Vibration and shock in vehicles: new challenges, new methods, new solutions.

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Abstract There are many components that contribute to the overall feeling of comfort in a vehicle. One of the important components in the exposure to vibration. Vibration can cause an acute increase in discomfort. Furthermore, the presence of vibration accelerates the onset of discomfort for long duration exposures. It is therefore important that vibration remains a key consideration in the development of vehicle seats. There are currently two opportunities for vibration research in vehicles. The development of autonomous cars means that the assumptions relating to driving task and posture are no longer valid and therefore new seats will need to be developed that allow for the variety of tasks that an autonomous occupant will need to complete. Small fast boats can expose their occupants to significant vibration and shock affecting the comfort, performance and health of the crew. There are a multitude of potential control measures that can be implemented as part of a control strategy including design of boat and seat, and operational design.

Keywords: Whole-body vibration, seating, marine, boats, autonomous, polyurethane foam

1 Introduction

‘Human Response to Vibration’ has been a well-established discipline within vehicle system research for many years. Classic texts include those from Griffin (1990) which summarised the field at that time, and Mansfield (2004) which was designed to be more introductory and accessible in nature but covering all core knowledge required for the practitioner. The discipline comprises three key words (Figure 1):

- *Human* : it is necessary to understand many aspects of human biology, physiology, and anatomy in order to grasp the discipline,
- *Response* : it is necessary to consider how the human responds in the context of vibration including their biomechanics, performance, psychology and potential health effects from chronic or acute exposures to vibration,
- *Vibration* : it is necessary to understand the physics and engineering of the vibration environment in order to understand control measures necessary to optimise the vibration environment.

Many of the greatest challenges in the study of Human Response to Vibration lie in the interactions between these key areas.

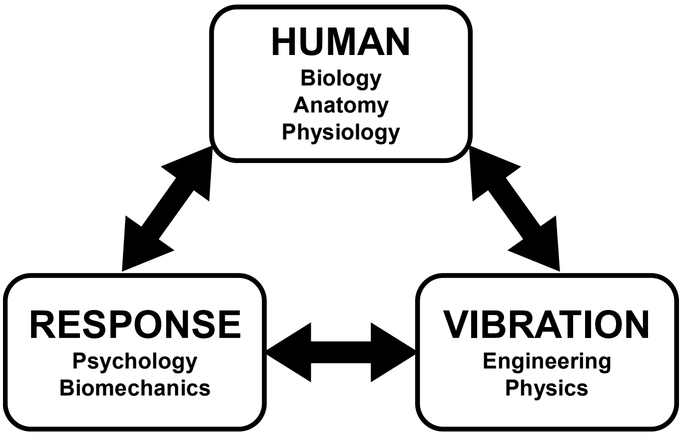

Fig. 1. Key elements of the study of human response to vibration (Mansfield 2004).

It is possible for vibration to exist at magnitudes that are measurable but are unperceivable. For example, seismic measurement apparatus will measure motion in the ground that humans cannot detect; once the vibration of the ground exceeds perception thresholds an earthquake occurs that could potentially damage structures. In this case the effects on the human are indirect (i.e. it is not the vibration that poses the greatest danger but the effects of the vibration on other structures). In vehicles the vibration is usually above a perception threshold. For the majority of kilometres travelled in modern society, the vibration poses minimal direct health risk but could be distracting, fatiguing or uncomfortable. If the exposure magnitudes and exposure durations are long enough the vibration could pose a chronic health risk. For example, a professional worker operating an earth-moving machine could be exposed to vibration for many hours each day with their discomfort levels gradually increasing as they fatigue. Over time, these exposures have been associated with an increased prevalence of health effects (e.g. Bovenzi et al. 2006). In the most extreme environments it is possible for vibration and shock to cause acute health effects such as spinal compression fractures or disc herniation (e.g. Johanning, 2015).

The effects of vibration depend on the frequency of the vibration, the magnitude of the vibration, the waveform and direction, and the application site. Broadly, the response to vibration can be categorised into three application areas (Figure 2):

- *Motion Sickness* : Very low frequency motion of the whole body, with effects including lethargy, nausea, loss of well-being and ultimately vomiting.
- *Whole-body vibration* : Vibration usually between about 1 and 50 Hz, typically experienced in vehicles and affects the whole body.
- *Hand-arm vibration* : High frequency vibration potentially into the kHz range, typically experienced through the use of power tools with effects including hand-arm vibration syndrome / vibration-white finger.

Research has led to the development of standards, directives and regulations for vibration exposure. For vehicle environments, the key document is ISO2631-1 (1997) : Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration: Part 1 - General requirements. This standard includes guidance on the evaluation of vibration in terms of perception, comfort and health. The key process for evaluation involves measurement of the vibration on the seat surface in the three orthogonal axes (x-, y-, and z-). These data are frequency weighted, providing an indication of the effect of the vibration on a human seat occupant. This can be compared to criteria for predicted levels of human response. Further measurements and calculations are required in order to generate an overall daily dose (A(8)) that can be used for basic risk assessments (Figure 3). The standard provides more complex methods of data analysis including guidance on how to assess vibration at the floor and backrest; how to assess rotational motions; how to evaluate motion sickness; how to use alternative risk metrics such at the vibration dose value (VDV).

Whilst the basic evaluation of whole-body vibration has been established for some years, there remain several areas that constitute a significant challenge and the focus for future research. This paper seeks to reflect on contemporary challenges in the field of human-response to vibration in the context of vehicles and transport systems.

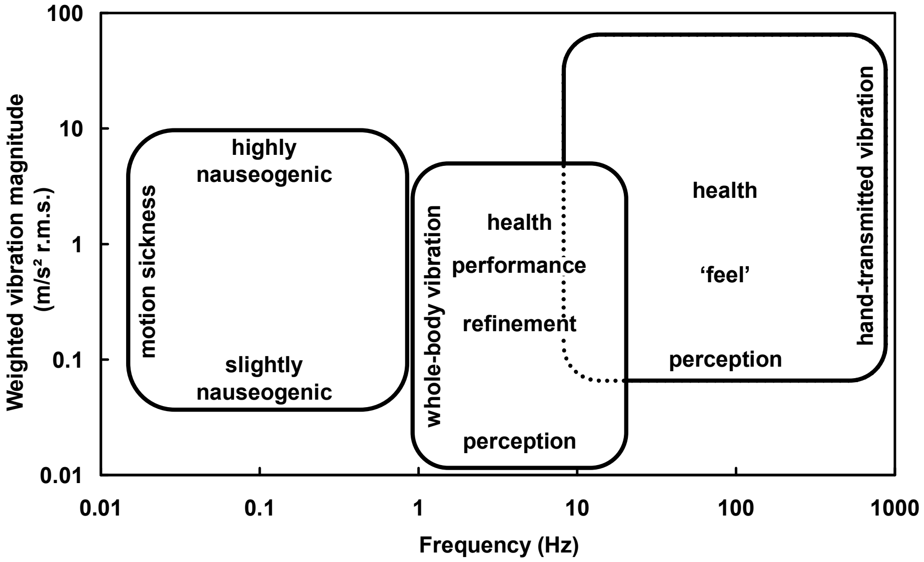

Fig. 2. Typical frequency ranges and effects of vibration on the body (Mansfield 2004).

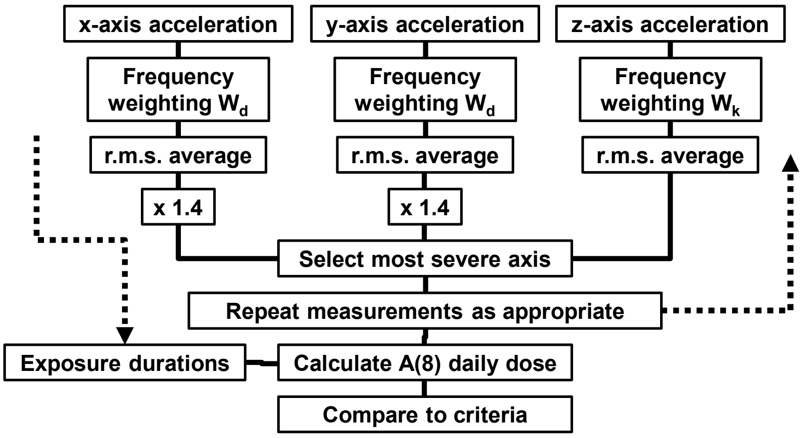

Fig. 3. Simplified schematic showing the process of evaluation of vibration according to ISO 2631-1.

2 Seat design for long-term vibrational comfort

Over the past two decades, seat technologies have progressed. Improved manufacturing methods and the drive for more sustainable transport has motivated development of lighter seats, many of which have maintained the requirements for comfort. In some sectors the seat requirements have significantly changed. For industrial machines, agriculture and forestry the cab was previously not seen as a priority in terms of marketing and development. However, this has changed such that owners now also prioritise the vehicle interior design and the associated comfort. Hence, there is great opportunity for development of comfort technologies including better seat design. After-market products have become viable; e.g. BOSE developed and market their ‘ride’ seat, acknowledging that it is a premium product with an associated premium pricing. This is marketed at holistic well-being of drivers after driving for long periods of time. Mansfield et al. (2016) showed how after extended periods of time the benefit of an improved foam composition become more important, especially where there is vibration (Figure 4). This interaction of vibration / comfort / duration has been developed into a multi-factorial model that allows for the prediction of discomfort over extended periods of time, and with different levels of vibration (Figure 5). Importantly, the model shows how the presence of vibration accelerates the onset of discomfort (Mansfield et al. 2014).

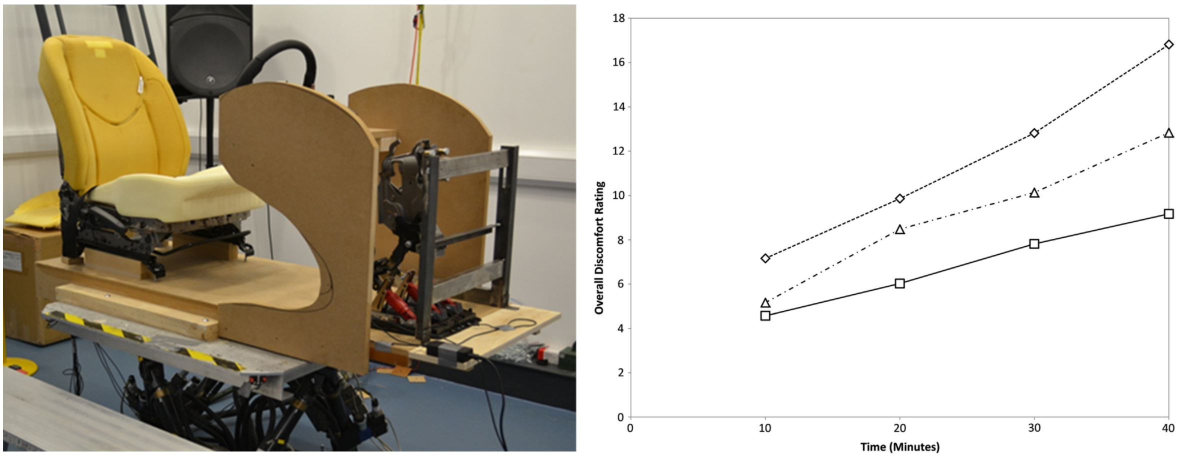

Fig. 4. Study of discomfort in car seat for Foam ‘A’ (no vibration -[]- ; with vibration --<>--) and improved Foam ‘B’ (with vibration - - Δ - -). Data from Mansfield et al. (2016).

3 New challenges for vibration discomfort in autonomous transport

With the unrelenting development of autonomous vehicles the context of use for automotive transport is changing. Whereas historically design guidelines have assumed that the driver is in a very constrained posture dictated by the position of the pedals, steering wheel and eye-point, autonomous driving no longer needs these constraints. For the foreseeable future even the most technologically advanced cars will need to switch between what are effectively alternative driving modes. Autonomous modes of driving would be possible at slow speed in urban centres where the speeds are low. On highways the car could also be in fully autonomous mode whilst driving at higher speeds in contexts where the traffic and road is predictable. For less predictable urban roads with a mixed transport economy, manual driving will be necessary. Whilst travelling a long distance on a highway the driver will inevitably want to carry out a variety of tasks including resting/sleeping, working, making calls, or engaging in entertainment activities. Therefore the posture in which the driver sits may need to be very different to efficiently perform these tasks in the same seat in which they were previously driving. Research shows that it is possible to have a radically different driving posture was maintaining comfort (Smith et al., 2105) but there is still significant research needed to be completed in order to establish the requirements and objectives of the necessary seat design for future vehicles.

It could be argued that many vehicles already consider the multiple postures that are necessary for autonomous automobiles. For example the vast majority of occupants in aircraft and trains are passengers rather than the driver. There are clearly synergies possible between the automotive industry and the passenger transport sectors.

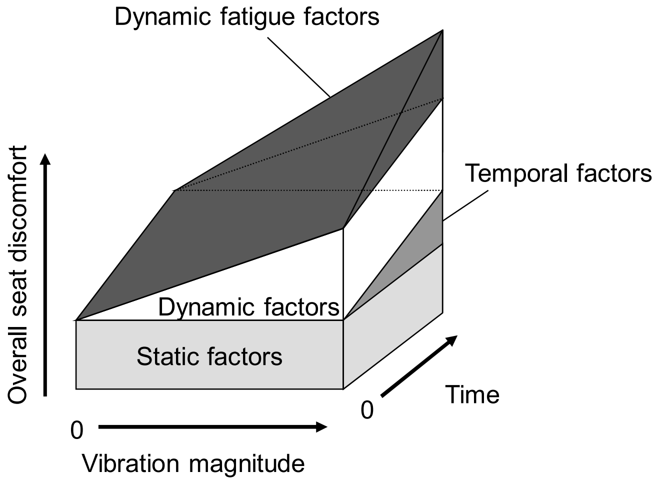

Fig. 5. Multi-factorial model of overall seat discomfort (Mansfield (2012)).

The secondary concern for autonomous vehicles is the discomfort that will come from motion sickness. Some have been argued that the effect of motion sickness could be a terminal problem for autonomous vehicles, significantly constraining their widespread use (e.g. Diels et al., 2016). For many occupants habituation will occur, where the symptoms decline with repeated exposures, but many may self-select and choose not to travel in that mode due to the motion sickness problem (Mansfield, 2004). There are opportunities for acceleration and routing algorithms for autonomous cars that could minimize the effects of motion sickness, especially in the context where time of travel shifts from being 'wasted' time to a useful part of the day due to opportunities for carrying out alternative tasks.

4 Marine environments: the problem of small fast boats

Small fast boats remain a challenge in terms of whole-body vibration exposure control. This type of craft includes search and rescue (e.g. RNLI in the UK), Coast Guard patrol boats, windfarm maintenance craft, leisure and thrill rides, military craft, and pilot boats. A pilot boat is the craft that is used to transfer a helmsman who has local knowledge (the 'pilot') that is required to direct a large vessel into a sea port. Whilst the large vessel may be able to adequately cope with rough sea conditions, if the pilot boat cannot transfer the pilot to the larger vessel the port is effectively closed with no vessels able to enter or depart. Military special forces have a requirement to transport personnel at high speed and potentially stealthily. Upon arrival at the destination the personnel may need to be immediately vigilant and able to perform at their best in order to succeed in their mission. The vibration exposure can reduce performance, increase fatigue and cause great discomfort. Search and rescue is a special case in which many crew members are civilian volunteers who may not have the seamanship experience and skill of a professional. The crews' role is to rescue those whose lives may be in danger in high seas and therefore if they receive an emergency call they do not have a choice but to set to sea.

The nature of the vibration and shock that small craft are exposed to its characterised by two components. There is a steady-state element as the craft moves with the sea. This is the most common component for non-planing craft. For planing craft, superimposed on the top of steady-state motion are repeated shocks. The boat will leave one wave crest at high-speed and move into freefall before it makes contact with the water again. The vibration profile is characterized by repeated impulses in the vibration signals (e.g. Rantaharju et al. 2015; Figure 6). In very high seas it is possible for free-fall to extent to 1-2s and the boat hits the trough of the next wave at high speed inducing what is known as a wave slam. These shocks can be significant and are the highest known shocks that workers are regularly exposed to in any industry (e.g. 10g; Haynes 2016).

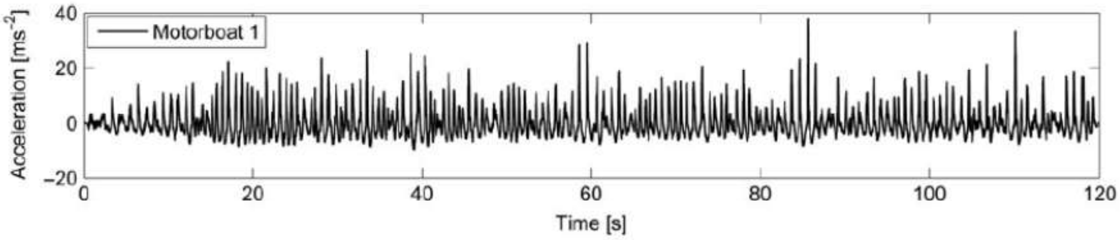

Fig. 6. Typical vibration profile on the seat of a high-speed motorboat without significant wave-slam. Data from Rantaharju et al. (2015).

Control measures for improving the comfort and well-being of occupants of small fast boats do exist. These include:

- *Avoid travel* : limiting use below certain sea states,
- *Hull design* : improving hull form to optimized ‘v’ rather than flatter bottom,
- *Coxwain skills* : skilled coxwains can drive the craft in a manner that minimizes shocks,
- *Reduce speed* : minimization of the free-fall component of the vibration,
- *Minimise operation time* : controlling the exposures of crews to ensure that minimal exposure occurs in high sea states,
- *Suspension decking* : the floor can be isolated directly or surface coatings can be used to minimize impacts,
- *Seat design* : new optimized marine suspension seats can be effective in minimizing the shock exposure.

In order to improve the comfort well-being and health of crewmembers the seats can be optimised to absorb the energy in each of the wave slams. These require sophisticated and reliable suspensions with a long displacement and with progressive damping to ensure that the motion of the seat is smooth and that end-stop impacts do not occur. New test methods have been developed for the seats but are as yet not established. The test method requires a drop tower where the seat being tested is mounted on to a sled which drops from a specific height. Beneath the sled a shaped probe impacts into a sand box. This provides a well-defined deceleration profile that can be used for repeatable seat testing.

5 Conclusions

The vibration performance of vehicle seats remains important. Research has shown that improvement in the dynamic environment to which a seat occupant is exposed will directly affect the comfort, not only acutely but also over long periods of time. Looking forwards, there are new challenges that face the discipline particularly in the development of mass market autonomous vehicles, and the specific challenges facing the niche of small fast boats.

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