2019 Conference
Earthquake risk and engineering towards a resilient world
9-10 September 2019, Greenwich, London

VSIMULATORS: HUMAN FACTORS SIMULATION FOR MOTION AND SERVICEABILITY IN THE BUILT ENVIRONMENT

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Abstract: *The two-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 a full range of environmental, motion, audio and visual cues in real-world settings. In addition to research on civil infrastructure, the facility has uses in a wide range of disciplines including healthcare.*

Introduction

The VSimulators facility at the Universities of Exeter and Bath*, funded by a £4.8m EPSRC grant and considerable institutional investment,* 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 *dual site facility has a* 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 within and beyond engineering. Between them the two simulators provide motion capabilities in all axes and in a frequency range covering serviceability-level operational vibrations in all possible types of civil structure. 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.

The Bath facility comprises a low frequency large amplitude biaxial platform, with wall-projected video and an array of environmental controls and physiological instrumentation. The complementary Exeter facility is aimed at mid-high frequency motion in six degrees of freedom from μm to cm level motion and is aimed at floors, stadia, footbridges. The Bath facility is expected to be operational in September 2019, the Exeter facility in December 2019.

Motivation

VSimulators aims to address the chronic lack of understanding of the way humans experience and react to motion within the built environment, including tall buildings, floors and grandstands. 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 withdrawal of specific guidance from the key international standard ISO 2631-2 promotes uncertainty in management of structures not fit for purpose. Structural engineering consultants describe existing standards as completely inadequate to properly address the actual experience of humans and there is a disconnect between current standards and reality. Psychology and physiology are just as important as structural behaviour in enabling design for, and mitigation of, structural vibrations and motion providing a tremendous opportunity for VSimulators to directly address this issue. The Institution of Structural Engineers' 2015 survey of its 27,000 members worldwide revealed that 49% had experienced vibration serviceability problems, with 23%

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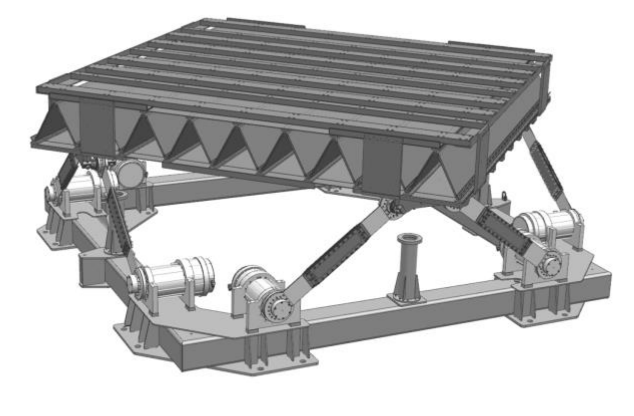
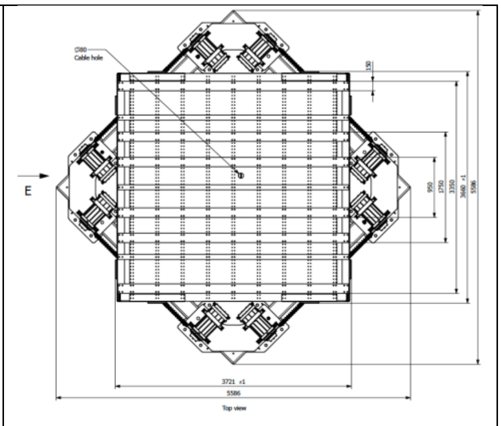
receiving complaints over human comfort to code compliant designs. This leads to long delays and associated costs in building handover, loss of tenants, expensive remedial measures, legal action and general loss of confidence. Tall building experts claim “this issue of the acceleration response and habitability 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. In 2019 there are already 20 buildings taller than 150m with 13 more under construction including the 278m 22 Bishopsgate. Worldwide, in China 30 ‘supertall’ buildings higher than 300m will be completed in 2019. For such structures wind-induced displacement largely controls design, through effects on cladding and occupant comfort. Meanwhile, footbridges are still designed that have vibration serviceability issues, huge numbers of floors in buildings are uncomfortable and even unserviceable for occupants, and users and public entertainment facilities regularly experience excessive vibrations due to audience participation presenting safety issues. Managing vibration serviceability in new and retrofitted structures requires an understanding of human tolerance and the environmental factors that bear on it, and such understanding is presently missing.

VSimulators at Exeter

Figure 1 shows the ‘octocrank’ motion platform and its design performance limits.





System performance

	Excursions single DOF			Velocity		Acceleration	
Surge	-0.021	0.021	m	0.3	m/s	2	m/s2
Sway	-0.021	0.021	m	0.3	m/s	2	m/s2
Heave	-0.021	0.021	m	0.3	m/s	2	m/s2
Roll	-0.7	0.7	deg	10	deg/s	80	deg/s2
Pitch	-0.7	0.7	deg	10	deg/s	80	deg/s2
Yaw	-0.4	0.4	deg	7	deg/s	80	deg/s2

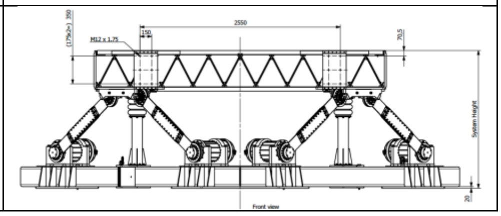


Figure 1: VSimulators@Exeter motion platform.

The displacement ranges are deliberately relatively small, consistent with the small levels of displacement associated with vibration serviceability problems other than for tall buildings with natural frequencies below 0.5Hz, which is the (design) low frequency limit for the platform. The platform is designed to accommodate movements down to the lower threshold of perception at frequencies up to 40Hz, and it is the high frequency requirement that is particularly challenging for two reasons.

The outline specification required a 4m x 4m platform carrying a one tonne payload on an array of nine 85kg 1.2m square AMTI force plates. Maintaining a first mode frequency of the platform and force plates in excess of 40Hz, and able to control platform deformation to support distortion limit of the force plates required careful design, leading to a deep, stiff and massive structure (Figure 1). The first mode shape (a rigid platform roll at 56Hz) and deformation for 1t load at the centre of the platform are shown in Figure 2. In the final design, the motion platform has square dimension 3721mm to achieve the required performance. Due to the high specification it is intended to keep the platform bare of walls and other sub-structures that would not be able to reflect reality with the platform moving at high frequencies and amplitudes, but it is possible that an enclosure could be built around the platform on the surrounding platform.

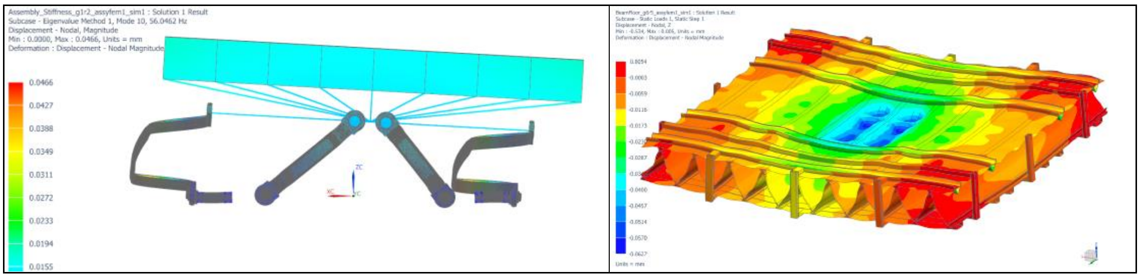


Figure 2: Platform first mode frequency and deformation due to 1t load at the centre pf the platform.

The design performance envelope aimed to reach the lower limits of the ISO 10137 comfort curve between 0.5Hz and 40Hz, with maximum acceleration 2m/s^2, subject to actuator stroke limit. The design envelope and the achievable performance (based on preliminary experiments with the actuator and control system) are shown in Figure 3.

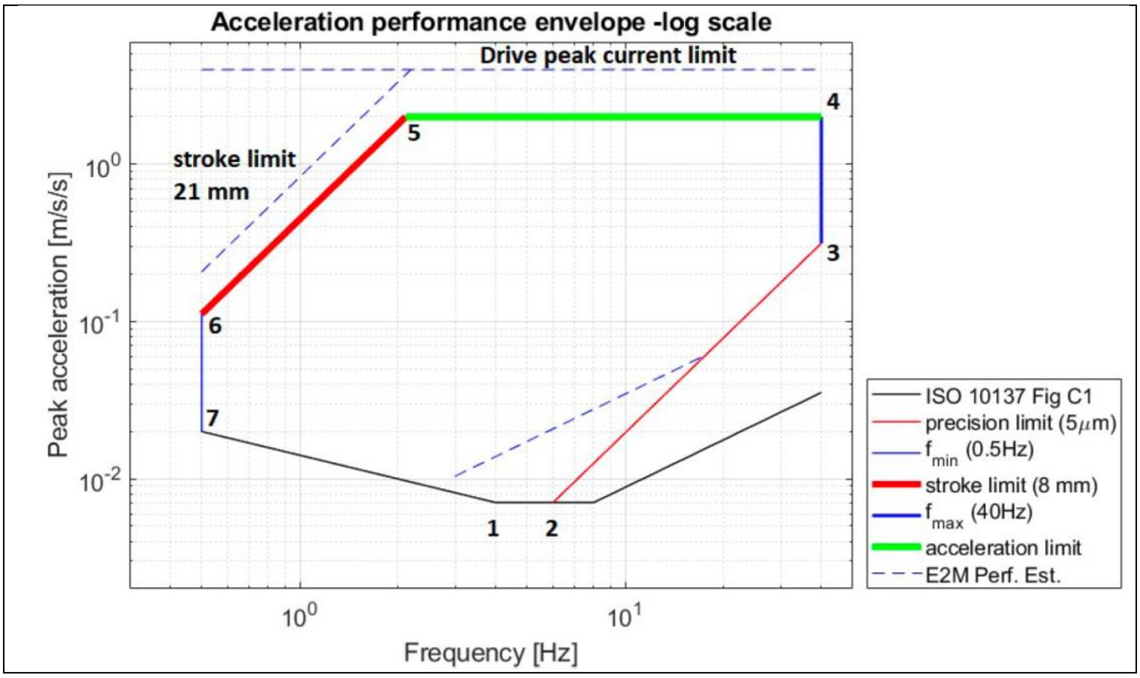


Figure 3: Vsimulators@Exeter performance envelope -high frequency/small displacement

The actuators are rotary electric motors with primary control on velocity, and needing a minimum 20 encoder steps from peak to peak in sinusoidal oscillation for proper tracking of the velocity setpoint, with bit-level resolution ~0.1mm/s. This constrains the performance at points 1 and 2 in Figure 3 as converted to acceleration. The lower corner of the ISO envelope as envisaged in the red line, relating to a desired displacement resolution of 5 micron was always expected to be the most challenging requirement.

Simulated capability to reproduce operational vibrations has been explored with a sample of drive files obtained from live measurements on: two very lively long span footbridges (sway and vertical), a 280m skyscraper (sway), floors in a hospital and in a disk drive plant (vertical), a remote offshore lighthouse (sway) and a train (Exeter-Paddington HST125).

Figure 4 is the recording for a footbridge exhibiting synchronous lateral excitation (red line) at a sway frequency around 1Hz. The signal is reproduced perfectly and perfectly suits the simulator capability. Figure 5 is for the microdrive plant, which uses ‘high frequency’ floors and for which the vibration serviceability is not human perception but the more demanding requirements of precision manufacturing equipment. This exercises the high frequency capability at low amplitude, but the signal appears to be reproduced almost perfectly. The lighthouse (Wolf Rock) signal Figure 6, which has earthquake-level acceleration, is also no problem for the simulator.

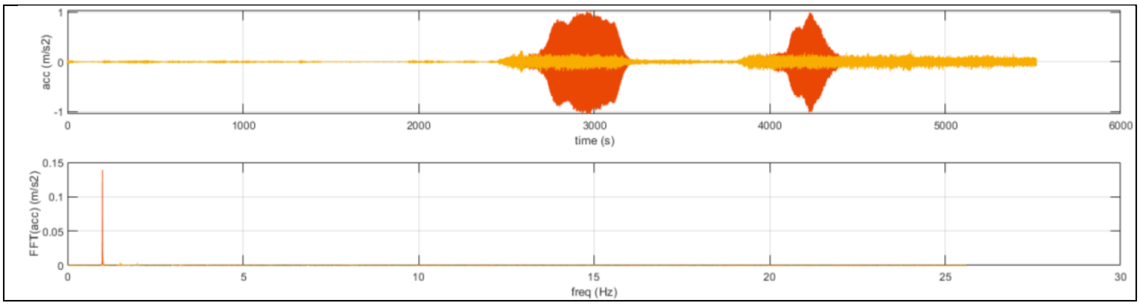


Figure 4: footbridge

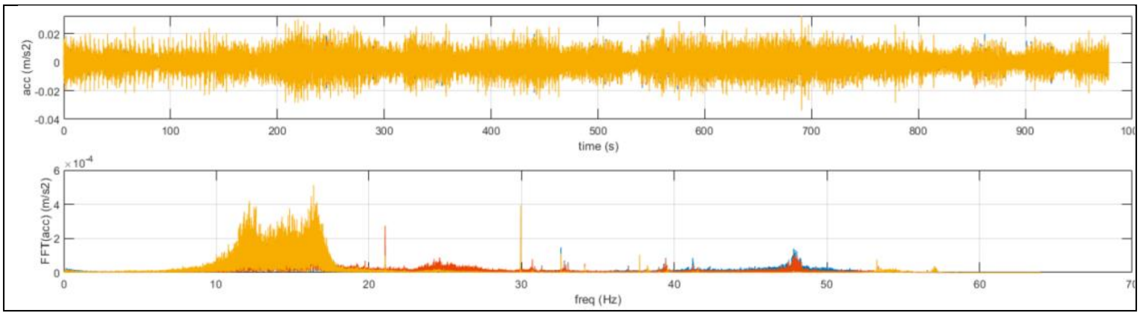


Figure 5: Microdrive plant

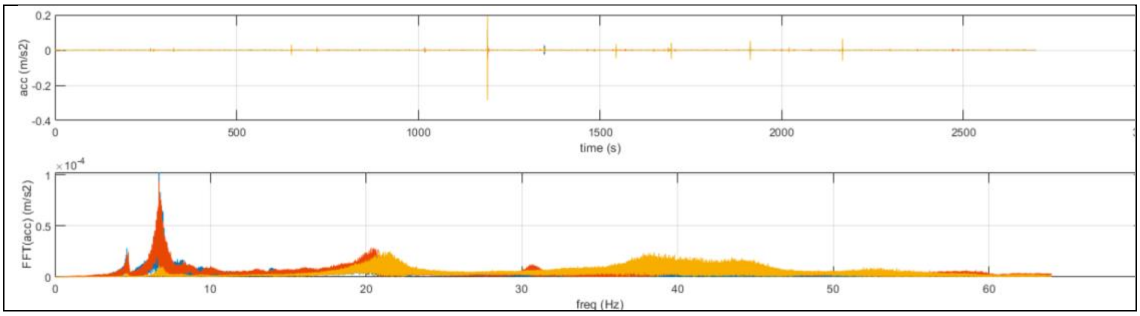


Figure 6: Lighthouse.

The train (HST125) signal, Figure 7, poses the greatest challenge as it includes sustained periods of sustained acceleration (blue line, on a curved rail section) which cannot be reproduced due to actuator stroke limit. A final example (not shown) for the tall building is at the limit of capability due to the cm level building displacement.

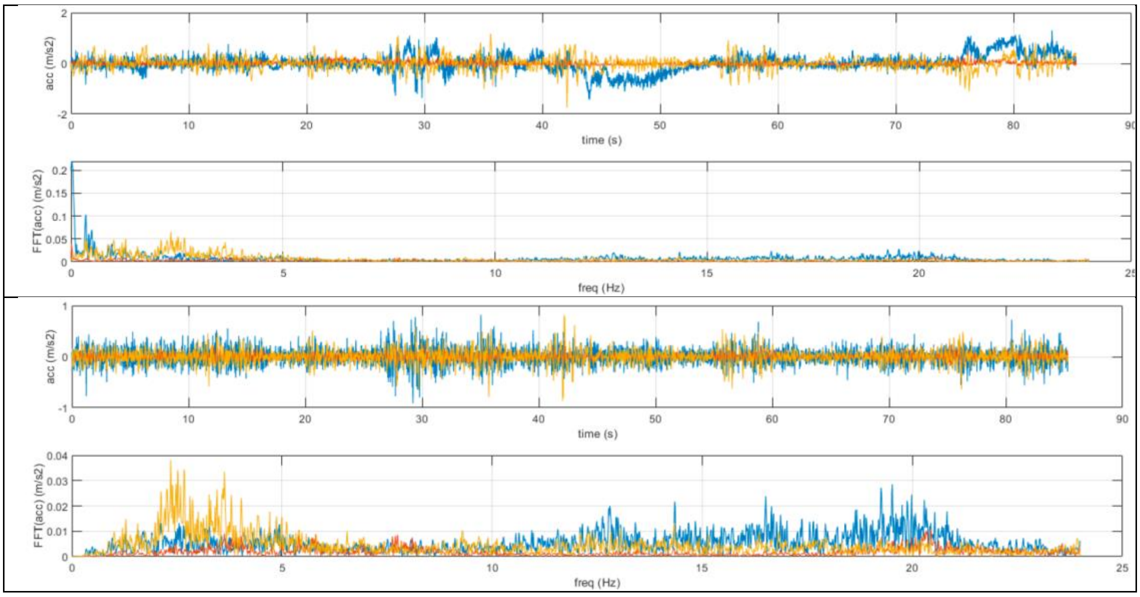


Figure 7: Exeter-Paddington HST; measured (upper, using iPhone) and reproduced (lower).

The motion platform will be housed in a purpose-built structure under construction at Exeter Science Park to be shared with other University of Exeter researchers. The artist impression Figure 8 and the state of construction at the end of March and May 2019 are shown in the right views, after casting of the 50t inertia block for the motion platform and erection of the frame.

Figure 8: Vsimulstors @Exeter building (left), inertia block, and building frame (right).

Supporting the motion platform will be a comprehensive array of environmental simulation and measurement equipment comprising:

1. HTC Vive Pro head mounted displays (HMDs) for up to nine occupants simultaneously engaging in a virtual reality environment.
2. Optitrak motion capture suing 16 cameras and active markers, allowing head tracking of none occupants or full body capture of one occupant
3. Nine AMTI 4.5kN capacity triaxial force plates to recover ground reaction forces.

The system of (E2M) motion platform, AMTI force plates, Optitrak mocap and Oculus VR are integrated by main contractor and experiental design specialists Holovis. ‘Peripheral’ equipment including instrumented treadmill, eye tracking and optional wall-projected VR will be added.

A sample environment is illustrated in Figure 9, representing a football stadium. There will be many experiments where either VR or motion (or both) are not required, and the majority of the 8mx8m space will be available, including the surrounding walkway.

Figure 9: Impression of stadium environment simulation

Research projects intending to use VSimulators@Exeter are currently being developed in areas of human-structure interaction and healthcare technologies where anomalous movement can be considered as a potential ‘biomarker’ for degenerative disease. Applied research (consulting) is aimed at simulation of conditions in buildings using novel construction technologies for sustainability e.g. long span floors and use of CLT flooring.

VSimulators at Bath

The Bath equipment is a building sway simulator but also uniquely features a climate-controlled chamber with precise environmental control, together with extensive occupant physiological monitoring. The main components (Figure 10) are the motion platform (supplied by Servotest), the test room (supplied by Temperature Applied Systems) and virtual reality (by Antycip Simulation).

Figure 10: VSimulators @Bath components (left to right), motion platform and climate-controlled chamber.

The motion platform performance range is shown in Figure 11. It can mimic biaxial (horizontal) building sway up to 0.8m at low frequencies (0.025-6Hz) and accelerations from below 0.04m/s^2 (below the threshold of perception) and up to at least 0.6m/s^2 (above which walking becomes difficult). This allows simulation of the full range of horizontal motions typical of medium to tall buildings, when subject to wind loading.

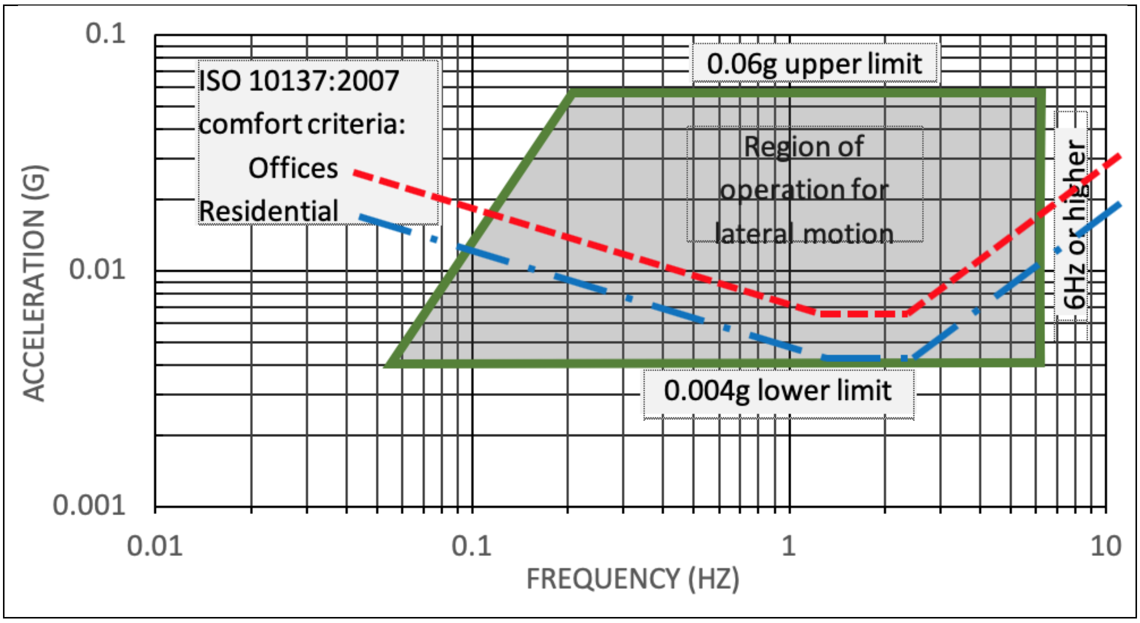


Figure 11: VSimulators @Bath -high frequency/small displacement

Figure 12 indicates some of the capability of the motion simulator from initial factory testing. This shows sine dwell tests at different frequencies and accelerations which represent points along the left hand and top border of the performance envelope shown in Figure 11. Of course, the platform is able to do this in the two lateral degrees of freedom, either individually or combined. Figure 13 shows an extract from a simulation replicating an acceleration response measured in a field test of a tall building subject to wind loading. As can be seen, the simulation provided by the motion platform tracks the desired accelerations well. The drift towards the end of this extract are largely due to having to drive the motion platform using a displacement signal derived by numerical double integration of the original acceleration record.

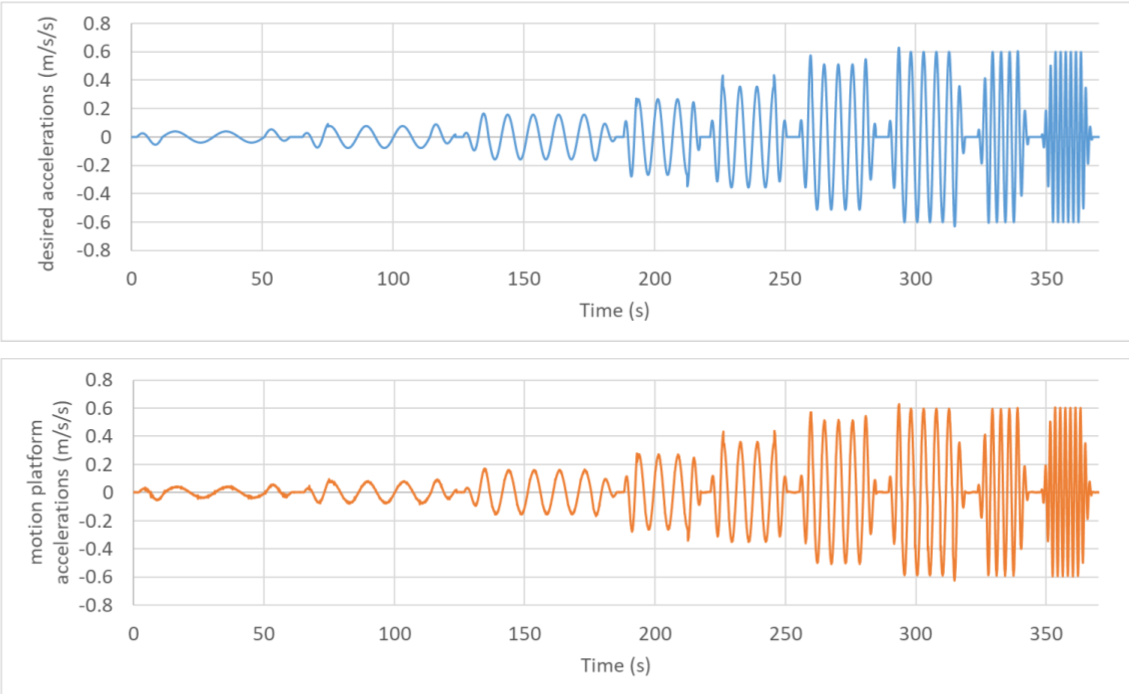


Figure 12: Sine dwell tests - desired accelerations (top in blue) vs actual motion platform response (bottom in orange)

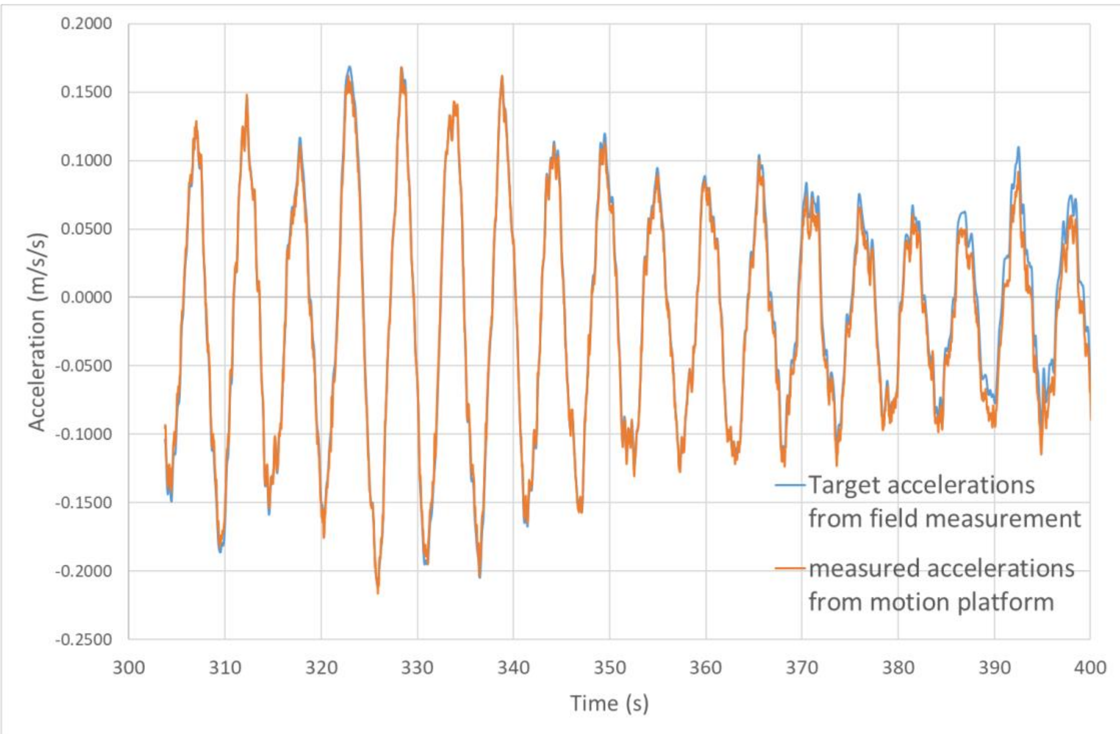


Figure 13: Comparison of desired accelerations and motion platform accelerations for simulation of real tall building

The climate chamber, which sits on top of the motion platform, is reconfigurable as an office, hotel, sitting room, hospital room, etc.. Optical 3-D virtual reality environments are projected on the walls of the chamber to give a sense of space and surrounding beyond the confines of the chamber (4), as well as virtual windows with views across a cityscape to give a sense of external conditions and height (5).

Figure 14: Virtual apartment

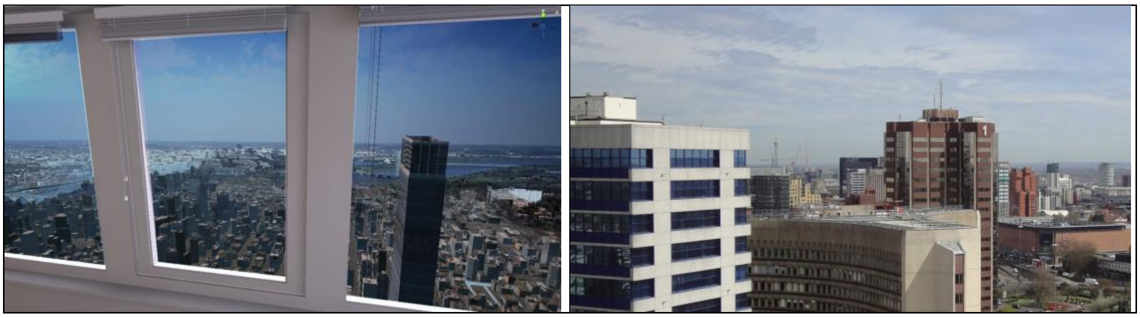


Figure 15: High rise and medium rise cityscape

The external actors (motion, view, surroundings) can be manipulated to explore their effects on occupants and their influence on perceived acceptability of motion and environmental factors. Internal environmental factors such as lighting intensity and colour temperature, air and radiant temperature, humidity, smell, noise, air flow and air quality can all be manipulated (with or without the physical motion and VR simulation) in the ranges shown in Table 1

Table 1: Human rated environmental chamber specification

Controllable parameters	Min	Max	Tolerance	Rate of change
Air Temperature (Degrees C)	15	40	0.5	10 / half hour
Radiant Temperature (Degrees C)	15	40	0.5	10 / half hour
Humidity (RH over the whole range of T)	20%	80%	5%	5% / half hour
Above three achieved at:				
thermal Load (W)		200		
moisture load (kg/hr)		5		
Air Flow (m/s)	0.05	1.5	0.05	0.05 / 15 mins
Fresh air requirement (l/s/p) (linked to CO2)	1	10	0.5	1 / 15 mins
input simulated sound SPL (Lp dB)	0	100	10	
Ability to adjust reverberation time (seconds)	0.2	1	0.1	steps of 0.1
Horizontal Illuminance (lux)	50	2000	25	ability to change
Correlated Colour Temperature range (K)	2000	6500	250	change in steps of 500k

Figure 16 provides some examples which demonstrate the stability and controllability of the environment taken from recent factory testing. Figures 16(a) and (b) show how combined humidity and temperature can be maintained simultaneously, at high and low levels respectively. Figure 16(c) shows how the humidity and air temperature controlled in real time by ramping both over time. The final Figure 16(d) gives an example of the controllability of the lighting, maintaining colour temperature while ramping the light intensity (Lux).

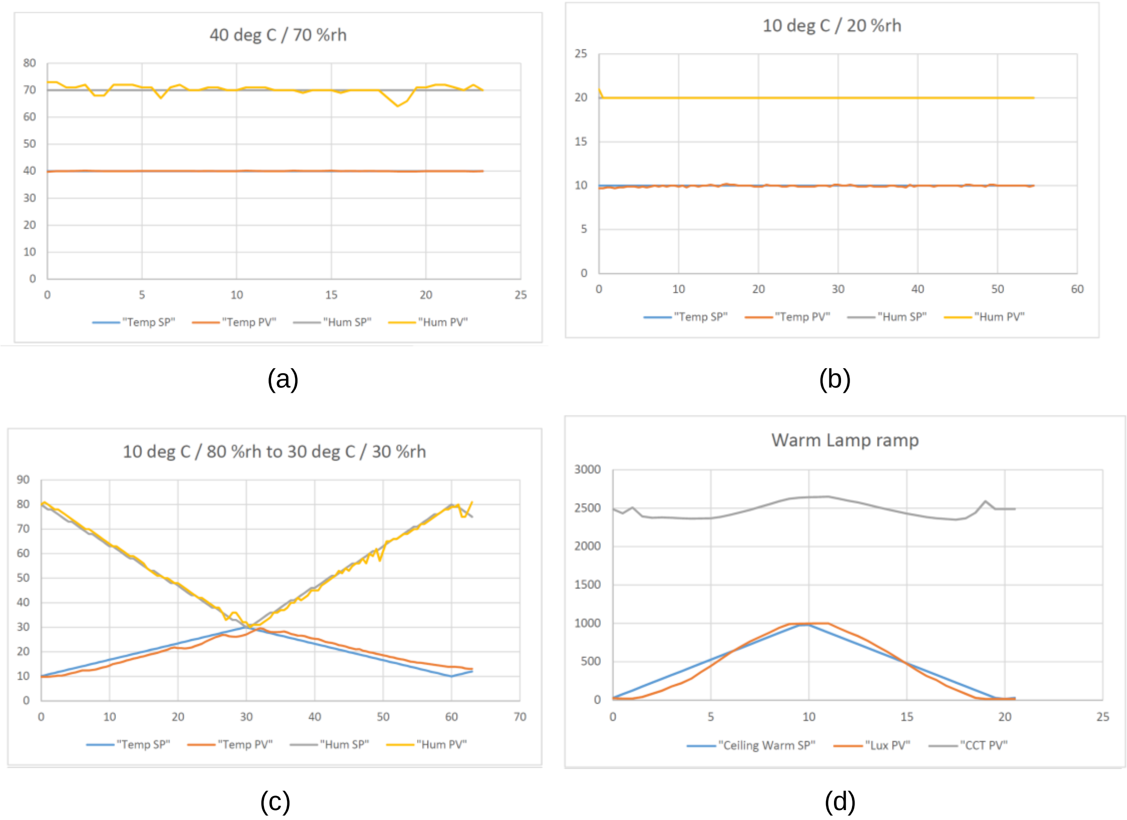


Figure 16: (a) constant high humidity 70% (yellow line) and high temperature 40C (orange line), (b) constant low humidity 20% (yellow line) and low temperature 10C (orange line), (c) constant rate variation of humidity (yellow line) and temperature (orange line), (d) constant warm light colour temperature 2500K (grey line) and ramping intensity from 0 to 1000 to 0 lux (orange line) In all cases the horizontal axis is time in minutes

All these controllable factors allow interactions among the various stimuli which affect building occupant health, comfort and productivity to be studied. In order to establish objective, quantifiable measures that represent the impact of the environment on users (such as increased stress, reduced concentration, tiredness) heat rate, blood pressure, galvanic skin reaction, eye movement, blink rate, electro-cardiogram and blood-oxygen levels can be measured using wireless sensors, with a low physical impact on occupants. By coupling the quantifiable measurements from these physiological sensors with the imposed environmental stimuli *and* with the more subjective responses of human test subjects through psychological testing protocols, it is possible to establish causal links between disturbing environmental inputs and their perceived acceptability. The equipment therefore allows researchers, for the first time, to study human response to the interaction between motion and/or environmental stimuli under fully controlled laboratory conditions yet in the context of real-world surroundings, provided by virtual reality. This will give a profound insight into the structural and environmental requirements for serviceable buildings.

Virtual reality (Figure 17) will be provided by means of multiwall, projected environment using ultra short throw projectors with 3D capability (using glasses), while occupant motion will be tracked.

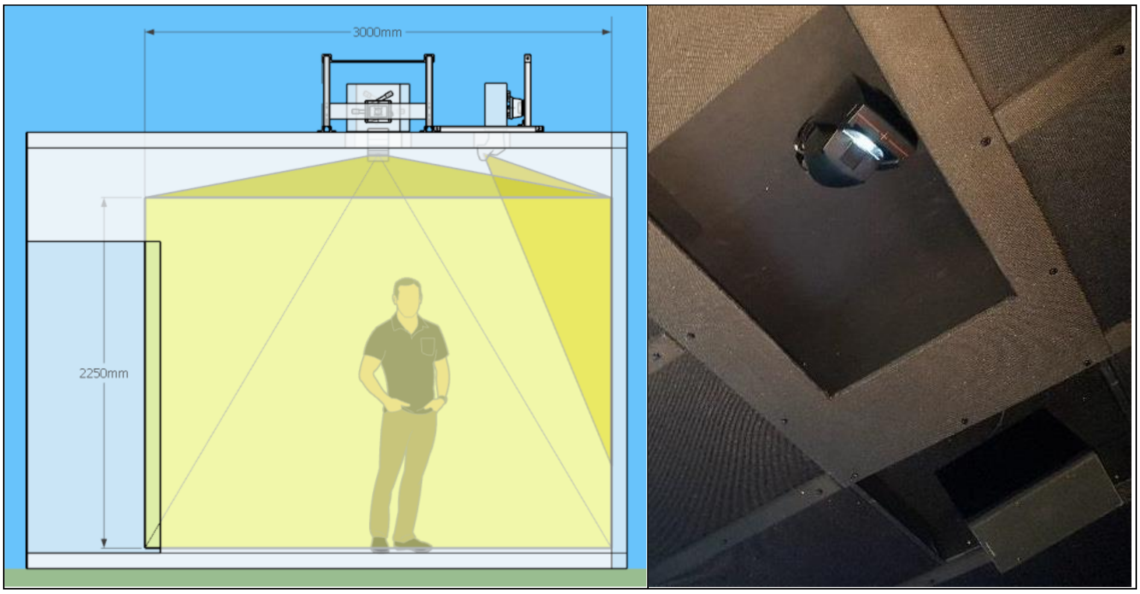


Figure 16: VSimulators@Bath virtual reality provision

Current research using VSimulators@Bath

As the Bath VSimulator equipment is being commissioned, there are two research projects underway to explore important research challenges as well as the capabilities of the equipment.

Designers of tall buildings face the difficulty that there is very little understanding of what level of motion is acceptable; current available guidance is based entirely on perception thresholds. Whether or not building motion can be perceived is almost entirely irrelevant since acceptability of the environment that building occupants work and live in involves many factors -it is context dependent. There is now evidence that motion below the perception threshold can still lead to negative changes in physiology and behaviour, in particular this is seen in the form of 'sopite syndrome' which correspond to feelings of drowsiness, lethargy, low mood and lack of energy. Therefore, the first project to use VSimulators@Bath will study use of acceptance rather than perception criteria as robust framework for assessing and designing buildings which are fit for purpose. The work carried out in this study will use realistic random narrow band motion.

Statutory regulation for the decarbonisation of the built environment through improved energy efficiency has the unintended consequence that new buildings (where people in industrialised countries spend 90% of their lives) are often overheated and poorly ventilated with poor air quality. This will certainly impact both health and productivity, but as yet there is limited evidence, so in the second research project VSimulators@Bath will be used to provide such evidence, through careful control of the indoor environment. Various human performance indicators to be monitored, include cognitive function and response rates in addition to physiological measurements which can then compared and correlated against changes in temperature, humidity and ventilation.

VSimulators operations

EPSRC funding for three years from May 2017 provides for a facility manager (FM) covering both sites, a senior experimental office (SEO) at Exeter and an experimental officer (EO) at Bath. Due to various delays, the grant has been extended for one year (without extra funding) and both Universities have provided significant contributions for estates and facilities, with FM/SEO/EO underwritten for two years while usage ramps up to full operation and sustainability in May 2023.

Prospective users should approach Julie Lewis Thompson J.A.B.Lewis-Thompson@exeter.ac.uk (FM) or either PI (JMWB/APD). RCUK use, costed into proposals, will be according to TRAC requirements, with minimum 40 days per annum availability. Commercial use for at least 40 days per annum will be at market rates and will be managed either via Full Scale Dynamics Ltd or direct through the respective university business units. Remaining time is for maintenance, upgrade and training, as well as for un-charged pilot studies leading to research or commercial funding which investigators aim to cover operational costs to ensure sustainability.