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Assessment of the influence of the eccentricity of tires on the whole-body vibration of tractor drivers during transport on asphalt roads

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Abstract

Agricultural vehicle operators are exposed to high levels of whole body vibrations (WBVs) which are related, above all, to surface irregularities, forward speed and vehicle setting. European Parliament Directive 2002/44/EEC sets the minimum requirements for the protection of workers from risks to their health and safety due to exposure to mechanical vibrations, and it is therefore of utmost to investigate any source of vibration during agricultural works and any machine-related transmission element. Tractor tires play a key role in damping vibrations; their response varies according to the tractor mass and tire inflation pressure and, during transport, they have to be taken into account at different forward speeds. The eccentricity of the tire is one of the factors thus influences the amplitude of the solicitations acting on the tire. This study was aimed at evaluating the influence of the "tire eccentricity" parameter on driver comfort and at introducing a test method for its assessment for validation purposes.

Keywords: Agriculture; Tires; Ride comfort; Safety

1. Introduction

Professional drivers are exposed to whole body vibrations [1,2] and agricultural vehicle operators, in particular, could be at risk to high levels of exposure [3,4].

The protection of workers from risks to their health and safety due to exposure to mechanical hand/arm vibrations and whole body vibration is reported in the European Parliament Directive 2002/44/EEC [5], which defines the minimum safety requirements. Moreover, in 2008, Italy adopted a specific national regulation [6] concerning worker safety, with a specific chapter on the limits regarding exposure to whole body vibration.

Considering agricultural tractors, in normal use conditions, irregularity of the working terrain and forward speed are the most important causes of vibrations (i) transmitted to the driver [7], (ii) on tool oscillations and (iii) on work quality [8].

This research has the aim to investigate and evaluate whether the value of the eccentricity influences the amplitude of the vertical solicitation and consequently, operator comfort and of defining a standard procedure to set the eccentricity of tires for test purpose.

2. State of the art

Several parameters, such as the tractor setting (mass, ballasts, tire pressure [9,10]), soil deformation [11], the type of seat and cushion [12] and the elasticity characteristics of the tires [13] influence driver comfort.

In order to investigate the role of tires on the whole body vibration (WBV) of the operator during track tests, the CRA-ING Laboratory of Treviglio has developed a method [14] that establishes the correct tractor settings and test conditions, taking into account the influence of different parameters, in particular, the (i) step forward

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speed, (ii) pressure and (iii) mass configuration, resulted to be significant on the tire characteristics and response.

This approach allowed us to define not only the test method, but also to focus on the worst case scenario, that is with the tractor unloaded and with tire pressure at $\geqslant$160 kPa. A 0.83 ms^{-1} step forward speed from 8.05 to 13.9 ms^{-1} was necessary to take into account the resonance phenomena of both the front and the rear tires.

The experiments underlined the importance of the eccentricity of the tires, a factor which had always been measured in previous tests but only as a control of the rim or tires.

In fact non-uniform wheel geometry and non-uniform tire stiffness excite vibrations in the ride frequency range [15–17].

In agricultural tractors the influence of the resonance of tires' first harmonic appears at different speed range, depending from the radius of the wheel: on the front axle at about 35–41 km/h, on the rear 44–51 km/h [14]. As only few countries allow tractor forward speed of 50 km/h, this research started focusing front tires.

The term "uniformity" was established in the tire industry and it always designates the uniformity of the forces the tire exerts on the road.

This phenomenon originates from the fact that the tire can be modeled as a series of radial and contiguous spring elements that are compressed when entering the road contact area, and recover as they exit the footprint [18,19]. Variations in the "spring" constants cause variations in the compressive and restorative forces as the tire rotates.

These forces variations run from tire center toward the tread, and from the roadway through the tire center toward the vehicle affecting handling and comfort.

Several methods, i.e. also a SAE standard [20], allow measuring the uniformity of the tire for cars interesting wheel geometry and stiffness taking into account also the factors load and speed [21].

The wheel geometry can be measured taking into account the value of the Radial Runout (RRO) that describes the deviation of the tire's roundness from a perfect circle. RRO can be expressed as the peak-to-peak value as well as harmonic values.

Interest in eccentricity of agricultural tires had also been reported concerning the development of one standard regarding rims [22]. A methodology that can be adopted to measure the geometric eccentricity of unloaded agricultural tires, based on the same concept of the standard regarding the definition of the first harmonic, has been developed [23].

This method also allows one to match the high spot and the low spot, or their particular settings, which are obtained from rotating the tire on the rim; this offers the possibility of optimizing their matching to obtain the best fitting or, as in this case, of changing the value of the eccentricity of the complete wheel.

3. Theoretical considerations

The factors that could affect the elastic behavior of the tires and influence the results of test on whole body vibration of tractor drivers during transport are the tractor mass distribution (impact on the value of resonance frequency), tire pressure (impact on tire stiffness) and forward speed (which characterizes the solicitation frequency input). One of the sources of vibrations on asphalt road results from a combination of tire eccentricity and forward speed.

The ISO 2631:1997 [24] testing standard was used for this study to assess exposure. Vibration assessment has to include a measurement of the weighted root-mean-square (RMS) acceleration. The total vibration value of the weighted RMS acceleration, determined from vibration in the orthogonal coordinates, is calculated as follows:

$$a_v = \sqrt{(k_x^2 a_{wx}^2 k_y^2 a_{wy}^2 k_z^2 a_{wz}^2)}$$

where k_i is a multiplying factor that is defined in the standard and which depends on the point being measured (seat, back or feet) and on the solicited axle (X, Y or Z), and a_{wi} is the weighted RMS acceleration.

The filters for weighing the measured acceleration are defined in the standard and depend on the point of location and of the solicited axle. CI is the overall total vibration value, which is determined from the root-sum-of-squares of the point vibration values.

The calculation of the amplitude of eccentricity has been carried out by means of harmonic analysis, based on the concept that a function or a signal can be considered as a superposition of basic waves, called harmonics.

The basic concept is based on Fourier's theory: it is possible to form any function as a summation of a series of sine and cosine terms of increasing frequency. According to the theory, and considering A the amplitude, ω the pulsation and φ the phase, we should consider the following:

$$y = A \cdot sen(\omega x + \varphi) = A \cdot sen\varphi \cdot cos\omega x + A \cdot sen\varphi \cdot cos\omega x$$
$$= a \cdot cos\omega x + b \cdot sen\omega x$$

If k is the $-n$ harmonic, the amplitude A can be calculated as follows:

$$A_k \cdot sen\varphi_k = a_k; A_k \cdot cos\omega_k = b_k; A_k = \sqrt{(a_k^2 + b_k^2)}$$
$$a_k = 1/\pi \int \mathrm{f(x)} \cdot coskx \cdot dx; b_k = 1/\pi \int f(x) \cdot senkx \cdot dx$$

where $\omega = 2\pi/T$ (T is the period) for the first harmonic (1H) $T = 2\pi$ and $\omega = k = 1$.

The integral calculus becomes a summation where the number of reliefs corresponds to the number of lugs (Fig. 1). If the tire has R lugs for each side, the number of reliefs will be 2R.