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Agricultural tractor vibrations according to terrain type and travel speed

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Abstract: In agricultural tractors, mechanical vibrations derive from the engine and the interaction of the wheel with the environment in which they move around. The occurrence of vibrations on such machines may cause structural failures, discomfort, and physical and physiological problems to users. The objective of this study was to apply a procedure to evaluate the vibrations at different points of an agricultural tractor, over different types of terrain and travel speeds. In this procedure, we quantified the values of intensity and frequency of the vibrations on the main components of the tractor, such as the engine, transmission, rear axle, operation point, seat, and steering wheel. For this purpose, we fixed accelerometers in various positions of the machine connected to a six-channel acquisition board. In the tractor, we considered specific factors for the study of vibrations such as mass, internal tire pressure, and travel speed. We processed the obtained data using codes developed in this work, analyzing the RMS, peak, and frequency values. We concluded that the vibrations with the highest energy occur in the paved terrain and derive from the engine. In mobilized agricultural soil, the vibrations of low frequency and with the highest energy depended on the travel speed.

Keywords: Ergonomics, vibration level, human factors

1. INTRODUCTION

Due to the versatility of the tractor in the performance of countless tasks in the rural environment, it becomes necessary to study the vibration levels on the machine. High levels may accelerate physical and mental fatigue of the operator and cause occupational illnesses due to the long periods of exposure. The spine is the part most affected by the occupational vibrations in agricultural machinery [1].

Besides the damages to user health, vibrations may cause structural failures in the equipment such as the loosening of screwed joints, cracks in tension-concentrating places, or the premature wear of bearings. In the study conducted by [2], the structural failures in a catamaran ship were due to the fatigue process, stemming from the vibrations of the propeller system.

Vibrations on a machine are due, mostly, to the interaction between inertial and elastic forces associated with the mass and inertia, as well as the rigidity of the mechanical system [3]. In the case of automotive vehicles, the sources of vibration are usually the engine speed and the variations in the pavement upon dislocation. In both cases, one may consider that there exists some harmonic force exciting the mechanical system and, therefore, generating dislocations and accelerations that vary in time throughout the structure.

One way of quantifying the mechanical vibrations is through the installation of accelerometers connected to an acquisition system which collects the signal data over time. The acceleration signal is composed of peaks and valleys, yet the intensity value is a quadratic mean of the values of such signal, resulting in the effective intensity value. According to [4], this value is called the Root Mean Square (RMS).

Obtaining a vibration signal over time also enables the post-processing of such signal through numerical methods. The Fast Fourier Transform (FFT) method allows obtaining the spectrum that represents the most energetic frequencies present in the signal. This method may be used to identify mechanical structural faults when exposed to the vibrations [5].

Due to the importance of the study of vibrations in agricultural machines and to the lack of knowledge of the critical points of their propagation, the objective of this study was to apply a procedure to evaluate vibrations at different points of an agricultural tractor, over different types of terrain and travel speeds. Specifically, we seek to identify the points with the most significant vibration amplitudes, as well as their sources, through the comparison with the frequencies associated with the engine and the type of terrain.

2. MATERIAL AND METHODS

2.1. Equipment used

For measuring the vibrations, we used six accelerometers, four of which were piezoelectric and two, capacitive. We positioned the accelerometers so to measure the vertical vibrations of the structure, fixed to the main components of the tractor: engine, transmission, rear axle, platform, seat, and steering wheel.

All the accelerometers used are by Brüel & Kjaer and were fixed using magnetic supports, except for the one on the steering wheel, in which case we used a specific adaptor. On the engine and the transmission, we placed sensors of model 4513B. On the rear axle and the platform, we used model 4370V. Over the seat, we used model 4524B, and model 4524B 001 on the steering wheel. The sensor signal acquisition was carried out by an acquisition board also by Brüel & Kjaer model 3050-B-060, with six input channels. The information collected was sent to the software through a LAN cable on the computer.

Fig. 1 presents the schematic representation of the agricultural tractor used and the disposition of the sensors on the machine, besides the means of communication through cables among the accelerometers and the acquisition board, and between it and the computer. During the test, we placed the computer and the acquisition board inside the tractor's cabin.

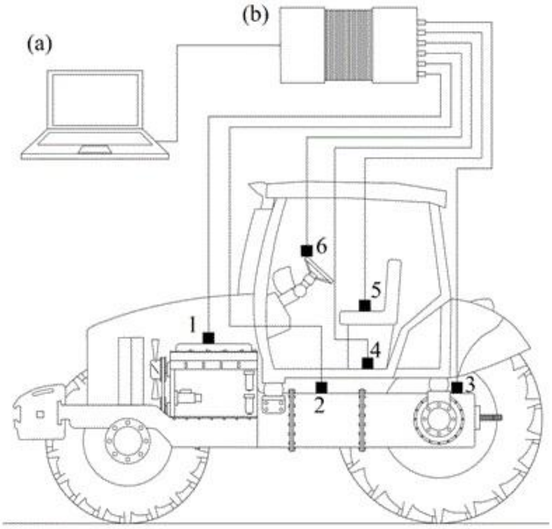

Fig. 1. Schematic representation of the accelerometer distribution on the agricultural tractor structure: (1) engine, (2) transmission, (3) rear axle, (4) platform, (5) seat, and (6) steering wheel, as well as the data collection system: (a) computer and (b) acquisition board.

We configured the equipment for an acquisition rate of 3.2 kHz and the analysis of frequencies of at most 400 Hz, with a data collection period of 16 seconds. Data collection started after the stabilization of the travel speed within the trajectory.

For the evaluation, we employed two factors, namely the travel speed and type of terrain. For the first, three operation speeds were chosen among those typically used in agricultural tractors: 4 $km.h^{-1}$ (V1), 8 $km.h^{-1}$ (V2), and 12 $km.h^{-1}$ (V3). The second factor encompassed three terrain surfaces: paved terrain (T1), firm agricultural soil (T2), and mobilized agricultural soil (T3), unstructured by a primary soil-preparation operation, with disk plows at an average depth of twenty centimeters. Therefore, the combination of the factors resulted in nine treatments, with three repetitions, totalizing 27 experimental units.

For the characterization of the type of terrain, we conducted assessments in the sense of characterizing the resistance to penetration, the vegetation, and the superficial roughness present in the firm and mobilized agricultural soil areas. The travel speeds were chosen based on the grading of gears of the tractor.

After the collection of the acceleration signals, a text file was generated with the signal values over time. Such signals were processed through the MATLAB computational program of numerical methods, resulting in the RMS values of the signal, besides the peak values and the most energetic frequencies through FFT.

2.2. Configuration of the agricultural tractor

For the evaluate we used agricultural tractor MF 6713R (Massey Ferguson, Canoas, Brazil), year 2014, with 97 kW (132 hp) of maximum power at 2,200 rpm of the engine. The transmission has sixteen ahead gears and sixteen reverse gears, resulting from the combination of four groups (speed 1 through 4) with four gears each (gears A through D), besides an ahead and reverse reversion system. The tractor was assembled with radial Trelleborg tires, model TM 800, with dimension 600/65 R 38 at the rear and 480/65 R 28 at the front axle. The seat was pneumatic by brand Grammer. We used the rotation regime of 1,920 rpm for all treatments.

Since the mass of a vehicle has a direct relation with the behavior of the vibrations, the mass/power ratio was adjusted to 60 kg.kW^{-1} which, according to [6], better suits this tractor size. The static distribution of mass was of 40% over the front axle and 60% over the rear, configuring a total mass of 5,825 kg, with 3,495 kg over the rear axle and 2,330 kg over the front axle. We obtained this distribution by the combination of three 55 kg metallic masses aggregated to the front support and two 72 kg disks in each rear wheel, with the addition of a hydraulic ballast at 25% of the internal volume of the rear tires. The internal pressure used on the tires was of 160 kPa (1.6 bar), recommended by the manufacturer.

The steering wheel and the seat of the tractor, which present systems for regulating height, depth, and rigidity, were regulated at intermediary positions to the total dislocation course.

3. RESULTS AND DISCUSSION

3.1. Paved terrain

After the collection and processing of the data obtained, we verified that, in the condition of traffic over paved terrain, the RMS and peak values presented a significant gradual reduction compared to the trajectory of the engine vibrations up to the seat and steering wheel. We also found that such values grow with the increase of the travel speed. Table 1 presents these values.

Table 1. RMS and peak values of the vibration signals for traffic over paved terrain.

Accelerometer positions	RMS (m.s^{-2})			Peak (m.s^{-2})		
	V1	V2	V3	V1	V2	V3
Engine	3.21	3.45	3.73	13.36	15.00	16.35
Transmission	1.52	1.54	1.63	5.29	5.18	5.53
Real Axle	1.11	1.11	1.15	3.81	3.97	4.01
Platform	1.83	1.66	1.48	6.22	5.50	5.09
Seat	0.07	0.15	0.24	0.22	0.48	0.66
Steering Wheel	0.32	0.39	0.47	1.18	1.58	2.21

In another study evaluating vibrations, [7] also found that the reduction in travel speed is a way of attenuating the intensity of vibrations. Only the platform did not maintain this reduction, given that, at this point, there was an increase of RMS and peak compared to the rear axle. Fig. 2 presents the behavior of the vibration signs over time on all points collected.

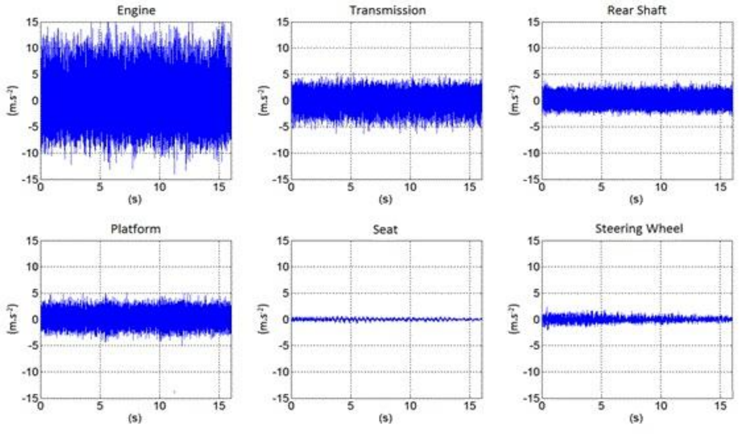

Fig. 2. Signals of acceleration over time of the points analyzed for a travel speed of 12 km.h^{-1}, over paved terrain.

When the frequencies present in the signal are analyzed, it is expected that they are related to the engine speed. For the chosen regime speed of 1,920 rpm, the corresponding frequency is of 32 Hz. However, this is a four-stroke engine with four cylinders, in which two combustion cycles occur per revolution of the crankshaft.

This results in a combustion-related frequency twice higher than that of engine speed, i.e., 64 Hz, becoming the main frequency of the system. Upon analyzing the more energetic frequencies using FFT, we observe the confirmation of this hypothesis. This frequency and its harmonics have more prominence in the engine and transmission, being less present in the other components.

To [8], the vibrations generated by an internal combustion engine depend on factors such as the number of cylinders, ignition order, balancing technology, fixation to the structure, speed, applied load, injection time, and ignition time.

At the rear axle of the tractor, the third harmonic of the primary frequency stood out, around 192 Hz. At the platform, we found an even higher frequency, close to 335 Hz. This frequency is not linked to the value of the harmonics, which may have occurred due to the fixation position of the accelerometer at this location.

Because the accelerometer was fixed to an intermediary point of the platform and it, in turn, is supported to the structure only at the extremities, it behaves as a simply supported beam. In this condition, the central part presents the highest dislocation amplitude through flexion. This context may have generated a frequency unlike the harmonics stemming from the engine.

In turn, on the seat and steering wheel, the engine frequency presented low intensity. At these points, frequencies around 10 and 15 Hz predominated. Such values are close to those found by [7].

Despite the prominence of these low frequencies on the steering wheel, it still presented a significant intensity of the frequency predominating on the platform (335 Hz), which did not occur on the seat. This finding and the fact that the highest RMS and peak values are on the steering wheel make evident its more significant transmissibility of vibrations to the operator compared to the seat.

The behavior of the frequencies on the evaluated components of the agricultural tractor did not change with the increase in travel speed when moving in paved terrain. Hence, one may verify that the essay about this type of surface allows the evaluation of vibrations stemming only from the engine, in regards to the frequency.

Fig. 3 presents the FFT of all components studied in this work for the condition of traffic over paved terrain, for the travel speed of 12 km.h^{-1}. The remaining travel speeds, which also simulate transport speeds, presented the same particularities.

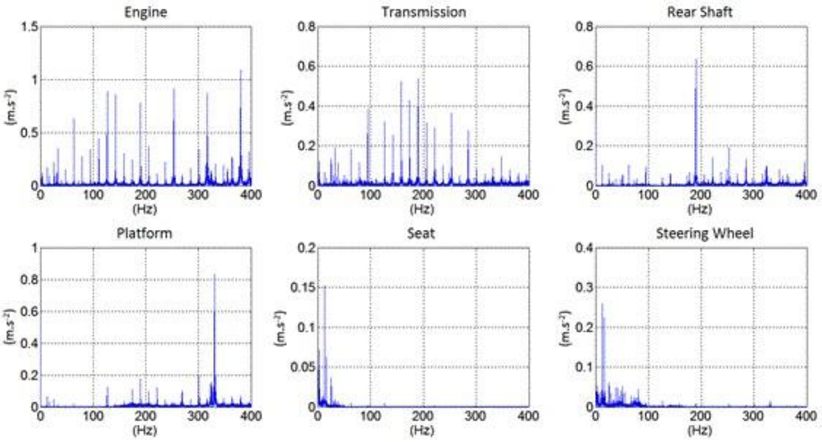

Fig. 3. FFT of the components of the agricultural tractor structure analyzed at the travel speed of 12 km.h^{-1}, over paved terrain.

3.2. Firm agricultural soil

In the procedure carried out over firm agricultural soil, we verified that the RMS and peak values behave similarly to those found in traffic over paved terrain. However, some points presented more significant values compared to the first surface analyzed.

The components that form the monoblock, such as the engine, transmission, and rear axle, besides the platform, presented RMS values quite close to those found in the previous treatment for the three travel speeds studied (Table 2). However, the points of contact with the operator, i.e., the seat and steering wheel, presented higher RMS and peak values compared to those obtained when moving over paved terrain.

Table 2. RMS and peak values of the vibration signals for traffic over firm agricultural soil.

Accelerometer positions	RMS ($m.s^{-2}$)			Peak ($m.s^{-2}$)		
	V1	V2	V3	V1	V2	V3
Engine	3.22	3.41	3.56	13.98	14.56	15.99
Transmission	1.55	1.77	2.09	5.12	6.22	7.37
Real Axle	1.33	1.37	2.09	4.05	4.18	5.12
Platform	1.58	1.36	1.26	6.11	5.87	6.14
Seat	1.90	0.45	0.64	0.62	1.47	2.01
Steering Wheel	4.25	6.28	9.44	54.99	102.95	102.17

The frequency values present in the signals for the firm agricultural soil condition have the same characteristics of the values found for traffic over the paved terrain, such as the presence of the main frequency of the engine and its harmonics, except for the platform, whose frequency was around 335 Hz.

The seat and steering wheel also presented frequency values lower than the other components, close to 2.5 Hz. This value is similar to that obtained by [9] when they evaluated whole-body vibrations in an agricultural tractor. The study by [10] also corroborates with this result. Upon seeking to characterize the frequencies that predominated on the tractor's seat, they found values between 2 and 4 Hz.

On the steering wheel, we found frequencies of 10 Hz, and, albeit with low intensity, the value of the prominent frequencies on the platform was of 335 Hz. Fig. 4 presents the signals for acceleration over time found at the travel speed of 12 $km.h^{-1}$.

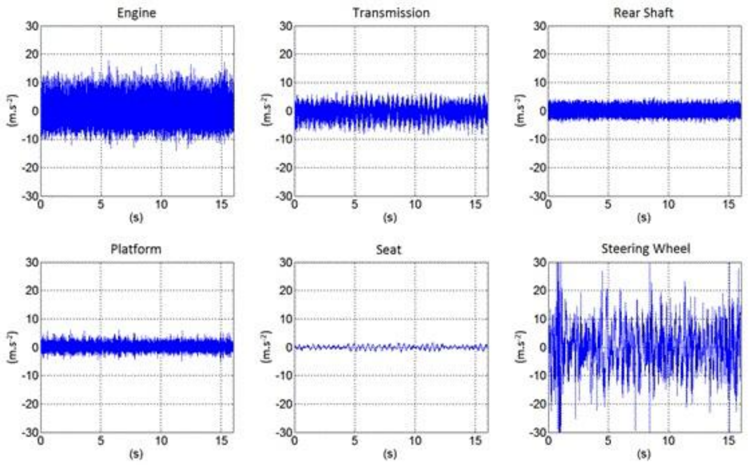

Fig. 4. Signals of acceleration over time of the points analyzed for a travel speed of 12 $km.h^{-1}$, with traffic over firm agricultural soil.

[11] determined that vibrations at the range of 0 to 19 Hz have their transmissibility amplified on the cushion that supports the platform when metallic and hydraulic ballast are used, with traffic over firm agricultural soil.

3.3. Mobilized agricultural soil

During the performance of the essay at the condition of agricultural soil mobilized with a disk plow, we verified that the third travel speed (i.e., 12 $km.h^{-1}$) is unfeasible for this type of study, given that the profile of this terrain presented an extensive amplitude of height variation of around 30 cm between maximal and minimal peaks. Hence, for this terrain condition, it was only possible to analyze travel speeds V1 and V2.

The behavior of the RMS and peaks remain with the same characteristics of the other terrains, with the gradual reduction of the values along the tractor's monoblock and the increase on the platform. However, in this case, the intensity of vibrations on the steering wheel was higher than on the other components (Table 3).

Table 3. RMS and peak values of the vibration signals for traffic over mobilized agricultural soil.

Accelerometer positions	RMS (m.s^{-2})			Peak (m.s^{-2})		
	V1	V2	V3	V1	V2	V3
Engine	3.38	4.70	-	14.72	22.46	-
Transmission	1.70	3.17	-	5.67	13.87	-
Real Axle	1.22	1.26	-	3.99	6.55	-
Platform	1.29	1.73	-	6.09	10.77	-
Seat	0.46	1.40	-	1.74	4.88	-
Steering Wheel	8.26	27.38	-	126.04	207.75	-

This fact may be explained by how the steering wheel is built, given that it presents regulations for angle and depth, and was adjusted at intermediary positions, so its steering arc is quite distant from the structure that supports it. This characterizes it as a cantilever beam in only one of the ends, thus amplifying the oscillations at the non-engaged end.

Fig. 5 presents the signals over time under this surface condition for the travel speed of 8 km.h^{-1}. Only the steering wheel signal was not shown at the same scale as the others due to its significant amplitude.

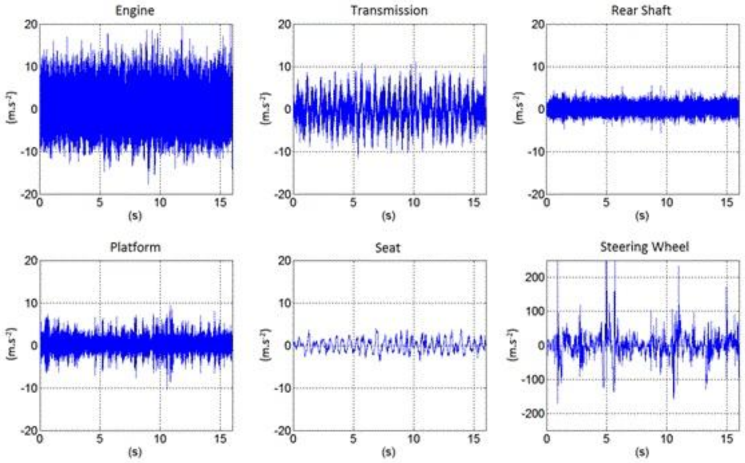

Fig. 5. Signals of acceleration over time of the points analyzed for a travel speed of 8 km.h^{-1}, with traffic over mobilized agricultural soil.

The behavior of the frequencies had distinct characteristics when compared to the same tractor components at the travel speeds of 4 km.h^{-1} (V1) and 8 km.h^{-1} (V2). For V1, at the engine and transmission, the main engine frequency and its harmonics stood out, as in the previous cases; yet, now frequencies around 2 Hz presents intensities at the same order of magnitude.

However, for V2, with the increase in travel speed, this frequency of around 2 Hz presents energy considerably higher than all the others, both on the engine and the transmission. In their study, [12] state that the travel speeds strongly influences the transmissibility of vibrations.

Fig. 6 makes evident the FFT comparison of these two components (engine and transmission) at the two travel speeds (4 and 8 km.h^{-1}).

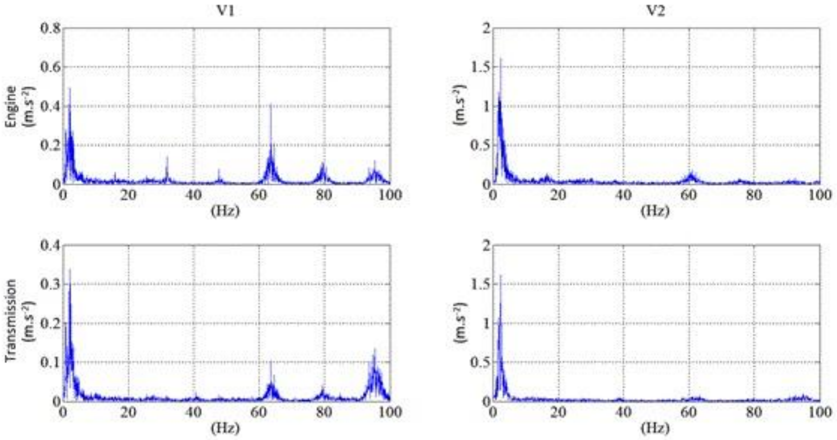

Fig. 6. Comparative analysis of FFT between V1 and V2 for the engine and transmission, under the condition of mobilized agricultural soil.

The rear axle presented, for this type of terrain, as for the others, greater prominence for the frequency corresponding to the third harmonic of the engine's main frequency, around 192 Hz. In turn, on the platform, for both travel speeds, there was a frequency different from such harmonics, confirming what occurred for the other treatments.

The seat and steering wheel maintained the characteristic of low frequency under this type of terrain, presenting values between 1 and 2 Hz. Fig. 7 presents such results.

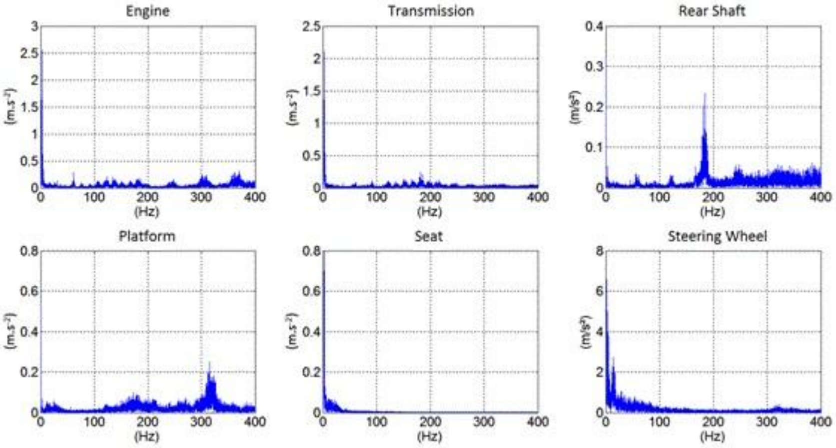

Fig. 7. FFT of the components of the agricultural tractor structure analyzed at the travel speed of 8 km.h^{-1}, over mobilized agricultural soil.

4. CONCLUSION

The more energetic vibrations were those that occurred for traffic over paved terrain, and stem from the engine of the agricultural tractor.

For traffic over firm agricultural soil, the main components of the monoblock presented a behavior similar to that over paved terrain, but the seat and steering wheel had higher values of RMS and peak of acceleration at low frequency.

For traffic over mobilized agricultural soil, the low-frequency vibrations became more energetic for all the components, increasing their energy along with the raise in travel speed.

In all cases, regardless of the travel speed and type of terrain, the rear axle and the platform maintained a characteristic frequency of oscillation.

The seat and the steering wheel are characterized for presenting low frequencies. However, due to how it is built, the steering wheel also presents part of the frequency present on the platform.

5. ACKNOWLEDGEMENTS

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