WHOLE BODY AND HAND-ARM VIBRATIONS ON OFF-ROAD VEHICLE USED IN ACADEMICALS COMPETITIONS

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ABSTRACT

Off-road vehicles, baja type, are designed for locomotion on irregular terrains with several obstacles, to pull loads with efficiency, furthermore, are compact and easy to operate. Such vehicles have wide use in agriculture, construction, transportation and military operations. Baja vehicle provide to pilot an exposure to high levels of mechanical vibrations. With the present work aimed to determine the whole body vibration and hand-arm vibration in the pilot using the vehicle designed by UFVbaja team. The vibrations levels incident on the pilot was measured in three different terrain conditions and different forward speeds. It was determinate the root mean square acceleration and daily vibration exposure at the seat pad and hand-arm of pilot. For whole body vibration was obtained the daily vibration dose value. The values were confronted with standards ISO 2631-1. The acceleration level, normalized to 8 hour, exceeded the warning limits for all worked conditions. To Baja vehicle operating in plowing soil, the transverse and vertical accelerations exceeded the limit level. In general, incident acceleration levels on the pilot were considered high, which reinforces the need for seats projects of suspension, steering and seat that effectively reduce the vibration transmitted to pilot body and hand-arm system.

Keywords: daily vibration exposure, daily vibration dose, baja vehicle.

VIBRAÇÕES DE CORPO INTEIRO E DE MÃO-BRAÇO EM VEÍCULOS FORA DE ESTRADA UTILIZADOS EM COMPETIÇÕES ACADÊMICAS

RESUMO

Veículos fora-de-estrada, tipo baja, são projetados para locomoção em terrenos irregulares com diversos obstáculos, para tracionar cargas com eficiência, além disso são compactos e fáceis de operar. Tais veículos possuem ampla utilização na agricultura, construção, transporte e operações militares. Veículos baja proveem ao piloto altos níveis de vibrações mecânicas. Objetivou-se com o presente trabalho determinar vibrações de corpo inteiro e vibrações de mão-braço no piloto do veículo fora de estrada desenvolvido pela equipe UFVbaja. Os níveis de vibrações incidentes no piloto foram medidos em três diferentes condições de terreno e velocidades de deslocamento. Foi determinada a aceleração média quadrática e exposição diária a vibrações no assento e no sistema mão-braço do piloto. Para a vibração de corpo inteiro, também foi obtida a dose diária de vibração. Os valores foram confrontados com a norma ISO 2631-1. Os níveis de aceleração, normalizado para 8 horas de trabalho, excederam os limites de alerta em todas as condições de trabalho. Para o veículo baja operando em solo arado, as acelerações verticais e transversais excederam o nível limite de exposição. Em geral, os níveis de aceleração incidentes no piloto foram considerados altos, o que reforça a necessidade de projetos de sistemas de suspensão, direção e assentos que efetivamente reduzam as vibrações transmitidas ao corpo e sistema mão-braço do piloto.

Palavras-chaves: exposição diária de vibração, dose diária de vibração, veículos baja.

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INTRODUCTION

Off-road vehicles, baja type, are designed for locomotion on irregular terrains with several obstacles, to pull loads with efficiency, furthermore, are compact and easy to operate. Powered off-road vehicles have wide use in agriculture, construction, cross-country transportation and military operations (WONG, 2009). In agricultural activities can be applied to pull small cultivators, seeders, trailers for transport of supplies and tools.

The Society of Automotive Engineers (SAE) promotes since 1976 a competition between universities aimed at developing vehicles off-road type baja. Engineering students are challenged to create different layouts vehicles that are subjected to various tests as an example of acceleration, traction, suspension and traction tests and endurance. These tests are held on terrain with obstacles varying from year to year (SAE BRASIL, 2016).

Baja vehicle provide to pilot an exposure to high levels of whole body vibration (WBV) and hand-arm vibration (HAV). The vibration power absorption of the vehicle operator thus strongly relies on the type of vehicle and its ride vibration spectra (MANDAPURAM *et al*., 2015). The terrain where the competitions occur are mostly very rough, which generates excessive vibration with great negative impacts on human health and reduces the useful life of mechanical components in vehicles (FERREIRA & FARIA, 2010).

Mechanical vibrations can influence on human driving comfort, driver fatigue and vehicular safety (SZCZEPANIAK *et al*., 2014). The WHV and HAV entail risks to the health and safety of workers; the first one causes lower-back morbidity and spine trauma and second one causes bone, articulation, neurological or muscular disorders (SCARLETT *et al*., 2005). The mainly rheumatic of HAV are Raynaud's phenomenon (vibration-induced white finger), digital neuropathy and carpal tunnel syndrome (PALMER & BOVENZI, 2015).

In recent years, the demand on off-road vehicles had a great increase what required safer and comfortable vehicles to supply needs of the customers. According to Drehmer (2012), the definition of comfort and safety vehicle is strictly subjective, since it is necessary to consider the interaction between the driver, vehicle and track. Several factors influence in dynamical behavior of the vehicle such as forward speed, tire inflation pressure, terrain conditions and type of steering and suspension systems (VELMURUGAN *et al*., 2014). The vibration transmitted for the pilot depends of the combination among the above factors. Furthermore, appropriate design of vehicle seat is essential to minimize the vibrations transmitted to pilot.

It is observed several researching relating to the study of WBV in automotive vehicles, many of them to verify the suitability of the driver's seat with respect to comfort levels established by standards. Blood et al. (2010) studied WBV in city bus to three different seat and different types of roads in order to find which design more attenuated vibrations from the road. Milosavljevic et al. (2010) verified WBV in farmers during their daily use of all-terrain vehicles (ATVs) wherein demonstrate high levels of vibration exposure within farmers needing to reduce their exposure. Scarlett et al. (2005) studied WBV and HAV in several agricultural vehicles such as tractors in different field operations, self-propelled sprayers and ATVs. These authors found that under similar operating conditions, WBV emission levels from smaller tractors are likely to be higher than from the larger models.

The vibrations consist of a complex composition of waves, which have different frequencies and directions (CUNHA *et al*., 2009). Several parameters can be used to analyze the WBV and HAV in automotive vehicles and industrials machines. The WBV and HAV acceleration time histories initially can be analyzed by frequency-weighted or root mean square acceleration. This can be used to study the sensitivity of the human body to vibrations in certain frequency ranges. In other words, it is to assess the exposure to vibration by a person over a period of time. The specific parameters Exposure Action Values (EAV) and Exposure Limit Values (ELV) are utilized as warning levels of exposure. However, if daily exposure levels exceed the EAV and approach the ELV, it is likely the level of health risk will increase (SCARLETT et al., 2005).

The harmful effects of vibration on the human body are proven in several scientific papers. This shows the importance of standards and legislation to regulate the levels of vibration and comfort. The most important international standards are ISO 2631 (1997) and ISO 5349 (2001). In Brazil, the main standard to supply information about health and vibrations appropriate levels is the regulatory norm 15 (NR15). So far, there are few studies that analyze WBV and HAV in Baja vehicles. These information are essential to adjust the car components design in order to reduce the vibrations transmission to the pilot.

The hypothesis of this work is that knowing the levels of WBV and HAV on pilot it is possible to improve the driver seat, suspension and steering system design of the baja vehicle, minimizing vibration transmissibility and keeping the vehicle comfortable at acceptable levels. In this way, the objective was to determine the vibration levels on the pilot using a vehicle designed by UFVbaja team in different terrain conditions.

MATERIAL AND METHODS

The determination of the WBV and HAV were realized in a prototype of off-road vehicle, Baja type, developed by UFVbaja team, which participated in three competitions BAJA SAE between 2013 and 2014. The main specifications of the Baja vehicle used in the vibration tests are showed in Table 1.

In the current prototype, the front suspension is of type Double-A, for ease control of the movement of the wheels, resulting in better tire-soil contact; and the rear is the swing axle type, first of all, due to the high degree of simplicity and reduced number of elements, in addition to low cost and weight. These systems influences directly in mechanical vibrations transmitted to pilot, well as the type and calibration of used tires. The concept adopted to steering system was rack and pinion, due to low complexity and easy installation compared to screw worm system. The direction of the vehicle contributes significantly to the incidence of vibration in the pilot hand and upper members.

The vehicle seat was designed according to ergonomic model proposed by Peacock (1993) which uses as a reference the percentile of 95% of the population to allocate the seat inside the roll cage. Furthermore, it was adopted the sporting driving characteristics, defining a lower position to the SgRP (*Seating Reference Point*). Aiming to the driver comfort, the pilot body members were specified to position themselves at angles within the comfort range. The seat is bolted to the vehicle chassis without the use of cushions or vibration absorbers. With tridimensional model, all members of the Roll Cage were willing to accommodate the driver comfortably alongside the drive and direction. The seat structure is fabricated of fiberglass cushioned with medium density foam with thickness of 10 cm on bottom and 5.0 cm on the back and additional parts.

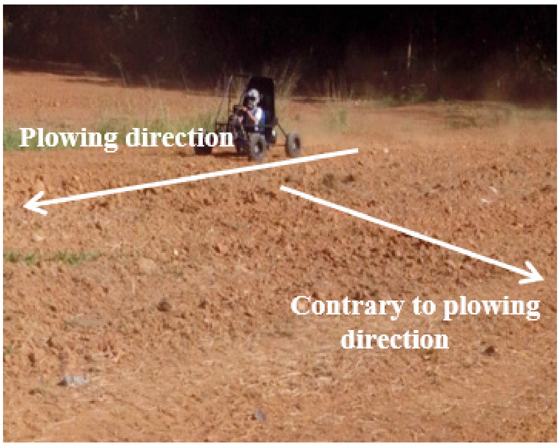
Table 1. Main specifications of the Baja vehicle used in the vibration tests

Engine model	420 DR, naturally-aspirated
Engine power (kW)	7.46
Nominal speed of engine (rpm)	4000
Baja mass without pilot (kg)	180
Front suspension system	Double - A
Rear suspension system	Swing Axle
Front tire	Dunlop KT391 AT21x7r10
Rear tire	Carlisle trail wolf AT21x7r10
Direction system	Pinion and rack

Experiments were conducted at the Department of Agricultural Engineering of the Universidade Federal de Viçosa, Minas Gerais State, Brazil. The experimental area was about 700 m^2 with low slope. Vibration levels were determined in scenarios designed to simulate the conditions of the track and maneuvers in parts of the endurance race in BAJA SAE competitions and similar to those found in agricultural areas, in general. The vibrations levels incident on pilot was measured in three different terrain conditions: flat terrain with hard soil without obstacles (Figure 1 – a), and the second and third conditions the vehicle was driven on tillage soil in favor and contrary to plowing direction, respectively (Figure 1 - b). In the third situation, the wheels motion against the furrows provided greater adversities and soil irregularities. For purposes of comparison were determined the vibration levels with the Baja vehicle stopped, to check the vibrations from the combustion engine.

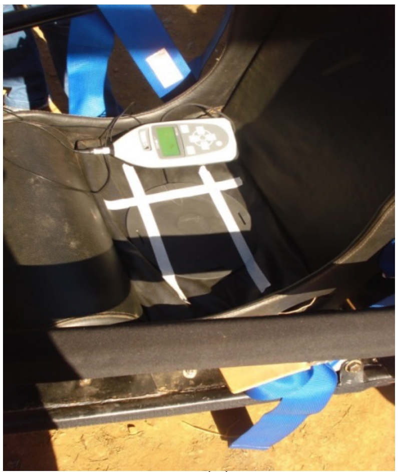
Each vibration test consisted of different tracks with sample time next to one minute where the speed was varied from 10 to 30 km h^{-1}. It characterizes the vehicle's operating range in most activities. The forward speed amplitude was monitored with a Vapor Tachometer. The tire pressure was kept constant throughout the experiment and the position of the spring suspension was kept in an intermediate position. Calibration tire was made using a common calibrator according to results


(a)



(b)

Figure 1. Experimental fields used in vibration tests with baja vehicle: (a) hard soil and (b) tillage soil.


(a)


(b)

Figure 2. Device utilized to measure vibrations in baja vehicle: (a) seat pad to measure whole body vibration (WBV) (b) hand accelerometer to measure hand-arm vibration (HAV).

of stability and grip on competitions, reaching values of 8.0 and 10.0 psi in the front and rear tires, respectively.

To monitor the incident vibration was utilized a portable vibration meter MAESTRO, model 01dB, coupled to a three axis accelerometer installed at predefined points. To quantify the WBV in the bottom seat, it was used a seat pad on a flexible disc made with standard semi-rigid material. The manufacturing material do not alter the dynamic properties on interface of the body with seat, because it moves together with the entire structure (Figure 3 - a). The HAV was determined by three axis accelerometer adapter positioned between the fingers of the pilot's right hand (Figure 3 - b). The pilot weight and height is 73 kg and 1.89 m, respectively, who drove the vehicle during all the tests. Four replications for each track condition were performed. The acceleration was showed in terms of average values and the exposure time in terms of maximum value.

The first parameter evaluated was the Root Mean Square (RMS) acceleration calculated at the seat pad for each axis, where x, y and z are the longitudinal, transversal and vertical relative to the vehicle axis, respectively (Equation 1). 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.

$$a_w(RMS) = \left(\frac{1}{T}\int_0^T a_w^2(t)\, x\, dt\right)^{1/2} \quad (1)$$

where,

a_w (t) = frequency-weighted acceleration time history , m/s^2;
T = duration of measurement, seconds.

Other parameters determined were the daily vibration exposure (A8), which is the normalized vibration to a working day of 8 h (Equation 2) and based on the European Directives 2002/44/EC, and also the warning and exposure time limit. The value to RMS acceleration and A(8) was determined to hand-arm of the pilot too.

$$A(8) = k\left[\frac{1}{T_0}\int_0^T a_w^2(t)\, dt\right]^{1/2} \quad (2)$$

where,

T_0 = reference duration of 8 hours (28,800 seconds);
k = orthogonal axis multiplying factor specified by ISO 2631-1(1997).

The daily vibration dose value (VDV) (m s$^{-1.75}$) for a person was calculated by Equation 3. According to Coles (2002) and mentioned by Scarlett et al. (2005) the VDV only provides an accurate estimate of the actual VDV if the prevailing vibration is continuous and devoid of transient high acceleration events and/or shocks. The Baja is a vehicle which is subjected to different conditions of shock and impulsive accelerations, therefore it is necessary a careful evaluation and use their values to match driver comfort.

$$\mathbf{VDV} = \mathbf{k}\left[\frac{1}{T_0}\int_0^T a_w^4(t)\, dt\right]^{1} \quad (3)$$

RESULTS AND DISCUSSION

In the next session, the results relate to vibration levels in Baja vehicle pilot are showed in different work conditions. The RMS acceleration to WBV is showed in Table 2. According to European Directives 2002/44/EC, the EAV and ELV to WBV are 0.5 and 1.15 m s^{-2}, respectively. The acceleration level A(8) exceeded the warning limits for all worked conditions, except when the vehicle is stationary with the engine running. To Baja vehicle operating in plowing soil the transverse and vertical accelerations exceeded the limit level. It is observed that the exposure time should be reduced to avoid possible health damage, such as cervical spine problems, for example. The Brazilian standard NR15 limits the maximum acceleration in 1.10 m s^{-2}.

According to Table 2, vibration levels observed stayed lower than the warning level when the Baja vehicle kept stopped with only the engine working, thus the driver may be exposed to vibration for

Table 2. Whole Body Vibration (WBV) obtained in Baja vehicle in different work's conditions

Work condition	RMS Acceleration (m s^{-2})				Time (hour:minute:second)	
	Axis			Global	Warning level	Limit level
	X	Y	Z	(A8)		
Engine on	0.18	0.08	0.29	0.29	24:33:16	129:53:37
Flat terrain	0.86	0.81	0.79	0.86	2:43:13	14:23:26
In direction of plowing soil	0.77	1.31	1.75	1.75	00:39:9	03:27:06
Counter direction of plowing soil	0.87	1.51	2.11	2.11	00:27:02	02:23:02

a long time. The longest proof of the Baja SAE competition is the resistance endurance, which can reach more than three hours and has adverse obstacles. On the flat terrain, the limit time that pilot may suffer injuries are 14 hours. The worst operational condition was with the vehicle moving towards irregular terrain, with the timeout of 2h 23min, which becomes insufficient for competition, and characterizes an unhealthy condition according to the standards. The highest vibration level was 2.11 m s^{-2}, to z-axis or vertical direction. The seat design and suspension configurations should be reconsidered to improve vehicular comfort and reduce the risks to health caused by excessive vibration.

In Table 3 are showed de VDV values determined to Baja vehicle on all worked conditions. All observed values are below those ones determined by the standard, which defines a warning value equal to 9.10 and a limit value equal to 21.0 m $s^{-1.75}$. Despite being extensively used for a parameter set limits of exposure to vibration, it may be limited in some cases. Counter the plowing furrows, it was observed the highest value for VDV, about 8.04 m $s^{-1.75}$ in transverse end vertical vehicle axis. Blood et al. (2010) observed significant WBV exposure differences between the various road types wherein older freeway segment had the highest WBV, which was shown across all bus seat types. Furthermore, it was observed that the VDV also occurs in vertical with values about 10.30 m $s^{-1.75}$ and both route producing WBV exposures slightly above the action limit for VDV. Values of VDV close to18.54 m $s^{-1.75}$ were found to suspended cabin tractor semitrailer working in rough road, at 60 km h-1 (VELMURUGAN *et al.*, 2014).

The RMS acceleration to HAV is showed in Table 4. According to European Directives 2002/44/EC, the EAV and ELV to HAV were 2.5 and 5.00 m s^{-2}, respectively. To the NR 15 Standard is characterized unhealthy condition when the daily limit of occupational exposure to hand vibration exceeds 5.00 m s^{-2}. The values observed to HAV obtained to Baja pilot was above those specified so it can be harmful to upper members when Baja moves in plowing soil. The steering system should be improved regarding the aspects of vibration absorption thus preventing these from being transmitted to the pilot. Considering the exposure time, the maximum value permited is 03h 46min, which is above the time of SAE Brasil competition endurance. This fact was also observed for to WBV. To HAV the highest value observed was to the vehicle travel direction (x-axis), being equal to 5.20 m s^{-2}, in counter direction of plowing soil condition.

Table 3. Daily vibration dose value (VDV) obtained in Baja vehicle in different work's conditions

Work condition	VDV Acceleration (m $s^{-1.75}$)			
	Axis			eVDV
	X	Y	Z	
Flat terrain	3.92	6.53	3.59	6.53
In direction of plowing soil	4.19	5.99	7.68	7.68
Counter direction of plowing soil	4.09	8.03	8.04	8.04

*eVDV – Estimated vibration dose value

Table 4. Hand-arm vibration (HAV) obtained in Baja vehicle in different work's conditions

Work condition	RMS Acceleration (m s^{-2})				Time (hour:minute:second)	
	Axis			Global (A8)	Warning level	Limit level
	X	Y	Z			
Flat terrain	1.24	1.36	0.57	1.92	13:31:00	54:02:00
In direction of plowing soil	3.18	2.67	1.98	4.60	02:22:00	09:26:00
Counter direction of plowing soil	5.20	3.90	3.63	7.29	00:56:00	03:46:00

CONCLUSIONS

- With the baja vehicle stopped, the levels of mechanical vibration transmitted from the engine to the pilot were below those that cause potential health damage. When the vehicle moves, the level increases significantly for all types of terrain studied.
- In general, incident acceleration levels on the pilot were considered high, which reinforces the need for seats projects that effectively reduce WBV and steering wheels with vibration isolators to reduce the transmission of HAV.
- The values found can contribute satisfactorily for steering, suspension and seat design in order to reduce the mechanical vibrations levels transmitted to the pilot and enable longer exposure without health damage.

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