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Do we need to revisit the methods used to measure and understand noise and vibration on military tracked vehicles?

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Abstract

When we assess compliance of crew exposure to vibration within a military tracked vehicle we use international standards, these are ISO 2631 and BS 6841. Within these standards, weighting factors based on research carried out 40 years ago are applied to the measured vibration. These weighing filters attenuate and remove vibration above 80Hz. After conducting tests for over 30 years, it is the author's intention to prove that these filters are no longer fit for purpose and the standards need revisiting.

1. Introduction

The main purpose of military land vehicles is for the movement of material and personnel for combat operations. These vehicles are designed with either a wheeled or tracked solution and can be powered by battery, internal combustion engine or gas turbine.

When recently researching the courses available for fighting vehicle design, many are provided by various Universities and Institutions and the key areas are identified under 27 headings including: Armoured Fighting Vehicle design characteristics, attack of armour and IEDs, suspension and ride, mobility, weapon fire control and stabilisation system, AFV power requirement, gun and cannon installation, Health and Usage Monitoring System, etc. Why is crew comfort not considered?

Within the automotive industry, when automobile seats are designed, human safety and comfort are fundamental design considerations. In the development of military vehicles, one needs to ask, where is the consideration for crew comfort? While the protection of the crew is paramount, are we sacrificing comfort with the sole purpose of survival? Can the two not complement each other?

Historically, when we have assessed crew comfort, we have used two parameters, noise exposure and whole-body vibration. Is this a too simplistic approach? Should we not consider the ability of the crew to carry out their duties? As per the Health and Safety Executives literature in the United Kingdom, 'The Control of Vibration at Work Regulations 2005' and 'The Control of Noise at Work Regulations 2005'. The Noise Regulations require you to take specific action at certain action values. These relate to:

- the levels of exposure to noise of your employees averaged over a working day or week; and
- the maximum noise (peak sound pressure) to which employees are exposed in a working day.

The values are:

- lower exposure action values
- daily or weekly exposure of 80 dB(A)
- peak sound pressure of 135 dB(C)
- upper exposure action values
- daily or weekly exposure of 85 dB(A)
- peak sound pressure of 137 dB(C)

For Whole Body Vibration (WBV), the regulations introduce an:

- Exposure action value of 0.5 m/s^2 A(8) at which level employers should introduce technical and organisational measures to reduce exposure.
- Exposure limit value of 1.15 m/s^2 A(8) which should not be exceeded.

The method of assessing WBV is accomplished through taking a series of measurements and these measurements are then analysed. This is done by using weighting factors / filters and the values from these are combined to give a resultant number. These weighting factors were derived over 40 years ago using technology and knowledge that was available at that time. It is the purpose of this paper to discuss whether these weighting filters need to be revisited.

2. Methodology for the Assessment of Whole-Body Vibration (WBV)

A method of assessing vehicle vibration discomfort, was evolved from laboratory and field research, conducted partly by the Institution of Sound and Vibration Research (ISVR) over a period from 1972-1984. This method was adopted by industries and was later incorporated within British Standard 6841 [1].

The procedure involves the measurement of vibration in 12 axes as shown in **Figure 1**.

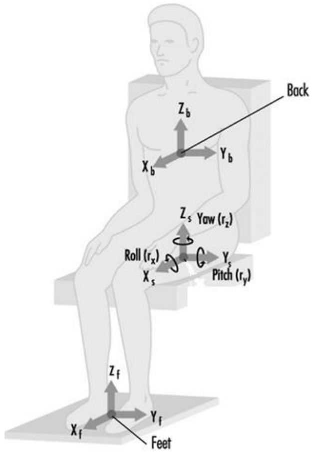

Figure 1. 12 Axis basicentric co-ordinate system.

Although, in many applications, the number of axes can be greatly reduced.

The vibration is weighted to allow for difference in discomfort at different frequencies and in different axis. The weightings are based on simple curve fits to experimental equivalent comfort. These are shown in **Figure 2**.

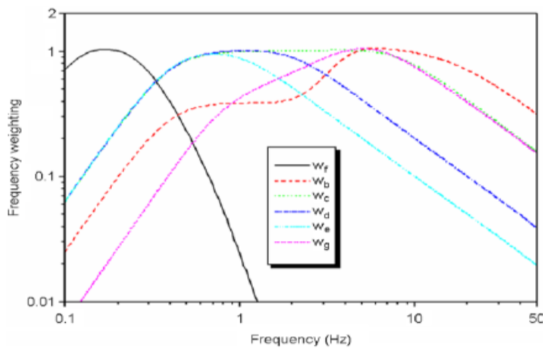

Figure 2. British Standard Weighing Function for Whole Body Vibration

The difference between the British Standard and the International Standard SO can be summarised as follows:

- For the X and Y axes on the seat, the weighting, Wd, has the same shape as corresponding weightings in ISO 2631 but with the frequency range extended down to 0.5 Hz.

- A change to the weighting for the Z axis vibration, has allowed the maximum gain of the filter for horizontal vibration to be the same as the vertical vibration, Wb, maximum gain in the Z axis (there is a difference of 1.4:1 in ISO 2631).
- The weighing for the vertical vibration, Wd, is formed from slopes of 0 and plus or minus 6 dB per octave, as opposed to 0, -3 and +6 dB per octave as in ISO 2631.
- The region of maximum sensitivity to acceleration indicated by the asymptotic curves extends from 5 to 16 Hz as opposed to 4 to 8 Hz in ISO 2631.

Input	Axis	Frequency weighting	Axis multiplying factor	Weighting, $W(f)$
Seat	x	W_d	1.00	$0.5 < f < 2.0$ $W(f) = 1.00$ $2.0 < f < 80.0$ $W(f) = 2.0/f$
	y	W_d	1.00	$0.5 < f < 2.0$ $W(f) = 1.00$ $2.0 < f < 80.0$ $W(f) = 2.0/f$
	z	W_b	1.00	$0.5 < f < 2.0$ $W(f) = 0.4$ $2.0 < f < 5.0$ $W(f) = f/5.00$ $5.0 < f < 16.0$ $W(f) = 1.00$ $16.0 < f < 80.0$ $W(f) = 16.0/f$
	r_x	W_e	0.63	$0.5 < f < 1.0$ $W(f) = 0.63$ $1.0 < f < 20.0$ $W(f) = 0.63/f$
	r_y	W_e	0.40	$0.5 < f < 1.0$ $W(f) = 0.4$ $1.0 < f < 20.0$ $W(f) = 0.4/f$
	r_z	W_e	0.20	$0.5 < f < 1.0$ $W(f) = 0.2$ $1.0 < f < 20.0$ $W(f) = 0.2/f$
Back	x	W_c	0.80	$0.5 < f < 8.0$ $W(f) = 0.8$ $8.0 < f < 80.0$ $W(f) = 6.4/f$
	y	W_d	0.50	$0.5 < f < 2.0$ $W(f) = 0.5$ $2.0 < f < 80.0$ $W(f) = 1.0/f$
	z	W_d	0.40	$0.5 < f < 2.0$ $W(f) = 0.4$ $2.0 < f < 80.0$ $W(f) = 0.8/f$
Feet	x and y	W_b	0.25	$0.5 < f < 2.0$ $W(f) = 0.1$ $2.0 < f < 5.0$ $W(f) = f/20.0$ $5.0 < f < 16.0$ $W(f) = 0.25$ $16.0 < f < 80.0$ $W(f) = 4.0/f$
	z	W_b	0.40	$0.5 < f < 2.0$ $W(f) = 0.16$ $2.0 < f < 5.0$ $W(f) = f/12.5$ $5.0 < f < 16.0$ $W(f) = 0.4$ $16.0 < f < 80.0$ $W(f) = 6.4/f$

Figure 3. BS 6841 Weighting Filters

3. Discussion

When researching this paper, it became apparent that studies into human exposure to vibration are subjective and based on participant feedback. The standards are based on research from the 1960s to 1980s, with a significant amount of the standards content coming from research in 1960-1970.

These results have variability based on many parameters including musculoskeletal system, body dimensions, Body Mass Index, age, gender, health, experience and training, sensitivity and susceptibility.

If one looks at the way these tests were conducted, with respect to input and response, like all technology, developments have led to better rig design and better sensor technology. Rigs used in the research of whole-body vibration were primarily hydraulic and were not capable of generating high frequency vibration. Sensors change the mass and stiffness of the component they were attached to, especially with a lightweight structure, consequently influencing the results. Modern sensor technologies are much lighter and have a lesser effect on the structure that they are measuring.

From the results and review of the standards it is hypothesised that the human body cannot feel vibrations above 80 Hz and in both the British and International standards vibration above 80 Hz are significantly attenuated if not completely removed. These weightings are outlined below in **Figure 4.**

When measuring whether a vehicle is compliant, noise and vibration are measured separately and these results are compared against the standard to assess exposure limits. Using this information, a conclusion is reached whether the vehicle is compliant or not. It is the author's opinion that these should not be looked at individually and whole-body vibration should not be filtered after 80 Hz.

Historically, Nprime have been involved in the capture of data on military tracked vehicles. A vehicle has been tested where all the parameters were controlled, and the only variable was the tracks. A series of tests were conducted on different surfaces, including cross country, track / unpaved road and asphalt road. The tests were performed over the full speed range of the vehicle. The platform was instrumented for WBV, Noise and reference points. The vehicle fuel was measured to ensure we had the same amount over the series of tests, as this can add over one tonne to the weight of the vehicle. The driver and occupants were also kept the same. The only variable was the tracks, as the vehicle was tested with traditional metal tracks and Composite Rubber Tracks (CRT).

The data was analysed using the filters as outlined in the standard and what became very apparent, early into the study, was that the experience the crew was relaying to the research team, differed to the results obtained and analysed.

The crew indicated that the noise level was significantly reduced, when driving with the CRT fitted. Their experience of vibration was considerably lessened and their 'real-life' experience was very different to what the results were telling us. The use of CRT was generating different noise and vibration experiences for the crew, than the traditional metal tracks. If the composite rubber track / rubber band track is perceived as being so comfortable, why are the WBV results presented not supporting this finding?

Figure 4. Weighted and Raw Vibration measurements.

The analytical results pointed towards there being no improvement in vibration to the occupants and in some cases it was worse. The question must be asked, if the occupants are reporting that the vehicle on the CRT is more comfortable than when on the traditional tracks, why are the results not supporting this? The weighted and unweighted results are presented in **Figure 4** for the X and Y orthogonal axis.

From the results presented, the effect of filtering the data is apparent to see when you compare the raw root mean squared (RMS) values with the weighted RMS values. But can it be argued that the human anatomy does not feel vibration above 80 Hz? It is found within Formula 1 racing that the drivers were experiencing the effects of high frequency vibration and it is hypothesised that these can lead to headache, tinnitus, fatigue, dizziness and nausea. These vibrations are now known to affect the teeth, crania, ears, eyes and head area in general.

Recently, Nprime conducted a measurement in the cabin of a military vehicle, with all the hatches closed and the vehicle travelling at different speeds. From previous readings it was apparent that there were resonances in the roof and floor plate structures at certain speeds. We are all aware of the oil drum affect when plates resonate and create panting pressure pulses inside the cabin. These are exacerbated when all hatches are closed. The measurements taken displayed the variation in pressure in the cabin. These results are presented colour map in **Figure 5.**

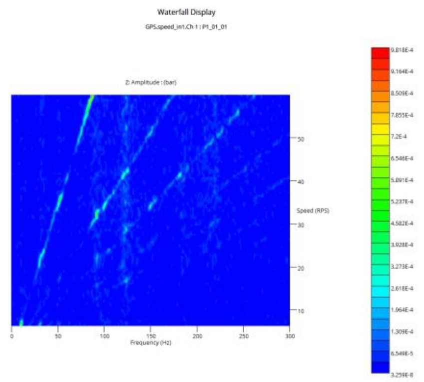

Figure 5. Cabin Pressure Pulse.

It is now standard practice to obtain feedback from personnel when testing for noise and vibration is being carried out. In April 1998 Schipani et al from Army Research Laboratory published a paper titled “Quantification of Cognitive Process Degradation While Mobile, Attributable to the Environmental Stressors Endurance, Vibration, and Noise”. Within this paper it was synopsised that :

“Cognitive performance decrement measured as percent correct was found for the cognitive concepts *time sharing, selective attention, inductive reasoning, spatial orientation, speed of closure,* and *memorization.*

Measured as percent of time taken to complete tests, degradation was found for the concepts *speed of closure, time sharing, inductive reasoning, spatial orientation, selective attention,* and *memorization.*

This investigation displayed the existence of dose response relationships, higher doses of vibration associated with more unfavourable effects.

Additionally, the trials effect recorded indicates that performance deteriorated as a function of time in the environment”. [2]

As Engineers, we have an on-going duty of care for the equipment we design and the occupant they carry. We use virtual modelling and are very reliant on its results. The interaction of the occupants within a vehicle is an extremely complex model. If we think of the makeup of the musculoskeletal system and then put this into a vehicle, that is a transient model. This dynamic model is extremely complex and only relevant for a small percentage of the population - due to the different makeup of individual people. That is, if it is possible to model. The most practical way of understanding this, is by measurement and it is our duty as Engineers to quantify this. The main vibration in tracked vehicles is generated by the track interacting with the vehicle and the road. This is termed track patter and in modern vehicles tends to range from 0-140 Hz, dependent on vehicle speed, but also has harmonics that are generated at second, third and fourth order. With filtering attenuating vibrations above 80 Hz, should we not consider vibrations above 80Hz?

When researching this paper and trying to obtain a greater understanding of the human perception of their exposure to vibration, there is significant work being carried out by the medical industry to better understand the effects of sound and vibration on the human anatomy. Bartel et al presented a paper in 2021 on Possible Mechanisms for the Effects of Sound Vibration on Human Health, [3]. Within this paper the authors mapped the landscape of the mechanisms of the effect of sound vibration on humans including the physiological, neurological, and biochemical. It begins by narrowing music to sound and sound to vibration. The focus was on low frequency sound (up to 250 Hz) including infrasound (1–16 Hz). Types of application are described and include whole body vibration, vibroacoustics, and focal applications of vibration. Literature on mechanisms of response to vibration is categorized into hemodynamic, neurological, and musculoskeletal.

If the medical industry is conducting studies similar to this, should we not put more emphasis into what sound and vibration are doing to the occupants of a vehicle and not simplify it into exposure limits.

As time has progressed since the standards were written, the human anatomy has changed, vehicle design and speed have changed, measurement and analysis technology has improved and the impact on the human is better understood. Have the standards kept up? Why is it that subjective feedback and measured data do not align?

4. Conclusion

In synopsis, these findings demonstrate that at the very least, more research is needed to gain a better understanding of the vibroacoustic behaviour in the cabin area and how this transmits into the occupants. We need to measure and better understand the transfer function between vibration sources and the human, especially the influence of vibration around the head area. When recently asked the question, ‘Are tracked vehicles compliant to the international standards?’ The answer was yes. But this led to another question, is there an inherent problem with vibration in tracked vehicles? The answer is yes. Can we fix the problem? Yes. It can be achieved through the isolation of the tracks from the vehicle or by changing the excitation mode from the tracks, by decreasing the pitch to increase the vibration frequency to that above which the human can feel. Changing the vehicle design will not suffice as the forced acceleration is still present. One needs to mitigate against this.

5. References

[1] Handbook of Human Vibration, M.J. Griffin, SBN-10 : 0123030412.

Academic press 1990.

[2] Schipani et al from Army Research Laboratory published a paper titled “Quantification of Cognitive Process Degradation While Mobile, Attributable to the Environmental Stressors Endurance, Vibration, and noise”.

[3] Possible Mechanisms for the Effects of Sound Vibration on Human Health
Lee Bartel and Abdullah Mosabbir

José Carmelo Adsuar, Academic Editor