Human factors simulation for motion and serviceability in the built environment

James Mark William Brownjohn[1*], Antony Darby[2]
[1]University of Exeter, UK, [2]University of Bath, UK
[*] j.brownjohn@exeter.ac.uk

INTRODUCTION

The to-site VSimulators facility at the Universities of Bath and Exeter will provide simulation capability that is worldwide unique and far beyond anything available in the UK, to address critical issues of human engagement with the built environment. The two sites will share a common mission: to enable fundamental and applied research into human interactions in and with moving civil structures with potential to transform research methods across a wide range of disciplines. Between them the two simulators will provide motion capabilities in all axes across a wide range of amplitudes and frequencies. However, unlike any other facility, VSimulators will also simulate the effects of the full range of environmental, motion, audio and visual cues in real-world settings on humans whose reactions and interactions will be recorded by a full spectrum of instrumentation.

VSimulators comprises a low frequency, large amplitude biaxial platform at Bath, with wall-projected stereoscopic Virtual Reality displays and an array of precise environmental controls and physiological instrumentation. This is mainly aimed at investigating human response to motion in tall buildings. The complimentary Exeter facility is aimed at mid-high frequency motion in six degrees of freedom from micron to cm level motion and is aimed at floors, stadia, footbridges, as well as health, sports and physiology applications. At the time of the conference the Bath facility is coming on stream while construction for the larger Exeter facility will have begun. The paper describes the facilities and their applications.

MOTIVATION

The overriding need for this equipment stems from the chronic lack of understanding of the way humans experience and react to motion within the built environment, including tall buildings, floors and grandstands. This impacts upon national and international economy, health and policy. The construction industry is worth £90bn to the UK economy, with UK contractors and engineering consultants involved in major projects worldwide. The UK has led the world in vibration serviceability, boasting the first footbridge vibration serviceability design guideline and world-leading design guidelines for vibration serviceability of grandstands and floors. However, the multiplicity of (contradictory) acceptance standards and the consequential withdrawal of guidance from the key international standard ISO 2631-2 leaves designers with uncertainty resulting in structures not fit for purpose. The feedback from structural engineering consultants is that these standards are completely inadequate to properly address the actual experience of humans and there is a disconnect between current standards and reality. Psychology and physiology, therefore, are just as important as structural behaviour in enabling design for, and mitigation of, structural vibrations and motion. There is a tremendous opportunity for VSimulators to directly address this issue. Hence VSimulators are much more than motion simulation and have applications far beyond civil structural engineering.

The Institution of Structural Engineers' 2015 survey of its 27,000 members worldwide revealed that 49% had experienced vibration serviceability problems, with 23% receiving complaints over human comfort to code compliant designs. This leads to long delays and associated costs in building handover, loss of tenants, expensive remedial measures, legal action and general loss of confidence. Tall building experts claim "this issue of the acceleration response and habitability performance of tall buildings can cost firms millions" and that the issue of human comfort "will continue to dominate the design process not just for signature super-tall buildings, but even for more conventional high rises as we move toward more lightweight and efficient systems". It's worth noting the current high-rise boom in London with 400+ tall buildings planned until 2030.

VSIMULATORS AT BATH & EXETER

The VSimulators facility consists of two machines at two sites providing complementary performance but with a degree of overlap. The Exeter machine will have 6-axis capability with relatively small movement (a few cm) at frequencies from 0.5 Hz or lower to 40 Hz, while the Bath machine will have ±400 mm motion in the two horizontal axis and operate from 0.05 Hz to 6 Hz or higher.

Design performance envelopes

Minimum capabilities for the two machines will be complementary as shown in Figure 1 and Figure 2.

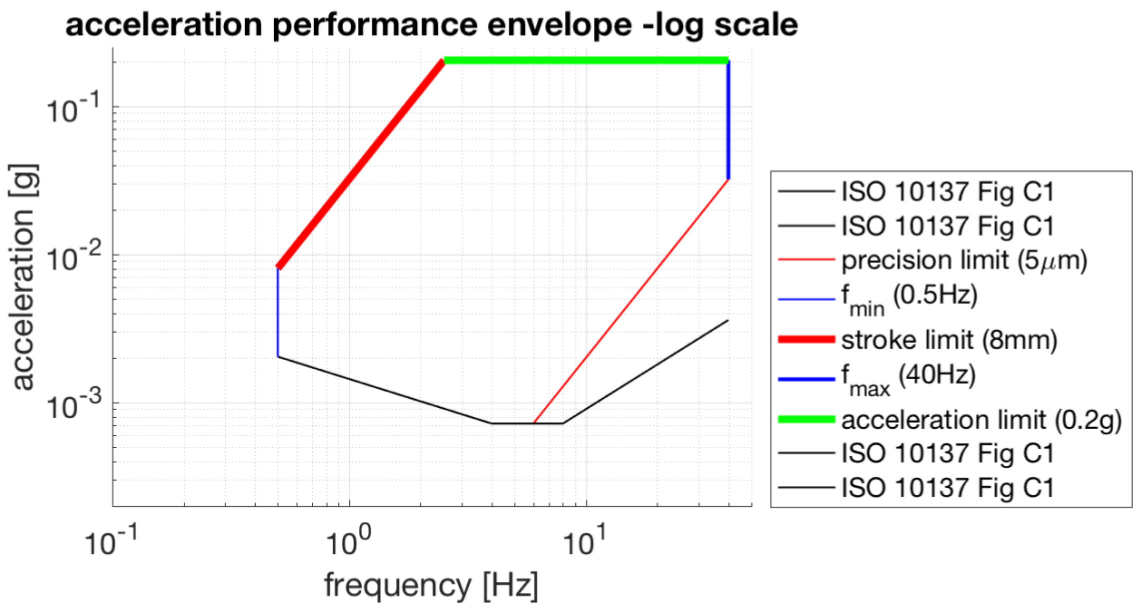

Figure 1: VSimulators@Exeter performance envelope -high frequency/small displacement

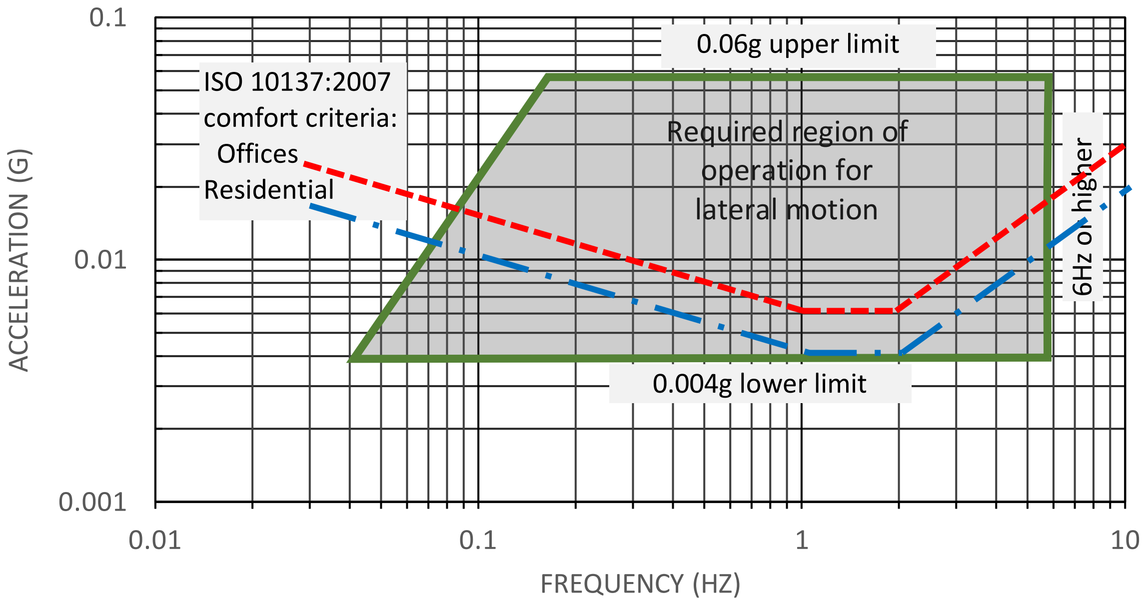

Figure 2: VSimulators@Bath performance envelope -low frequency/large displacement

The aim is to explore user comfort criteria using ISO10137 as the basis. VSimulators@Bath (VS@B) is primarily intended to study occupant comfort in tall building due to the low frequency capability, while VSimulators@Exeter (VS@E) is intended to operate at higher frequencies, which translates to micron-level displacements at the high-frequency/low acceleration corner of the envelope. Realisation of these specifications requires different forms and configurations of platforms and actuator systems.

VS@B uses four conventional hydraulic actuators and a 3 m x 4 m platform supported on hydrostatic bearings. The platform will support a carefully environmentally controlled (radiant and air temperature, lighting intensity and colour, humidity, sound, air quality) 2.5 m tall room, with stereoscopic projected virtual reality (VR) of internal and external environment. Full wireless biosensors will track GSR, ECG, pulse, eye tracking, pressure, head motion. These physiological responses will be linked to observed psychological behaviour to provide objective indication of acceptability and comfort of humans subjected to motion in different environments and surroundings.

The specification of VS@E is very strongly driven by the high frequency performance requirement. Hence a high-rigidity 4 m x 4 m platform will be mounted on an octopod comprising rotary motors and possible air bearing support for dead load. The platform will usually be open (no walls) with visual context provided using VR head-mounted displays (HMDs). Full optical motion capture and a 3.6 m x 3.6 m array of force plates will record interactions of up to nine users with both the platform motion and each other. The VS@E equipment will be housed in a an 8 m cube, and climate and environmental control will be coarse and limited, with the possibility to build a small climate controlled room for specific studies at the low frequency end of the performance envelope.

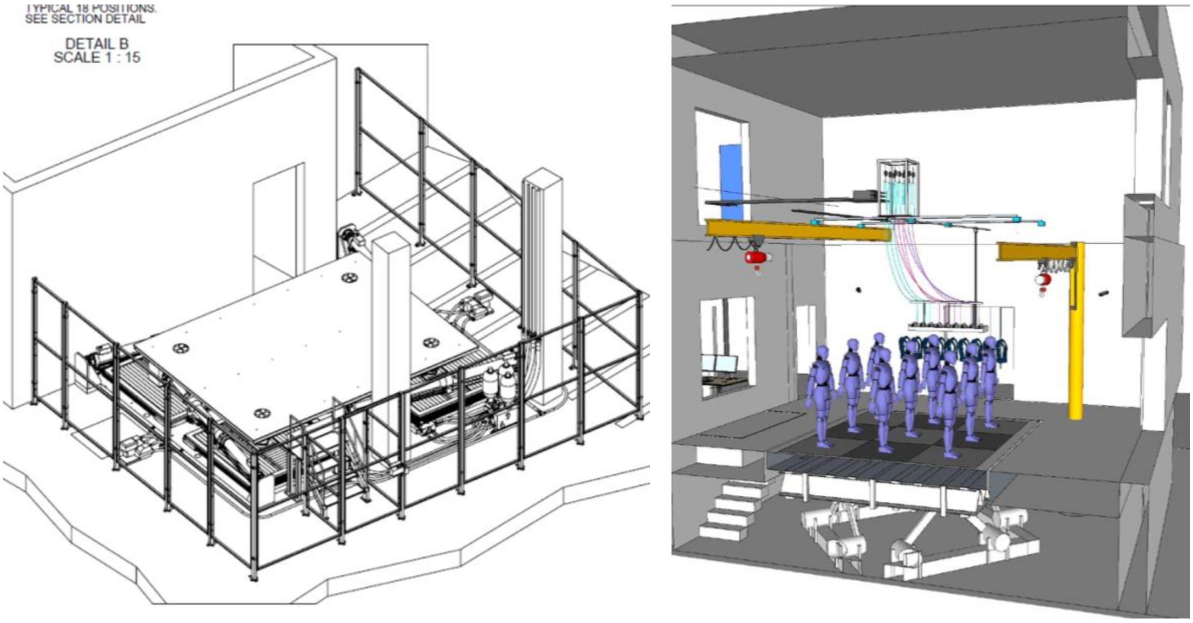

Figure 3: Bath (left) and Exeter (right) simulators

Virtual reality (VR) and human movement

The two machines will use different approaches to VR.

VS@B will create a multiwall, projected environment using ultra short throw projectors to represent building external environments (Figure 4 left), the traditional approach for facilities such as at the Centre for Marine Simulation at St John’s Newfoundland, as well as extended internal environments, such as an open plan office or residential apartment. The chamber will typically have a single occupant whose movement in the space will be tracked allowing the correct perspective to be achieved. Both monoscopic and stereoscopic projection can be applied, the latter requiring 3D glasses.

VS@E will primarily use head mounted displays (HMDs). Up to nine occupants can use the space simultaneously e.g. for simulating grandstand environments, although the usual requirement will be for one or two users, such as for the infinite footbridge (Figure 4 right). For low latency and high resolution the present state of the art requires wired HMDs. Full motion capture of up to nine occupants will be achieved by an array of cameras positioned above the platform and fixed rigidly to the building foundation. Three stock VR environments have been created: a football stadium (simulating spectator interaction with each other and flexible grandstand), a busy office (with a floor that vibrates while virtual colleagues walk past) and a footbridge which will use treadmill arrangements to study effects of vertical and lateral motion and the effects of other bridge users. The rotational capabilities of VS@E will complement VS@B building studies by introducing the element of rotation, allowing the effect of moving horizon to be simulated.

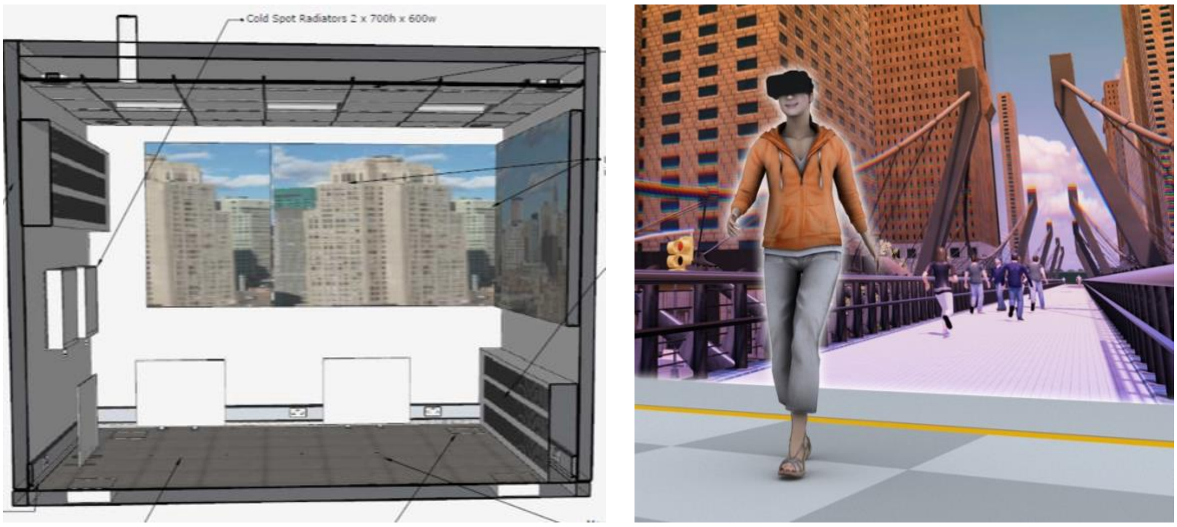

Figure 4: Virtual reality (left) of tall building view for VS@B using projectors and (right) for infinite footbridge at VS@E using HMDs.

RESEARCH ENABLED

The research team have lined up the following immediate projects**:**

Tall building motion, active and passive countermeasures: According to Prof Kenny Kwok, *"Due to the subjective nature of human perception of vibration and tolerance to wind-induced tall building vibration, there are currently no internationally accepted occupant comfort serviceability criteria". Perception* thresholds do not correspond to *acceptability*, which depends on factors such as environment and expectation. There is a very clear need for a research programme to provide guidance. There is also potential for non-structural counter-measures whose mitigating effects are best explored using a facility that includes a full range of environmental stimuli and comprehensive VR capability. Kwok also says *"multi -axis motion (including roll, pitch and yaw) is believed to be a factor [on occupant comfort and wellness] and has never been systematically investigated".*

Sopite syndrome: Factors leading to sopite syndrome (a form of motion sickness related to subconscious motion perception) are not understood, and while it is known to be induced by low frequency building sway, it may occur with motion in other axes. It is certainly exacerbated by poor environmental conditions and when people are tired or unwell and there is evidence of a strong link to sick building syndrome. Advised by Kwok and his team who discovered sopite syndrome in tall buildings, VSimulators will enable the first rigorous investigation in building environments.

Human-human and human-structure interactions (HSI): Interactions of the kind that occurred at the London Millennium Bridge still occur in footbridges, grandstands and other lively structures and have significant impact on structural behaviour, user comfort and safety. VSimulators will investigate the interactions between structures and users which have positive or negative effects leading to improved structural efficiency, safety and comfort. VSimulators will be used to explore effects of a wide range of other sensory feedback on interactions that can lead to excessive vibrations. There is transformative potential through linking with groups researching movement science.

Other possible topics include

- Control strategies for human balance on dynamically responsive structures;
- Linking computer simulation of structure response to laboratory motion perception studies;
- Agent-based modelling of groups or crowds interacting dynamically with lively structures;
- Effects of sway, oscillations, and locomotion on object holding and carrying ability;
- Cross-validating motion simulator studies with data from full-scale measurements;
- Occupant comfort for large amplitudes at extreme low frequencies of super-tall buildings.