acceleration level, in longitudinal direction, was verified for the combination of the higher operational speed and the lower inflation pressure of the tractor tires. In this case, the estimated RMS acceleration was 0.71 m s^{-2}, which was lower than the acceleration estimated for the vertical direction. According ISO 2631-1 (1997) standard, this acceleration level is in the range considered slightly uncomfortable to the operator, if all generated vibration was transmitted to body of the operator.

$$A_{cl} = -0.77 + 0.33 \cdot V + 6.57 \cdot 10^{-2} \cdot P + 1.91 \cdot 10^{-2} \cdot V \cdot P$$

where,
A_{cl} = RMS acceleration in longitudinal direction, m s^{-2};
V = operational speed, km h^{-1};
P = inflation pressure of the tires, psi.

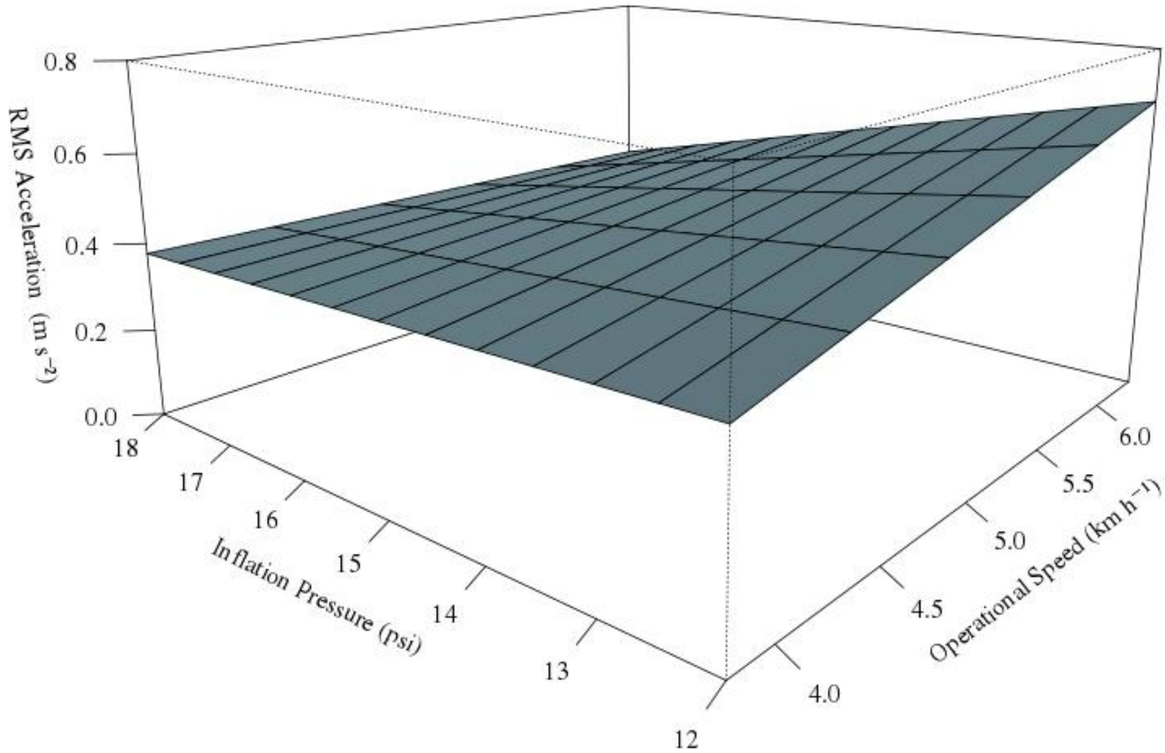

Figure 3. Response surface fitted to RMS acceleration in longitudinal direction at the seat base of the tractor.

In Figure 4 are presented the travel reduction ratio means, for front and rear wheels. For longitudinal vibrations, it was observed that the for the increase of the inflation pressure of the tires, there is a decrease of the travel reduction ratio and, consequently, a reduction on vibration levels generated, this effect becomes more pronounced at highest operational speed, as shown in Figure 3. Vibration levels in longitudinal direction are more influenced by the travel reduction ratio during the subsoiling operation, this effect can be explained due the variation of the speed component along the displacement of the tractor-subsoiler set which significantly influences the incident vibrations at the seat base of the tractor.

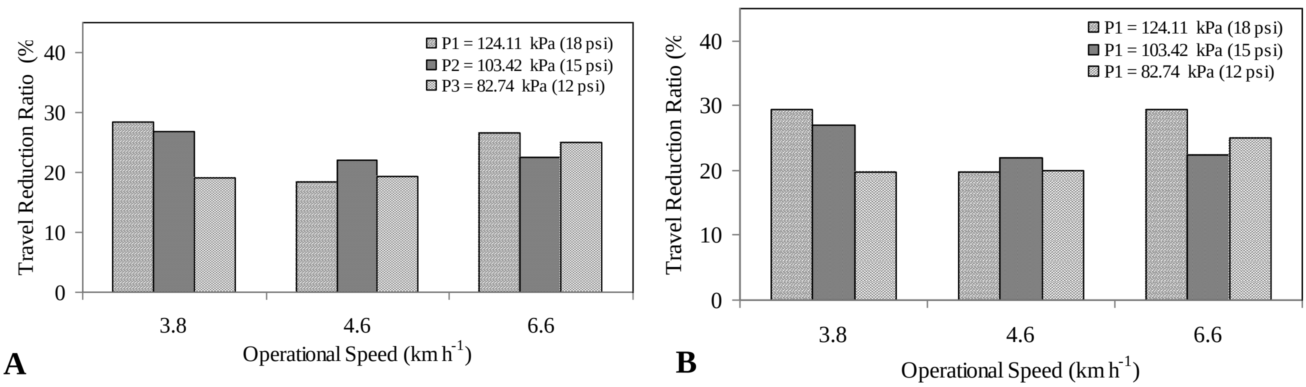

Figure 4. Travel reduction ratio, for the treatments, to front wheels (A) and rear wheels (B) of tractor.

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From frequency spectrums, it was possible to verify that the frequency ranges presented the larger amplitudes during the tests. Independent of the operational speed, the inflation pressure of 18 psi (124.11 kPa) generated the highest peaks in the range of 0 to 2 Hz, during the displacement of the tractor-subsoiler set. In Figure 5 are presented some results in order to clarify this behavior.

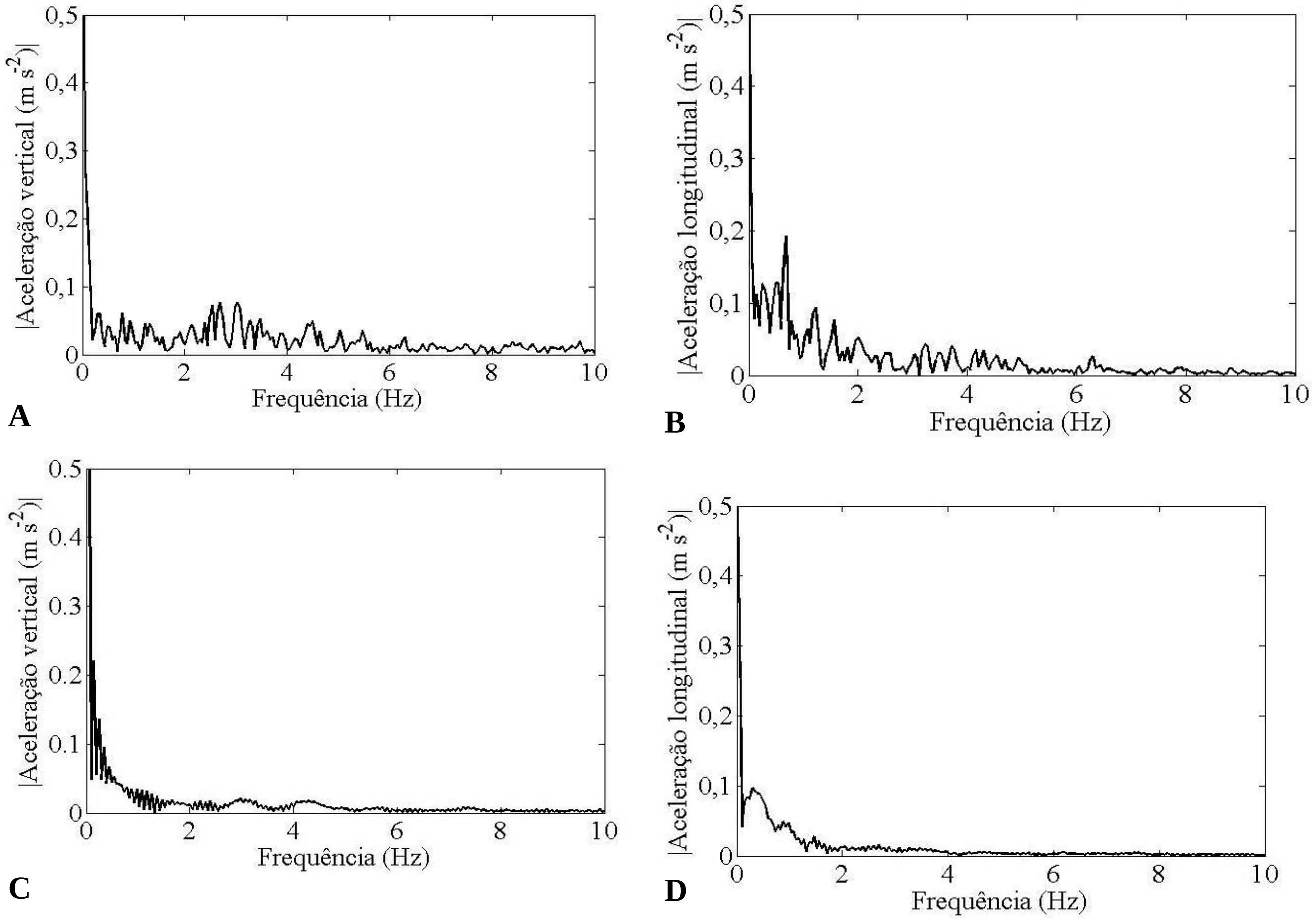

Figure 5. Vibration response at the seat base of the tractor to operational speed of 3.8 km h^{-1} and inflation pressure of 18 psi (124.11 kPa) (A) vertical direction and (B) longitudinal direction; operational speed of 6.6 km h^{-1} and inflation pressure of 18 psi (124.11 kPa) (C) vertical direction and (D) longitudinal direction.

From analysis of the frequency spectrums, for the inflation pressure of 12 psi (82.74 kPa) and operational speed of 6.6 km h^{-1} (Figure 6), it was observed acceleration peaks in vertical direction of 1 m s^{-2} near to the frequency of 2 Hz. For the longitudinal direction, the peaks of acceleration were also verified in a frequency of 2 Hz, however with amplitudes of 0.4 m s^{-2}. Legs bent at 90° has a dynamic response in the frequency of 2 Hz (Brüel & Kjaer, 2002), which can be considered part of the human body that would be subjected to greater injuries for the combination of the operational speed of km h^{-1} and a inflation pressure of 12 psi (82.74 kPa).

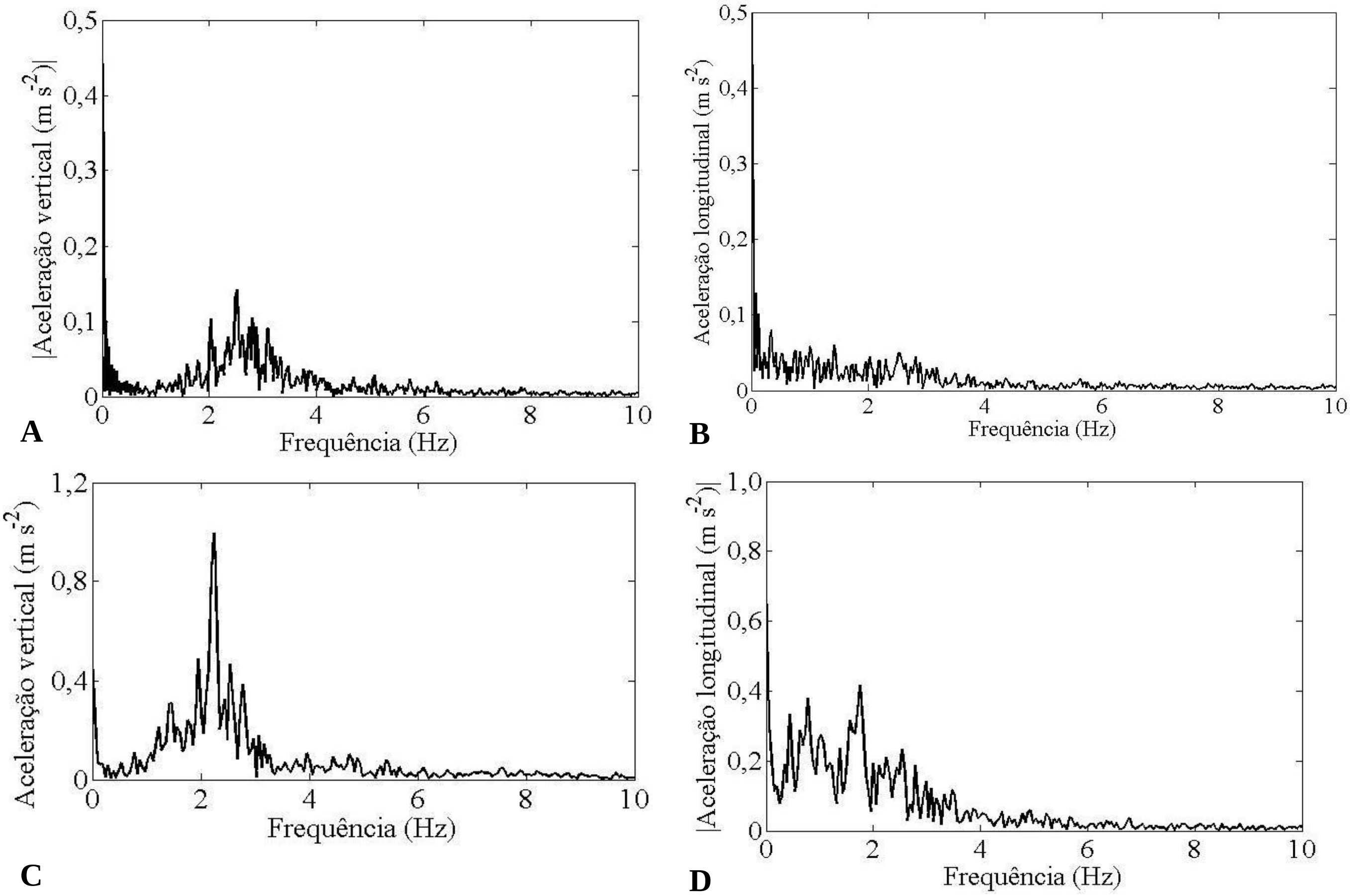

Figure 6. Vibration response at the seat base of the tractor to operational speed of 3.8 km h^{-1-1} and inflation pressure of 12 psi (82.74 kPa) (A) vertical direction and (B) longitudinal direction; operational speed of 6.6 km h^{-1} and inflation pressure of 12 psi (82.74 kPa) (C) vertical direction and (D) longitudinal direction.

Conclusion

Vibration levels observed at the seat base of the tractor in the vertical direction in relation to tractor displacement were higher than the longitudinal direction. Lower inflation pressures of the tires associated with higher operational speeds provided higher values of the RMS acceleration in both directions studied. The highest vibration levels were observed in the frequency range from 0 to 2 Hz for all inflation pressures employed. Vibration levels at the seat base of the tractor during the subsoiling operation were out of the comfort range, which reinforces of the seek for designs that improve the comfort of operator.

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