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VSimulators: A New UK-based Immersive Experimental Facility for Studying Occupant Response to Wind-induced Motion of Tall Buildings

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Abstract Current vibration serviceability assessment criteria for wind-induced vibrations in tall buildings are based largely on human 'perception' thresholds which are shown not to be directly translatable to human 'acceptability' of vibrations. There is also a considerable debate about both the metrics and criteria for vibration acceptability, such as frequency of occurrence or peak vs mean vibration, and how these might vary with the nature of the vibration. Furthermore, the design criteria are necessarily simplified for ease of application so cannot account for a range of environmental, situational and human factors that may enhance or diminish the impact of vibrations on serviceability. The dual-site VSimulators facility was created specifically to provide an experimental platform to address gaps in understanding of human response to building vibration. This paper considers how VSimulators can be used to inform general design guidance and support design of specific buildings for *habitability*, in terms of vibration, which allow engineers and clients to make informed decisions with regard to *sustainable design*, in terms of energy and financial cost. This paper first provides a brief overview of current vibration serviceability assessment guidelines, and the current understanding and limitations of occupants' acceptability of wind-induced motion in tall buildings. It then describes how the dual-site VSimulators facility at the Universities of Bath and Exeter can be used to assess the effects of motion and environment on human comfort, wellbeing and productivity with examples of how the facility capabilities have been used to provide new, human experience based experimental research approaches.

Keywords Tall buildings, Walking, Swaying, Ground reaction force, Inertial measurement unit, Force plate, Treadmill, Vibration testing, System identification

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1. Introduction

In recent years, with a pause due to the COVID-19 pandemic, the number and height of tall buildings built across the world has grown to meet the demands of city-based urbanisation (MIT Technology Review, 2018). For example, the number of 200 m+ tall buildings increased from 614 to 1478 between 2010 and 2017 (Council on Tall Buildings and Urban Habitat, 2018). Modern tall buildings with progressively more slender form-factor and open-plan floors often have low stiffness and consequently low natural frequencies of vibration which make them more vulnerable to horizontal sway due to wind loads. Such vibrations are usually of narrow-band random nature within a frequency range of 0.1-1 Hz (Kwok et al., 2009) and may be due to both along wind buffeting and across wind effects e.g., vortex shedding. Furthermore, the need to design and construct sustainably means that new buildings are ever more 'lean' in construction (i.e., minimising material use) and the use of renewable materials, such as timber (with inherently low stiffness), is growing. As a result, while buildings can easily be made to satisfy strength design criteria, their structural design is increasingly governed by vibration serviceability, requiring added stiffness, mass and/or damping to be introduced to ensure the building is habitable. To keep the costs and embodied carbon to the minimum, among all the other factors influencing design, it is imperative to define vibration acceptability limits that are appropriate for potential building occupants, and not unnecessarily onerous.

Up to now, vibration serviceability limits have usually been defined based on human perception thresholds. Recent studies, however, show that human perception thresholds are not always directly related to human acceptability of

vibrations and their use can lead to non-rational or even over-conservative design (Lamb et al., 2016; Lamb & Kwok, 2017). Although field data are notoriously difficult to obtain, there is evidence that vibrations can be perceptible but still acceptable, not adversely affecting performance (Burton, 2006; Denoon et al., 2000; Jeary et al., 1988). The opposite scenario can also be true, where long term exposure to sub-perceptible motion can be potentially unacceptable due to adverse effects on human health and wellbeing (Hammam et al., 2014). Moreover, acceptability is both subject- and context-dependent i.e., it is likely to depend on what occupants do in an environment and what their expectations are. Lamb et al. (Lamb et al., 2016) argue the current serviceability criteria is unsuitable, mentioning that vibration frequency is not the only parameter that can determine serviceability of buildings, but several other motion-related factors such as acceleration amplitude and duration should also be considered. In addition, maintaining normal levels of work performance and wellbeing should be addressed by, if not underpin, future serviceability criteria. Therefore, while simple metrics are suited to structural design, structural engineers need more nuanced criteria based on fundamental human response that can be used in optimised design for habitability in terms of serviceability and associated factors which affect the quality of the living and working environment.

2. Existing Codes and Standards

The modern era of tall building design began with the World Trade Centre 'Twin Towers', completed in 1972. With the innovative framed tube design of the Twin Towers and high wind speeds which would be experienced, it was realised, through wind tunnel testing, that the sway motion would be excessive. Not only would this cause problems with maintaining proper function for lift shafts, but it was clear that this level of motion would be unacceptable for occupants. At the time, however, there was no criterion by which the acceptability could be assessed, other than relying on precedent. For such large motions there was no comparable precedent; the previous tallest building, the Empire State Building, was a much stiffer, heavier and highly damped construction, typical of tall buildings up to that point. Thus, Chen and Robertson (Chen & Robertson, 1972) carried out the first motion simulator tests on humans within the sub 1 Hz frequency range, using two motion simulators, one of which consisted of a box hung within a ventilation shaft in the Lincoln Tunnel, with bicycle wheels to guide, pushed by engineers at different amplitudes.

Although over 50 years old now, this work was a landmark in the fields. Several observations were made that are still generally accepted today: Period of oscillation, body movement, expectancy of movement and body posture all significantly affect perception thresholds. Perception thresholds were seen to increase as the period of oscillation increased (or frequency of vibration reduced), hence, the conclusion that vibration perception is frequency dependent. Perception thresholds for standing subjects were seen to be significantly lower than those walking, due to masking effects of physical movement, while sitting subjects had higher perception thresholds than those standing. Thus, type of activity has an influence on perception of vibration. The expectation of the motion event was also a clear factor, with subjects perceiving vibrations at much lower levels when expecting, or having previously experienced, vibrations compared to those who were not expecting any vibrations (subjects were initially not told the nature of the testing). Ultimately this work led to the design and installation of 10,000 visco-elastic dampers into the Twin Tower structures to reduce the maximum sway to imperceptible levels under the predicted 80 mph winds.

Since this pioneering work, many studies have been carried out, both reported from occupants of full-scale buildings known to have motion related problems (of which there is no short supply, but limited access) and motion simulators (which are rare, but accessible). This started with Hansen (Hansen et al., 1973), who carried out a human response survey of two tall buildings, both with quite low frequencies of 0.2 Hz, following strong 50 mph winds. His findings revealed that 47% of occupants had experienced some symptoms of motion sickness or discomfort in upper floors. However, such data is very subjective and has limitations in the numbers of samples which can be obtained, the repeatability, and the measurement and control of conditions experienced. Moreover, there is limited opportunity to study actual building occupants; building owners rarely permit accelerations to be measured, let alone published, and there is little in the way of field data on the complaint rate. As a result, since the 1980s, most objective and quantitative measurement of human response to building sway has involved motion simulators. This creates challenges in realistic simulation of the vibrating environment and context, as well as accurate representation of the wind induced motions.

Kwok et al., (Kwok et al., 2009) present a detailed review of previous studies of vibration *perception* through full scale observations and use of motion simulators and how these studies, e.g. (Chen & Robertson, 1972; Goto, 1983; Hansen et al., 1973; Irwin, 1978) led to the various codified criteria on acceptable vibrations; first in the 1975 National Building Code of Canada (NBCC) via the commentary (National Research Council of Canada, 1975), then in ISO 6897 (International Standards Organisation, 1984), which at the time of writing remains in service even though overshadowed by the simpler ISO 10137 (International Standards Organisation, 2007). The various guidelines and standards, such as these, which define acceleration metrics for occupant comfort in different types of tall building have been collated in the Council on Tall Buildings and Urban Habitat (CTBUH) monograph (Kwok et al., 2015) and summarised by Burton et al.

(Burton et al., 2015). It is apparent that almost all such codes and standards derive from the same basic perception threshold criteria, adapted to account for different return periods, acceleration measures, and occupancy type.

Despite this, to quote Kwok et al. (Kwok et al., 2009) "There is currently no single internationally accepted occupant comfort serviceability criteria which set a design standard for satisfactory levels of wind-induced vibration in tall buildings." However, the CTBUH monograph offers its own general guidelines on peak acceleration levels in terms of perception, adverse comment and fear and safety, with qualitative definition of frequency and duration of occurrence but commenting on neither frequency of oscillation nor return period.

Several researchers (Burton et al., 2015; Howarth, 2015; Kwok et al., 2009) have provided comparisons between codes and guidelines, but this is complicated by use of different return periods, T, different metrics (peak or RMS acceleration) and different units (0.1%g equates to 1milli-g, while approximating to 1 cm/s^2 and 0.01 m/s^2). Vibration may be characterised as sinusoidal, multicomponent and/or random. The different types of vibration signal have different ratios of peak to RMS ('peak factor') accelerations, which influence acceptability; 1.414 for sinusoidal motion, ~ 2 for crosswind (vortex-induced) response and upwards of 3 for narrowband random along wind response (Boggs, 1995).

3. Limitations of Current Approach to Vibration Acceptability

The considerable range of guidance available, much of which, as discussed above, is conflicting, tends to stem from the early studies (Chen & Robertson, 1972) of perception thresholds, which are viewed as the most objective measurable metric (Tamura et al., 2006). These perception thresholds are relatively easily observed but are, at best, only a proxy (Lamb et al., 2016) for the range of other consequences of tall building sway on occupants, such as reduced work performance, health and well-being, i.e., the human impact of motion, regardless of whether occupants feel it. That impact can be unacceptable, whether it appears as physical symptoms, such as tiredness, dizziness, muscle strain, inability to carry out physical tasks, or as disturbed concentration and disruption of mental work tasks. Thus, recent studies in human acceptability of vibrations have highlighted limitations in the current perception-based vibration serviceability assessment guidelines that need addressing in order to better inform the design process. These limitations are categorised to some extent according to different factors and effects.

3.1. Vibration return period

Acceptability of vibrations is generally considered to increase with time between occurrence (return period T in years), i.e., people will more tolerate discomfort provided that it is infrequent and/or for short periods of time, less if experienced routinely.

The first codified criteria were from Canada in 1975 (National Research Council of Canada, 1975) providing for T = 10 years at 1-3%g peak acceleration. ISO 6897 (International Standards Organisation, 1984) and the British Standards Institution equivalent, BS6611, (ISO 10137 has no BSI equivalent) use T = 5 years, worst 10 minutes (as RMS). The corresponding T = 1 year criterion was tentatively suggested by ISO 6897 to be 0.72 times the T = 5 year criterion. This guidance was based on a combination of motion simulator perception threshold tests and field observations.

Current ISO 10137 guidance (International Standards Organisation, 2007), which developed directly from ISO 6897, has moved to T = 1 year (peak acceleration). Current Canadian guidance is provided in the latest NBCC commentary, currently for the 2015 code (National Research Council of Canada, 2015b) and reflects the ISO guidance of T = 1 year, whereas practitioners e.g. (Burton et al., 2014) recommend that accelerations occurring with T = 1 year are reviewed because this shorter recurrence interval is more relevant to occupants' daily life. In particular, slender supertall buildings may experience vortex shedding leading to cross-wind response events with short return periods of 1 month to 1 year.

The Japanese AIJ – GBV-2004 guidelines use a series of probabilistic peak acceleration perception thresholds for T = 1 year, based on work by Tamura (Tamura et al., 2006) with the decisions on acceptable levels left to the client and designer.

CTBUH (Kwok et al., 2015) avoids specific return periods. The guidance suggests 5milli-g peak as perceptible but acceptable if not frequent or continuous for extended periods; that 10 milli-g, will be perceptible if occurring frequently or for extended period of time; and that 35-40 milli-g is a fear and safety threshold sufficient to cause loss of balance.

Hence, there is no consensus in the literature on choice of design return period (other than increasingly common use of T = 1 years), nor its dependence on the vibration characteristics and building use.

3.2. Vibration metrics

Cross-calibration between different metrics of acceptable vibration is an open research challenge. To date, all vibration serviceability metrics used in guidelines have been based on acceleration, whether or not frequency-dependent. ISO 6897 (International Standards Organisation, 1984) uses RMS acceleration for the worst 10 minutes (T = 5 year). Architectural Institute of Japan (AIJ) (Tamura et al., 2006) use percentile values of perception with the 90^{th} percentile value aligning with the ISO 10137 residential criterion, both using peak acceleration. ISO 6897 references early work (Hansen et al., 1973) with acceptability at a limit where 2% of people object to the motion.

RMS or peak acceleration, which are almost universally

used in current guidance, are convenient measures in terms of both design and assessing performance, but provide little information about the characteristics of the motion. Sinusoidal motion can be produced with the identical peak or RMS acceleration as a narrow band random motion, but the characteristics of these motions are very different. Moreover, the cross-wind and along-wind response of buildings have different character. As a result, use of peak acceleration, which in reality occurs infrequently and is difficult to predict, can result in overly severe criteria (Boggs, 1995).

However, the duration of exposure to vibrations is not meaningfully considered in any current requirements for tall building sway. Root mean quad or vibration dose values (VDVs) are commonly used in other situations where exposure to ongoing vibrations is a health and safety concern and are referred to in ISO 2631-2 (International Standards Organisation, 2003). The VDV approach is more sensitive to peaks than the RMS approach and is often used in shock analysis, so takes some account of whether an unacceptable vibration will occur within a certain period of time. Fundamentally though, time (i.e., duration)-dependency, including habituation (becoming tolerant of perceptible vibrations over time) is not accounted for in perception threshold-based design criteria. While some researchers have included investigation of habituation (Denoon et al., 2000; Lamb, 2013) they are inconclusive and not represented in current guidance.

3.3. Dependence on natural frequencies of the building

The majority of the design guidelines (including the ISO, AIJ and British Standards) include the dependence on natural frequency of acceleration thresholds, with minima in the range 1-2 Hz corresponding to first modes of building heights up to 46 m, using Ellis's formula (Ellis, 1980). For frequencies below 1 Hz, the allowable acceleration thresholds linearly increase. The assumption is that higher modes of taller buildings are not strongly excited by wind-buffeting.

Recent commentaries of NBCC (National Research Council of Canada, 2015a) reference the lowest natural frequency (f_n) dependent limits of $0.61f_n^{-0.454}$ for residential, and $0.11f_n^{-0.454}$for office occupancies used in ISO 10137. Due to form factor and symmetry, tall buildings may have two or more closely spaced 'first mode' natural frequencies involving combinations of translation and rotation, resulting in complex motion trajectories that have been observed in numerous tall building monitoring exercises.

Rather than labelling multi-component motion with a single frequency, some guidance sidesteps the issue. North American practice from 1975-2000 referenced in the NBCC commentaries adopted a frequency-independent range of 15 to 25 milli-g, the lower value for residential, the upper value for offices, although at least in USA there is anecdotally a shift to use of ISO 10137. More recently, AS/NZS 1170.2 (Australian/New Zealand Standard, 2011) suggests a single value of 10 mill-g (peak) with no frequency qualification (or reference to return period) while the CTBUH (Kwok et al., 2015) recommendations are also not frequency dependent.

3.4. Direction and form of motion

The majority of existing guidelines and previous motion simulator studies are based on unidirectional or elliptical motion. This is very convenient when establishing perception thresholds by providing different frequencies and amplitudes of motion, but does not represent real tall building motion. Moreover, cross-wind (due to vortex shedding) and along-wind (due to buffeting) acceleration time histories are qualitatively very different and constantly vary in amplitude and frequency content. Multiple natural frequencies can occur at close or well separated frequencies with degrees of torsion depending on location of centre of rotation and there may also be contributions from higher order sway/torsion modes in the overall response. Thus, criteria for acceptability of motion have been largely based on idealised motion trajectories at specific frequencies which may not be experienced in practice. The type of motion, choice of frequency and choice of metric are all linked and need further investigation.

3.5. Sub-perception response to vibration

The range of vibration levels increasing from perceptible to annoying can apparently be narrow (Burton et al., 2015). While there is a different problem when vibration levels are below the threshold of perception, it may, nevertheless, have distinct negative physiological effects. Sopite syndrome (Graybiel & Knepton, 1976; Lamb et al., 2016) is a form of sub-nausea motion sickness, associated with symptoms of "excessive drowsiness, lassitude, lethargy, mild depression, and reduced ability to focus on an assigned task (Matsangas & McCauley, 2014). Believed to occur at imperceptible vibration levels, it depends strongly on environmental conditions and possibly exposure time, and potentially affects millions of tall building users worldwide, yet it is not mentioned in any design guidance and is an area requiring further study.

3.6. Dependence on context, environment and usage

Context dependency is dealt with only in a few guidance documents and in a somewhat simplified way. ISO 6897 does not differentiate building type but focuses on use and expectation, while AIJ leaves the decision on which percentile to adopt to building owners. ISO 10137 states that the allowable peak acceleration for people in residential buildings should be two-thirds that of people in office buildings. Whether this is, as (Isyumov, 1993) suggests, because more time is spent in residences than offices, and that it is more usual to vacate a place of work in strong winds; or that relatively sedentary occupants without the distractions of work are more sensitive to feeling sway motion is unclear, but there appears to be little evidence

or justification for the difference. In fact, the opposite may be true (Lamb & Kwok, 2017); office environments are primarily designed to support and facilitate work, and patterns of activity are markedly different. Typical office environments are mainly associated with sedentary work at a desk, compared to the greater range of activities that occur in residential environments. Due to relatively more sedentary and task directed activities performed at work, building motion may be more obvious, distracting and disruptive in office environments than in residential buildings.

Categorising as either 'Office' or 'Residential' is a very limited view of activities which may take place in a building and deserves greater study with better representation of real environments. Certain activities (particularly those involving physical movement) are, as previously observed, likely to mask building vibrations and, thus, influence both perception and acceptability levels. It is the consequence of the sway motion on a person and the impact their comfort, well-being and activities that is important, not the perception of the vibration itself.

3.7. Auditory and visual cues

Auditory and visual cues to movement are neglected in most motion simulator studies, being an enclosed box designed deliberately not to make noise which may unintentionally alert users to movement in perception experiments. ISO 6897 mentions such effects in its copious notes. Creaking, whistling or howling of wind, exterior views of adjacent buildings (parallax due to rotation in purely torsional vibration modes as well as eccentric sway modes), as well as swaying flags, signs or even trees, and interior visual cues such as swinging lights, vibrating computer monitors or moving curtains/blinds, are all strong indicators of motion. The question remains as to how these cues influence perception of motion and, more importantly, affect acceptability.

4. Physiological and Psychological Effects of Vibration and the Rationale for VSimulators

With the above discussion in mind, it is clear that human perception and response to vibration is a technically challenging and conceptually sophisticated area requiring application of modern psychological and physiological approaches and study methods to improve guidance.

There are many external factors, experienced consciously or unconsciously, which may influence acceptance of motion. Internal and external visual and audio cues might enhance effect of vibration or, conversely, provide a reassuring expectation of movement. Forewarning occupants about the possibility of noticeable motions during strong winds may help them adapt to significant motions. Sopite syndrome, where occupants are unaware of the effect of building vibration yet still adversely affected, adds an additional challenge. Added to this, human responses are likely to be filtered by the way they are measured and reported and are strongly affected by a range of environmental and other cues that are not well understood. Hence the need for addressing all the factors and using effective reporting.

Research leading to the range of acceleration values used for design has typically only asked questions about how the vibrations are perceived and whether they are tolerable or acceptable. More recent research however, (Burton et al., 2015; Denoon et al., 2000; Lamb, 2013) has explored how the motion effects people, their comfort and their cognitive performance. Current research aims to expand on this research to provide objective measures of physiological and psychological response and effects on human performance. To recalibrate existing standards in this way, a more sophisticated approach is required, in which working and living environments are better simulated.

Existing standards and guides mentioned above are convenient for designers since they offer a single numeric target value. However numeric values face the additional difficulty that people not accustomed to living in tall buildings - or their designers - have no sense of what 5,10, 20 milli-g feels like, even as a continuous steady-state vibration let alone the rarely occurring, short duration narrow band random multi-directional vibration experienced in reality. Hence it is very helpful to inform discussions between tall building designers, owners, occupiers and wind specialists by getting them to experience these in a moving room. This has been the approach by tall building vibration specialists RWDI who have historically used the ship's bridge simulator at Memorial University, Newfoundland (Memorial University Newfoundland, 2020) for simulating skyscraper motion with client feedback on e.g., effects of vibration mitigation devices.

There are, and have been at least as far back as the World Trade Centre study (Chen & Robertson, 1972), motion simulators specifically designed to study human perception and tolerance of vibration. These include the currently operational ISVR Southampton 6-axis motion simulator (University of Southampton, n.d.) and the HKUST motion platform (Burton et al., 2005) which was taken out of service in 2015. Without the HKUST machine there was a case for a new facility with enhanced capability and environmental simulation to explore the wide range of factors on acceptability not limited to return period, metric or oscillation frequency. A proposal developed in 2016 through collaboration in the UK GW4 network and funded at ≤4.84M by Engineering and Physical Sciences Research Council (UK) in 2017 led to the creation of complementary facilities, in Bath and Exeter, which now form part of the UK Collaboratorium for Research on Infrastructure and Cities (UKCRIC).

5. VSimulators descriptions

The machine at the University of Bath was created for

large horizontal stroke, large amplitude and low frequency motion. It combines this with projected 3-D virtual reality (VR) scenes in an environmentally-controlled chamber, and is aimed at simulating tall and supertall buildings. The machine at the University of Exeter was designed for low amplitude precision multi-axis motion with VR provided using head mounted displays (HMDs) on an open platform, and is targeted at sway and torsion in medium to high rise buildings as well as floor vibrations in all types of building.

5.1. Bath machine: description and performance envelope

The University of Bath VSimulator has been specifically designed with tall building vibration and motion in mind. It consists of a 3 m × 4 m biaxial motion platform (with the ability to also provide some torsional movement about the vertical axis) on which sits a climate-controlled room Figure 1(a).

The platform is hydraulically controlled, which was challenging due to the very low forces required to move the platform at the low accelerations required to be simulated. The platform is supported on hydrostatic bearings at each corner to minimize friction and provide a smooth horizontal movement without 'rumble' or unwanted vertical vibration. Unwanted vibrations are kept below 0.7 milli-g across the full frequency range, considerably below commonly accepted perception thresholds. The maximum movement in each horizontal direction is +/-400 mm and this provides an upper limit on maximum accelerations at lower frequencies. The performance envelope is shown in Figure 2.

This encompasses current ISO 1013 perception threshold



Figure 1. Bath VSimulator (a) for simulating tall building motion and environment and (b) concept image indicating control parameters

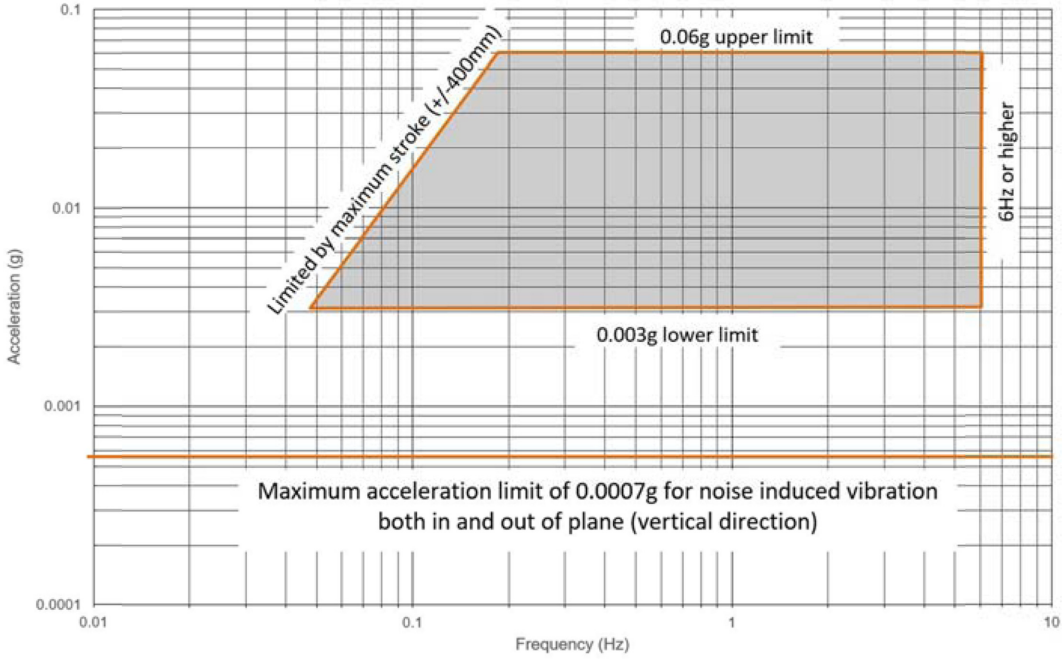


Figure 2. Performance envelope for Bath VSimulator lateral motion capability.

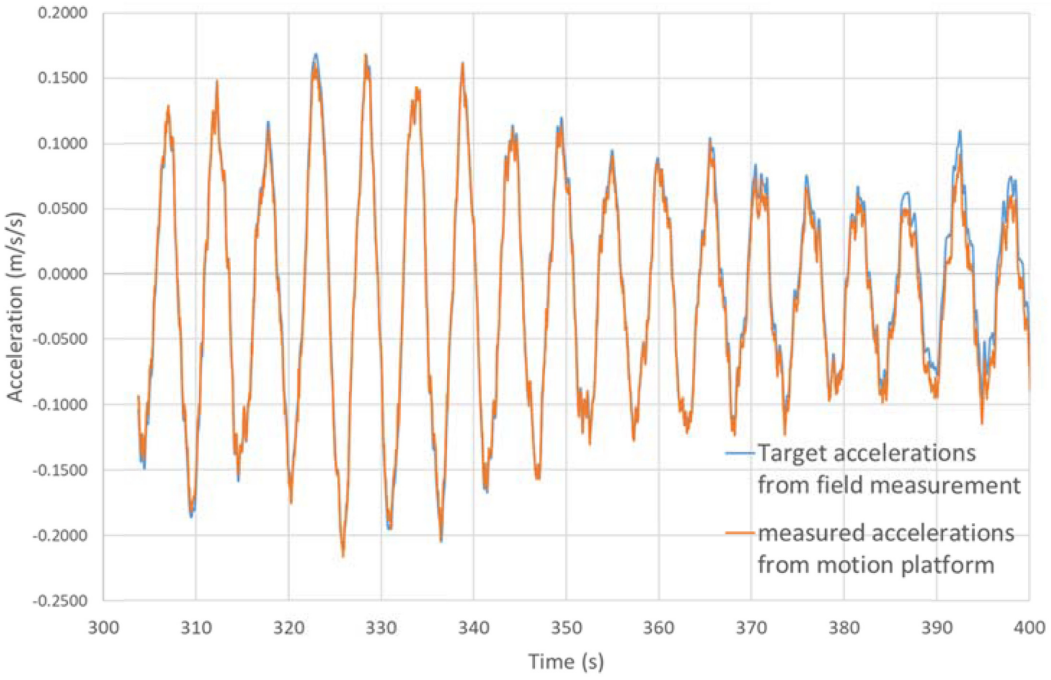


Figure 3. Example of actual (VSimulator measured) vs desired (target) accelerations.

Table1. Environmental control specification

Parameters for control	Min	Max	Tolerance	Rate of change
Air temp. (Degrees C)	15	40	1	10/half hour
Radiant temp. (Degrees C)	15	40	1	10/half hour
Relative humidity (over full temperature range)	20%	80%	5%	5%/half hour
Air Flow (m/s)	0.05	1.5	0.1	0.05/15 mins
Fresh air requirement (l/s/p)	1	10	0.5	1 / 15 mins
input SPL (Lp dB)	0	100	10	
Horizontal illuminance (lux)	50	2000	25	
Colour temp. range (K)	2000	6500	250	

limits to allow study of the effects of sway motion both above and below these thresholds. Measured or simulated representative building motion acceleration records can be accurately replayed through the platform following a calibration procedure. The two horizontal axes can be programmed to simultaneously deliver different motions, representing along- and cross- wind response in any combination within the performance envelope of the machine. An example acceleration time history is shown in Figure 3.

The environmentally controlled chamber on top of the platform is 3 m × 4 m and 2.6 m high, and provides full control of air temperature, radiant temperature, humidity, lighting intensity, lighting color temperature, air quality and air speed (Table 1 and Figure 1(b)). This allows steady state ambient conditions to be maintained, so that subjects taking part in a vibration test are not unwittingly influenced by other external factors. For instance, subjects' comfort or work performance may be affected by hotter or colder than average temperatures, which might mask the effect of any vibrations. It also allows the interaction of different environmental conditions to be examined, some of which may mitigate or exacerbate the negative effects of motion.

Internally, 3-dimensional virtual reality scenes can be projected on the walls of the chamber. This provides subjects with a sense of surroundings to provide situational context rather than simply being inside a windowless box. For example, the internal environment can be simulated as an office or apartment (see Figure 4(a)) while external views through virtual windows give a sense of height within a building, time of day, and surrounding cityscape, currently consisting of two alternative scenarios of a medium rise city with much green space, and a more densely developed high rise city, Figure 4(b). Audio stimuli are also able to be provided to simulate work-place noise or external traffic noise, for example. Motion tracking of occupants, wearing 3-D glasses, allows the correct visual perspective to be



Figure 4. Examples of a) internal (open plan office) and b) external (low rise city) Virtual Reality environments.

provided in relation to where they are in the room, as they carry out activities, but also provides the capability of full body motion tracking, allowing the biomechanical response of subjects to motion to be monitored. The advantage of projected VR compared to VR using an HMD is that occupants can carry out physical activities and interact with equipment in the real-world, rather than entirely in the virtual world. It also prevents any potential for unwanted motion sickness effects associated with HMD VR.

The facility also provides a full range of wireless physiological measurement capability, including Electrodermal Activity (EDA), Electrocardiogram (ECG) for measuring heart rate variation, chest strap for monitoring respiration, Electro myography (EMG) for measuring muscle activity (including eye blink rate and duration), triaxial accelerometers and inertial measurement units (IMUs), for measuring dynamic response of participants and Electroencephalogram (EEG) to monitor brain activity and analyse cognitive state. These sensors are crucial to the understanding of how tall building vibration physically and physiologically affects occupants, including drowsiness, changes in cognitive performance, increased stress and onset of nausea. This provides quantitative and objective measures.

Finally, the facility has developed a suite of psychological tests and simulated work tasks which provide a quantifiable insight into cognitive effort. Coupled with questionnaires (NASA-TLX, MSAQ and KSS), this enables the link to be made between physical vibration motion and other environmental factors, and the effect these have on physical and mental human response. This facility will support research aimed at developing a more comprehensive understanding of how people are affected by low-frequency wind-induced vibrations associated with the serviceability design of tall buildings.

5.2. Exeter machine: description and performance envelope

The University of Exeter VSimulator has been specifically designed to simulate vibrations in low displacement higher frequency applications, typical of those observed in structural floors, footbridges grandstands and high-rise (if not tall) builsings.

The Exeter VSimulator features a 3.7 m × 3.7 m platform designed to support a 1 tonne payload, have a natural frequency exceeding 30 Hz and movement in all six translational and rotational degrees of freedom.

The platform is an octopod, driven by rotary electric motors which move within an arc of ±45° to generate single axis translations ±21 mm. The performance specification (Figure 4) aimed to achieve controllable sinusoidal motion with a lower limit set at the ISO 10137 base curve, displacement precision at 5 micron, frequencies down to 0.5 Hz (recognizing the Bath VSimulator capability at lower frequencies), accelerations up to 2 m/s^2 (200 milli-g) which might be experienced on lively structures such as footbridges and grandstands and frequencies up to 40 Hz that might be generated by rail vehicles.

Practically, acceptance tests show the performance criteria to be largely met and usually exceeded. The performance limitations arise due to the maximum 21 mm stroke (the upper left boundary), the maximum force of the actuators (the upper limit) and the motor drive encoder precision. Although the lower by upper frequency limits are to some extent arbitrary, the characteristics of the control system (which effectively controls velocity) and the mechanical characteristics of the system result in a very heavily damped and flat rigid-body resonance above 30 Hz.

Multi-axis motion is possible subject to motor stroke limits, enabling realistic simulation of multi-axis building floor motion involving tilt and torsion, as well as multi-axis motion of footbridges (sway, torsion and vertical motion) and grandstands (vertical and 'nodding' vibration modes). The platform can be driven continuously via a multi-axis, multi-signal function generator as well as using finite duration 'drive signals'. These are generated via a script taking as input either arbitrary accelerations

generated by numerical simulations or signals acquired in situ on structures using an acceleration logger. In principle, compatible displacement and velocity signals can also be included and rotations included either via differences of translational accelerations or via gyroscope signals from inertial measurement units (IMUs).

The Exeter VSimulator motion platform occupies a room approximating an 8 m cube (Figure 3), and in its neutral state the platform level is flush with the floor so that users can walk across the floor in one direction with several strides. An array of nine 1200 mm square AMTI force plates atop the platform captures occupant ground reaction forces. Occupant behaviour is also captured using an Optitrack motion capture system with an array of cameras providing sub-mm positional accuracy of (passive) reflective markers worn by occupants. These can be attached to skin or clothes but are typically attached to a full body suit worn by one or more occupants. VR for up to nine occupants is currently provided by wired HTC VIVE Pro HMDs incorporating eye tracking. Active markers enable avatars to be tracked in VR environments. A set of stock VR environments is available, while custom environments incorporating platform motion can be created in Unity environment. A suite of body-mounted devices includes IMUs, EMGs and functional near-infrared spectroscopy (brain monitoring) to record occupant physiological response, while cognitive and work performance can be assessed using tablet computers.

Not all experiments require VR, but the possibility of HMD-induced sickness is mitigated, if not completely excluded, through ethics protocols and choice of (test subject) sample size.

6. VSimulator Pilot Studies

This section provides some initial results from research used demonstrate the potential of the capabilities of the VSimulators facility to produce new insights.

6.1. Work performance

With the commissioning of the Bath VSimulator, research is now underway to study the acceptability of wind-induced vibrations in tall buildings with a focus on impact on human experience rather than perception. As previously discussed, various factors are involved in defining acceptable levels of horizontal motion such as occupant activity, building type (office, residential, hotel), different perception thresholds for different people, motion expectancy, and habituation to motion.

Recent field studies in the area of wind-excited tall buildings have shown that wind-induced vibrations in real-life tall buildings degrade work performance of office workers and affect their wellbeing, with evidence of sopite syndrome symptoms (Lamb et al., 2014; Lamb & Kwok, 2019). Nevertheless, in these studies, motion characteristics (acceleration, frequency, duration of exposure, and direction), and participant factors (pre-exposure to motion) are not able to be controlled. The most recent study using the Bath VSimulator has been aimed at exploring the effects of simulated wind-induced vibrations on work performance and incidence of onset of sopite syndrome in research participants under fully controlled motion conditions and participant factors.

Rather than use sinusoidal type motion, the tests used realistic simulated random motion signals. These were numerically generated with specific characteristics for peak acceleration, frequency and peak factors, and representing both along- and cross-wind motion. Three peak accelerations; 3 milli-g (generally below perception threshold), 6.5 milli-g, and 10 milli-g (clearly perceptible for all participants), and two natural frequencies (0.5 and 0.2 Hz, representing tall and super-tall buildings respectively), and up to 140-minute duration of exposure to motion were considered to generate different motion conditions.

It should be noted that preliminary tests were carried out with a peak acceleration of 12 milli-g which is below that deemed acceptable for some design guidelines, but after two participants independently felt symptoms of nausea to the extent that they requested the tests to stop, the highest acceleration record was reduced to a peak of 10 milli-g.

Motion signals in the along-wind direction were simulated using the spectral representation method for multi-degree-of-freedom systems (Shinozuka & Deodatis, 1991). This simulates the fluctuating wind velocity and wind force time histories which are then applied to structural models to create modal acceleration time histories. Wind-induced vibrations in the crosswind direction were simulated based on the method proposed by (Gu & Quan, 2004) which uses wind force spectra obtained from wind tunnel tests. The physical displacement response time histories of the structures were calculated using the Newmark method.

Using the VSimulator allowed physical simulation of the full range of bi-directional motions, even at the sub-perceptible level of 3 milli-g. A virtual reality projection on the VSimulator's internal walls was used to provide a sense of interior surroundings of an office environment and external views at upper floors of a tall building. In all motion conditions, the VSimulator's environmental chamber maintained the indoor air parameters within the generally accepted comfort range for an office environment i.e. temperature between 20°C and 22°C (ASHRAE, 2017), relative humidity at 50%, and CO_2 level below 1000 ppm (ASHRAE, 2001).

Cognitive work performance in all motion conditions was assessed psychologically by developing and programming a set of cognitive tests in a visual interactive software, PsychoPy v2020 (Bouzit & Pierre, n.d.). A set of eight tests were designed to explore four different cognitive aspects; attention, memory, executive function and simulated work activities. For each test, the cognitive effort was defined as the time taken to complete the test divided by



Figure 5. Exeter VSimulator, chamber (left) and octopod setup (right).

the accuracy of the response, such that a higher score indicated worse overall performance.

Twenty-one test subjects were subjected to seven motion conditions (the three different peak accelerations each at the two different natural frequencies, and a control, no motion, condition). Each condition was experienced for around 20 minutes during which the subject was asked to complete the cognitive tests and respond to questionnaires, all while being monitored for blink rate and duration. The motion conditions were randomised in order to account for learning effects over the course of the tests over the whole group of subjects.

The initial results show that, compared to the control condition, the effort score increased (i.e., performance reduced) as acceleration amplitude increased. As an example, Figure 5 shows increases in the scores of the executive function aspect of cognition with respect to increases in peak acceleration magnitudes from 0 to 10 milli-g. It is also seen that for higher frequency of motion, the performance is consistently worse than at the lower frequency. Subjective measures of work performance, i.e. self-reported performance and subjective effort derived from NASA TLX (Task Load Index) questionnaires assessed via 7-point Likert scales, showed agreement with the objective cognitive performance measures, demonstrating a clear trend in subjective scores due to increases in acceleration and frequency magnitudes.

6.2. Sopite syndrome

A second test was carried out to investigate the onset of sopite syndrome. This was assessed objectively though electrooculography as a physiological measurement. Figure 6 shows participants wired with electrodes attached to the electrooculogram used to measure participants' eye blink duration. This is an indicator for the occurrence of drowsiness, a principal indicator of sopite syndrome (Matsangas et al., 2014), i.e., longer blink duration indicates increased tiredness.

Two test groups of 10 participants each were created. One set (the control group) was subject to no motion, while the second set was subject to sub-perception threshold motion (with a peak acceleration of 3 milli-g). Subjects were exposed to the motion (or no motion for the control group) for a 2 hour period, with eye blinks recorded for

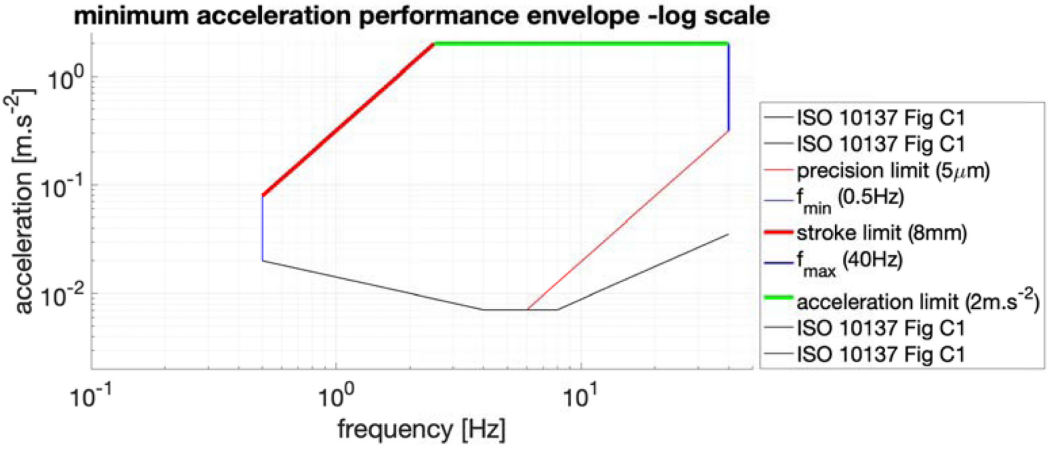


Figure 6. Performance envelope for Exeter VSimulator, single axis translational axis.

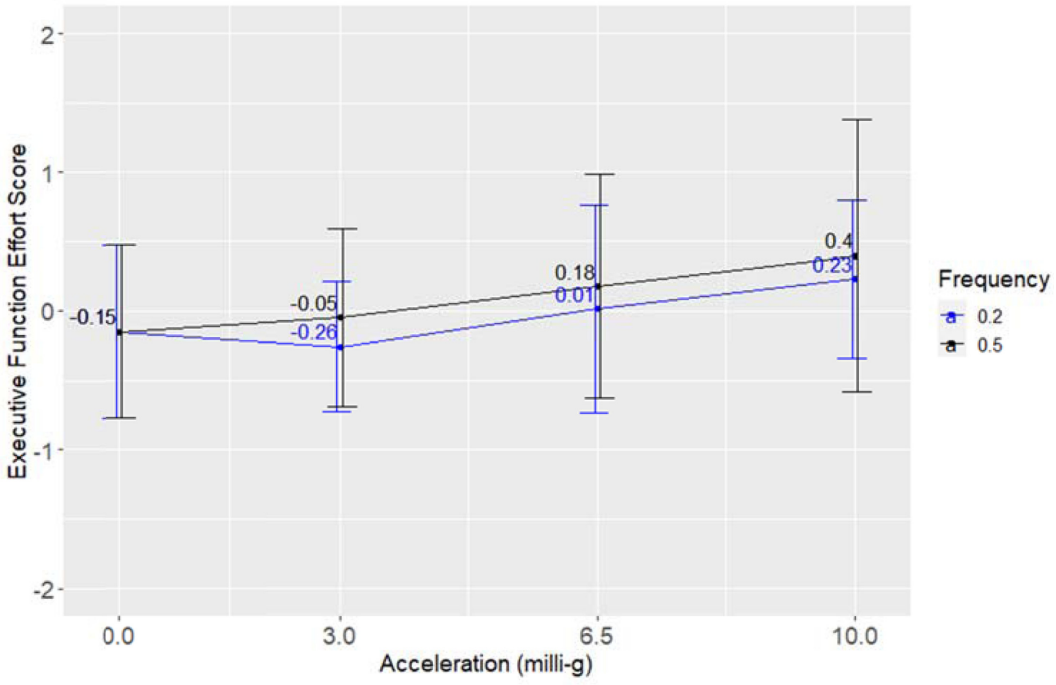


Figure 7. Executive function effort score at different acceleration and frequency magnitudes.

100 minutes and analysed using BIOPAC Student Lab software. The results show that the average blink duration for participants who experienced vibration was significantly higher than for those who did not (the control group). The set of cognitive tests was carried out at the start and end of the session and, as seen in Figure 7, the executive function effort significantly increased in the motion group whereas, it slightly reduced in the control group (no vibrations). These quantitative findings were further corroborated by the self-reported results of a Karolinska Sleepiness Scale questionnaire KSS (Shahid et al., 2011), showing increased feelings of drowsiness for those experiencing motion.

During all tests, further questionnaires were used to assess comfort and wellbeing. The results presented here are indicative of how different experimental approaches can be used and combined to give a greater insight. Full results, analyses and discussion are presented elsewhere, including fully by Heshmati (2022).

6.3. Balance and Risk of falls

In the UK, 10% of the high-rise occupants are aged 65+ (National Statistics, 2020). Amongst this population, particularly for those with a balance disorder, falling is a major health risk, causing serious injuries, long hospitalization and even death. There is evidence in the literature that wind-induced tall-building vibrations, characterized by low-frequency and large displacement amplitudes, can significantly challenge the human motor control system (Burton et al., 2015; McAndrew et al., 2010, 2011; Nawayseh & Griffin, 2006). Despite such evidence, our understanding of the effects of wind-induced vibrations on human balance and risk of falls is conspicuously limited. If the effects of wind-induced vibrations on risk of falls in vulnerable populations is meaningfully significant, it must be considered as part of the 'acceptability' criteria for vibration serviceability assessment of tall buildings.

To examine this, two sets of experiments were designed, initially on healthy young subjects, to analyze the effects of tall-building vibrations on a) the sensory system i.e., visual, vestibular, somatosensory and proprioception; b) the central nervous system, including loss of concentration, overload, reduction in cognitive performance, and drowsiness and c) their subsequent effects on balance strategies, performance, and reaction time.

A series of physical tasks representing activities of daily living, inspired by established clinical balance tests such as MiniBestTest (Franchignoni et al., 2010) and Berg Balance Scale (Berg, 1989), was designed to assess subject's balance with or without vibrations. The assumption was that presence of vibration can negatively affect the balance metrics (e.g., reaction time, displacement of body center of mass during standing still, step length and width, etc.) through affecting the sensory-motor system as well as occupying some of the resources otherwise available to the motor control system to maintain balance. A set of bi-directional numerically generated vibration signals representing both along- and cross-wind motion with peak accelerations between 5-10 milli-g and two natural frequencies (0.5 and 0.2 Hz) were used to drive the motion platform. The 3D virtual reality system was used to simulate the internal environment of an apartment



Figure 8. Use of Electrooculogram in VSimulator.

flat on top of a high rise. A motion capture system was used to measure subjects' kinematics and physical reaction time synched with the base vibrations. After each test, the subjective assessment of subjects from their performance, vibration experienced, and how challenging the test was, were obtained via a purposefully designed questionnaire. The results were subsequently translated into z-scores for comparison.

Tests unanimously showed an increasing trend in level of difficulty and marked reduction in balance performance, as the peak acceleration increased from 0 to 10 milli-g (Figure 8).

The results of the cognitive tests also confirm that wind-induced vibrations can create dizziness, fatigue, and drowsiness and can reduce concentration, all adversely affecting the ability to maintain balance.

A combination of anticipatory (proactive) and reactive balance strategies are used to maintain balance, which heavily rely on sensory inputs. The results of these tests further showed that subjects were mostly unable to determine reliably the direction, magnitude, and frequency of the bidirectional vibrations up to 10 milli-g. Such uncertainty is shown to increase the neural and physical load of maintaining balance (Mills & Sveistrup, 2018).

6.4. Exeter VSimulator

The majority applications of the Exeter VSimulator to

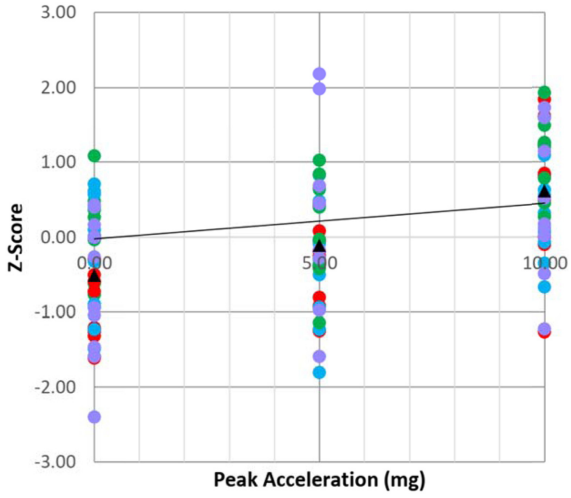


Figure 10. z-score of balance difficulty - all tests combined.

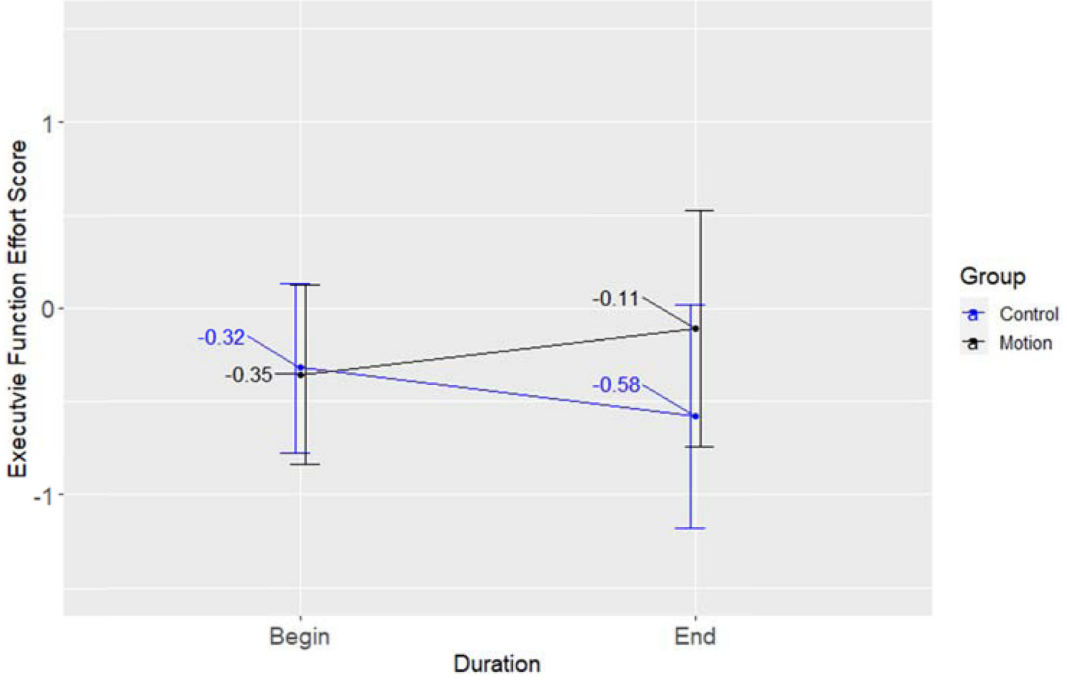


Figure 9. Executive function effort score during longer term exposure to motion.

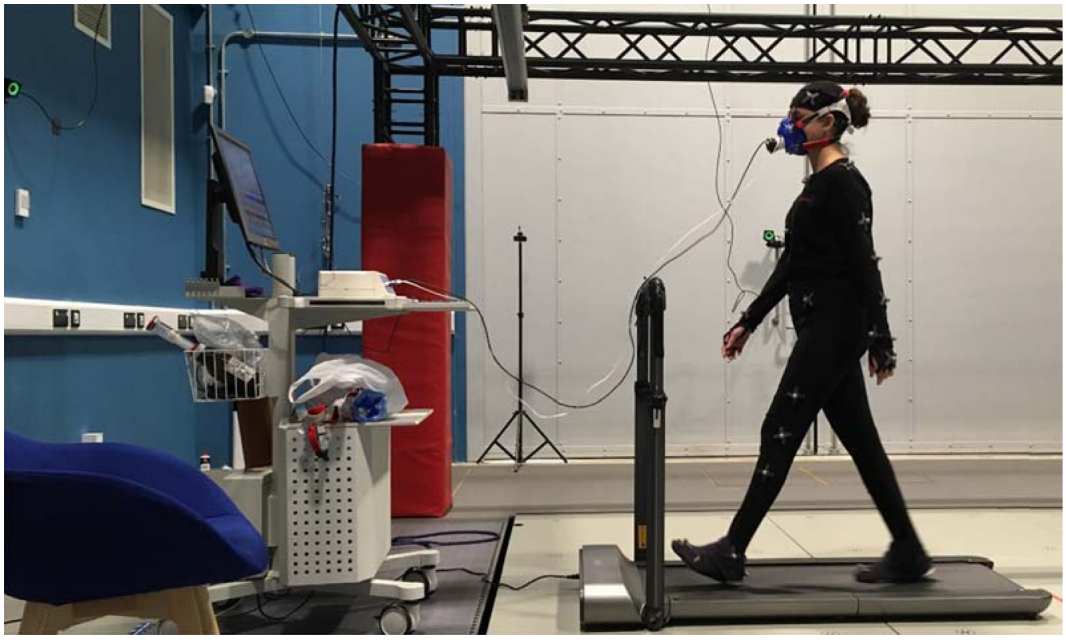


Figure 11. Facilities for motion capture and physiological response measurement.

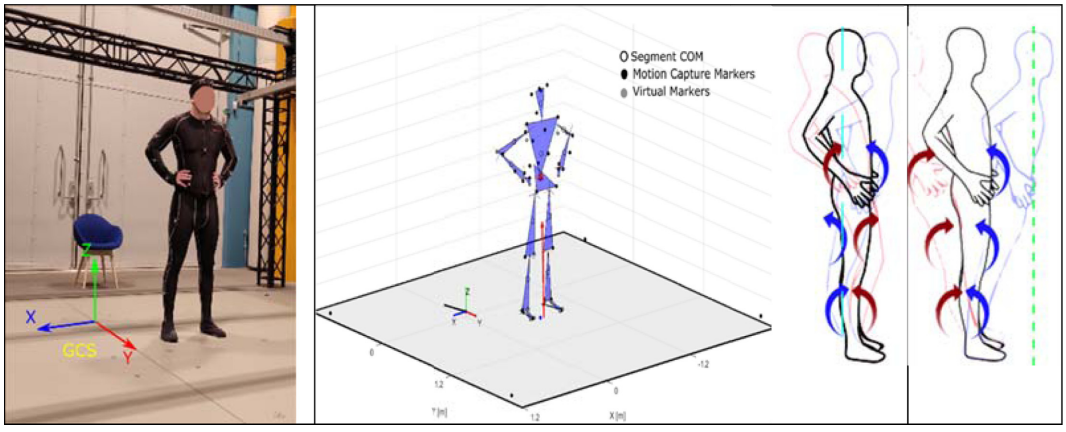


Figure 12. Balance studies on the Exeter VSimulator.

date have been for research on medical conditions in which gait and stability are a factor, such as Parkinson's disease and Meniere's disease. Projects have linked research in disciplines of human movement science and civil engineering through studies on human balance on swaying surfaces and human-structure interaction with both horizonal and vertical structural motion. An example of the latter, for vertical motion, is shown in in Figure 9, where respiration is monitored, with full-body motion capture and ground reaction force measurement (Zhang et al., 2023). The black frame structure provides emergency support to mitigate risk of falling of test subjects due to frailty or strong acceleration.

The Exeter VSimulator has also been used for research on balance mechanisms (Taleshi et al., 2022). Figure 10 shows the test subject, who is exposed to anterior-posterior motion with 2 mm amplitude sweeping from 0.4-6 Hz and uses a combination of ankle, knee and hip muscles to maintain balance. It is found that increasing sway frequency above ~2 Hz, corresponding to 32 milli-g, results in a switch from an 'ankle strategy with rigid legs to a 'knee strategy' with bent knees.

As with the Newfoundland ship's bridge simulator, the Exeter VSimulator is used to expose structural consultants to consequences of their tall building design decisions. In particular cross-laminated timber is increasingly popular in construction of high-rise buildings, not only for floors, but also vertical systems. As there is little data available on full-scale performance, recent project DYNA-TTB (dynattb.com) included a work package on in-situ measurements.

These have included instrumentation and modal testing of the 85 m Norwegian Mjøstårnet wood hotel (https://www.ctbuh.org/buildings-of-distinction/mjostarnet) and of the seven-storey Yoker residential block (Kurent et al.,

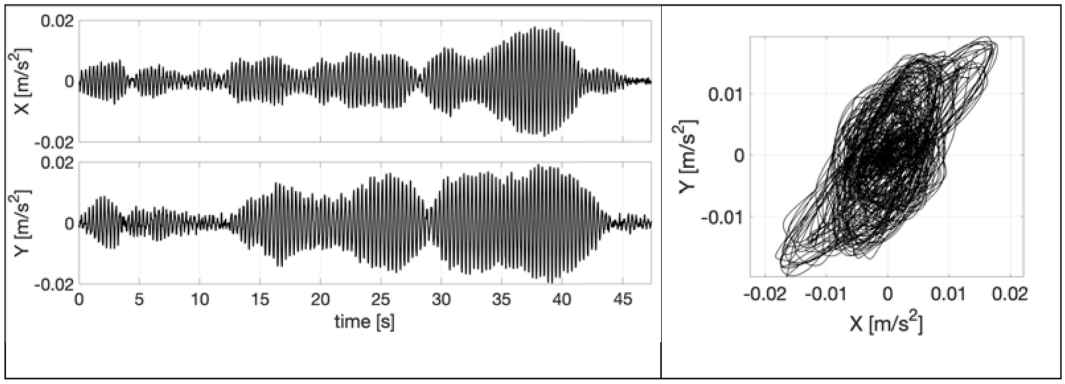


Figure 13. Sample Yoker building acceleration signals for Exeter VSimulators demonstrations, with peak levels ~2milli-g.

2021) situated on the north bank of the River Clyde, northeast of Glasgow. Yoker building has a cluster of four vibration modes in the range 2.8-3.7 Hz with mode shapes having similar horizontal variation, and is noted for its perceptible wind-induced response. Figure 11 is a short sample of monitored response, comprising components in two of the vibration modes in both horizontal axes, used for purpose of demonstration to structural wood specialists. Such signals can be directly scaled to represent response to stronger winds. The specialists who experienced this motion commented that motion they experienced was perceptible but not annoying.

7. Conclusions

Acceptability of vibration motion in tall buildings has traditionally been linked in some way to perception thresholds. This paper has clearly outlined the known limitations of this approach and sought to describe a more nuanced but rational approach where objective human experience of vibrations is put at the centre of acceptance criteria. It is not whether a vibration can be perceived but the affect that the vibration has on an individual, whether perceptible or not, in terms of comfort, well-being and ability to carry out activities, cognitive or physical. As such there needs to be a fundamental shift in emphasis for developing rational design criteria, which requires a new, holistic research approaches.

The VSimulator facilities at the Universities of Bath and Exeter represent the next generation of motion simulation capability, building on previous experience, to improve understanding of the effects of building motion on human occupants. The aim is to leverage the capabilities to improve guidance through a holistic approach to motion simulation including a wide range of influencing factors along with comprehensive tools to quantify the effects on human subjects, both subjective and objective.

Pilot tests using the Bath VSimulator have begun to use this capability to examine the effect of tall building sway on work performance and the onset of sopite syndrome. Initial findings reveal a clear increase in cognitive effort (and reduction in performance) even at the lowest levels of vibration. This effort increases with larger amplitude and higher frequencies of vibration, with both objective performance measurements and subjective self-reported performance in agreement. Furthermore, longer term exposure to sub-perception level vibrations also appears to result in increased tiredness and reduction in performance, aligning with theories surrounding sopite syndrome. While these preliminary studies alone do not provide a definitive metric or firm conclusions by which design can be carried out, it does indicate the negative effects that vibration has on occupants even at levels which are well below most current design criteria. VSimulators provides a means by which this can be explored further.

It is clear that this is just the start of future studies in this area. With tall buildings being designed and built in an age where climate change, sustainability, resilience, regenerative design, staff well-being, business and financial pressures all compete, there is a clear need for vibration serviceability design criteria which are based on a new set of metrics which stem from user experience.

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