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Vibration stability of Orion laser facility

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In 2005 the UK Ministry of Defence awarded a contract for construction of the Orion laser facility at the Atomic Weapons Establishment (AWE). Orion delivers a power density of 10^{21} W/cm^2 on a 5 μm target, making it a world-class facility for the study of high energy density physics. The ability to target to such high precision depends on the 'stability' of the building and internal structures with respect to thermal expansion and vibration. This paper concerns experimental activities supporting the prediction and evaluation of the minute vibrations against a 'budget' comprising the effects of all vibration sources, internal and external, and the sequence of experimental campaigns and signal evaluation that fed into this process. This involved a sequence of dynamics-based measurements of foundation pile stiffness, vibration propagation from both controlled and uncontrolled sources at stages during the construction and, finally, evaluation of vibration levels in the as-built facility due to internal machinery and the few external vibration sources passing through the sophisticated vibration barrier. The approach focused on time series of vibrations in the design phase and on the evaluation of statistical properties of displacement power spectral density functions.

1. Introduction: capability and requirements for Orion

In 2005 the UK Ministry of Defence awarded a contract for construction of the Orion high-power laser facility at the Atomic Weapons Establishment (AWE) (Edwards, 2006). Orion was designed to support research on the performance of warheads in the UK's nuclear stockpile under restrictions of the Comprehensive (nuclear) Test Ban Treaty by enabling experimental measurements of the physical properties of materials in extreme regimes of temperature and density that occur in an operating warhead. Such measurements will help to bridge between interpretive and predictive computer codes by providing experimental data for benchmarking. Construction activities began in 2005 and commissioning tests continued through to 2013 with the first experimental results (Hoarty *et al.*, 2013).

The Orion facility comprises ten 'long-pulse' lasers that will deliver up to 5 kJ at 351 nm (ultraviolet) in 1 ns pulses and two 'short-pulse' beams that will deliver 500 J at 1053 nm (infrared) in 0·5 ps pulses (Oades *et al.*, 2004). The long-pulse lasers can be used to compress the target material and the short-pulse lasers to heat it to many millions of degrees centigrade, enabling the behaviour of matter at extreme densities and temperatures to be studied. Orion delivers 10^{21} W/cm^2 to target, making it a world-class facility for research into high energy density physics.

Orion's capability is also valuable for research on plasma physics, for example to study conditions on stars and super-dense matter, as well as particle acceleration, isotope production and advanced energy production (fusion) schemes. Hence 15% of Orion's time is made available to the academic community.

2. Orion components

The laser (Figure 1) is housed in a purpose-built structure having a 97 m by 57 m footprint. The building ground floor houses plant rooms and offices, while the long- and short-pulse laser beam lines are supported on steel frames bolted

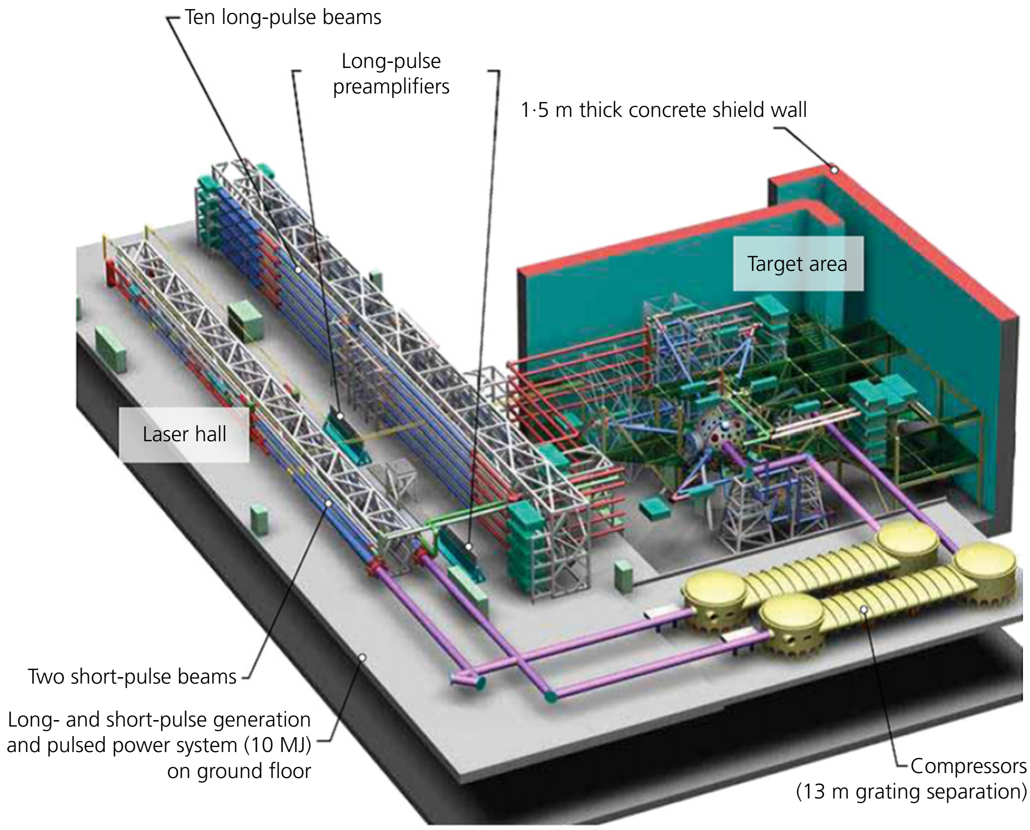


Figure 1. Schematic illustration of Orion

directly to a concrete slab in the first-floor laser hall. These frames were designed to have natural frequencies exceeding 20 Hz for undisclosed reasons. Short-pulse laser beams pass through optical compression stages (also on the first floor) and both long- and short-pulse beams are directed at the target, which is fixed to the ground floor in a multi-storey target hall with 1·5 m thick concrete walls. The ground floor is a 0·6 m reinforced concrete slab with 0·6 m edging supported by a grillage of 0·9 m piles at 5·4 m centres while the first floor, supported on 0·6 m square columns, is a waffle slab with 0·9 m sub-grid spacing. The building envelope is a separate structure supported on double-sleeved piles, which isolate the foundations of the vibration-sensitive elements from wind buffeting of the envelope. Although final pile details are unknown, 0·9 m test piles were 22·5 m depth, passing through layers of Silchester Gravel, Bagshot Formation and a transition zone, with London Clay formation for the lower half of the pile.

In order to function correctly, the Orion laser system must control the propagation of the laser beam over a path length of hundreds of metres with multiple reflections with a targeting accuracy of 25 μm for the long-pulse lasers and 5 μm for the short-pulse lasers. The alignment of the laser lines over the long term is not a concern due to realignment before each firing sequence, but positional stability is required during the alignment and firing sequence, which is expected to last 1 h. This led to the development of a ‘stability budget’ to be applied in the design of the structure and the optical support structure (Swensen *et al.*, 1997). The sources of instability were considered to be dynamic, due to vibrations, and static, due to thermal effects and ground settlement and creep. This latter movement, which is normally important in structural design, is truly ‘long term’ and is compensated for in the laser realignment. This paper considers the harder-to-deal-with dynamic component due to ground-borne vibrations and dynamic wind pressure, for which 2·5 μm was available to the facility designers, BuroHappold. This 2·5 μm is the stability budget, which could not be exceeded by the sum total of all dynamic displacements during the firing sequence.

The main source of ground-borne vibrations was considered to be vehicles moving around the facility and along the A340 road that runs along the perimeter close to the Orion site (Figure 2). The effects of infrequent discrete events such as hydrodynamic testing would not to be considered. For wind, direct forces on the building envelope were considered along with the effect of vibration transmitted from nearby structures buffeted by wind, including trees.

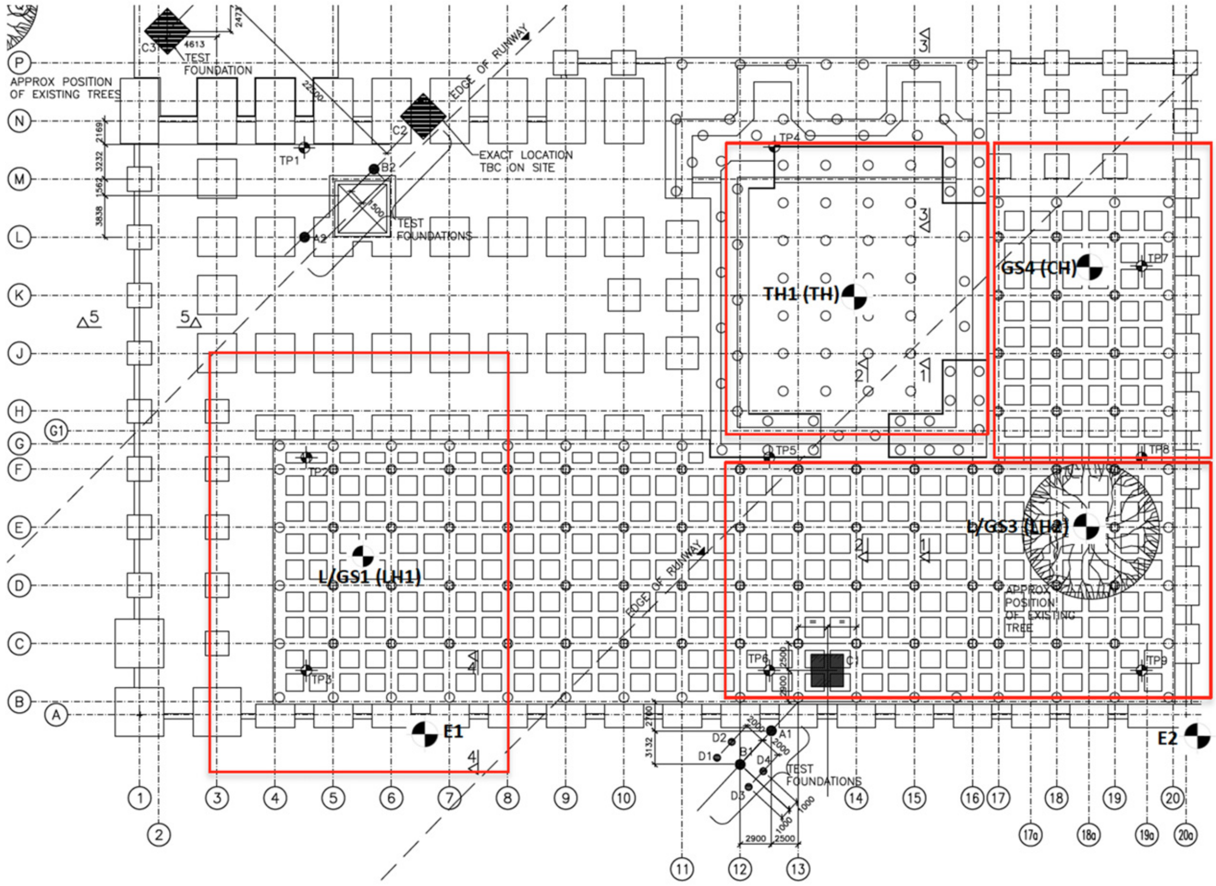


Figure 2. Orion site

3. Outline procedure and timeline for design and assessment of vibration stability

The procedure began with an evaluation of the vibration environment on the site by an independent contractor in 2005; this provided the statistical frequency domain characteristics of the site vibrations. The measurements also provided two scalable design signals representative of both frequency content and direction of the vibrations propagating through the site.

As the building foundation is a major component in the vibration transmission path and one that could be optimised for best stability performance, a number of foundation types were considered and evaluated using shaker testing and ambient vibration measurements.

The two design signals were adapted to represent propagating vibration waves providing direct displacement input at locations for groups of piles in the detailed finite-element (FE) model created to represent the foundation, superstructure and laser support frames. Inputs were applied through a pile–soil interface model whose characteristics were determined from the pile shaker tests. The simulations did not account for the mitigating effect of the structure, a strategy with acceptable conservatism proved by sample vibration measurements during the construction sequence.

The FE model was used in an exhaustive sensitivity analysis by trying all combinations of sensible design parameters of piles and superstructure. Rotations and displacements of components of the laser optical system were combined in a square root sum of squares sense for comparison with the stability budget.

The work culminated in a design that met the stability specification, and foundation construction began in April 2006. Vibration measurements were made of the foundation and partially complete ground-floor slab in November 2006, then of the complete ground-floor and first-floor slabs in 2007 under similar controlled conditions. It was found that there was generally a ratio of 2·0–2·5 reduction in measured vibrations due to the presence of the structure.

In June 2009 vibration measurements were again made of the completed structure, this time including the effects of internal machinery (compressors, environmental control), confirming the stability of the structure due to external and internal vibration sources. A parallel desk study of dynamic (buffeting) wind forces on the building envelope demonstrated that, for the final envelope design, wind was a lesser concern and through statistical combination with structural vibrations would not compromise stability.

Due to the nature of the site and the constraints of the commercial arrangements, the study could not be perfectly controlled, for example with the exact same measurement points under the exact same conditions from 2005 to 2009, and there were no opportunities to repeat or extend measurements that might be available within a controlled research experiment. Nevertheless, there is sufficient linkage, as intended by the overseeing authority (AWE), to demonstrate a logical sequence leading to proof that the building satisfies the original stability requirements. The final proof was obtained in the extended commissioning that demonstrated no adverse effect of vibration instability and in early experimental results in 2013 (Hoarty *et al.*, 2013).

4. Brownfield site vibration survey

The AWE was built on the site of the World War II Aldermaston airfield, whose runway ran diagonally across the present site of the Orion building. The runway was still in place at the vacant Orion site when preliminary vibration measurements were made in 2003, followed by a more comprehensive survey in 2005 whose main aim was to establish the levels of ambient vibration associated with activities adjacent to the site such as vehicles moving on internal roads and public highways outside the perimeter. A total of 14 d of measurements had already been conducted by a third-party contractor over a 3-week period using a combination of Willmore Mk IIIA seismometers supplemented by Ranger and Geospace units and sampled at 250 Hz. This sample rate (or 200 Hz or 256 Hz) is typical of seismometers, although in fact displacement levels were of little consequence above 35 Hz.

The majority of the 2005 measurements (White, 2005) were of ambient vibration at groups of measurement points selected from a grid of locations covering the site to indicate any likely sources, the degree of commonality and its spatial extent. The duration of the measurements also allowed for estimation of the 95th percentile vibration (displacement) levels reaching the structure footprint.

The measurement points (or test points (TPs)) are indicated as TP1–TP9 in a regular grid in Figure 2 and marked with a small ⊕ symbol. The focus of measurements was also on three types of test foundations installed within the footprint of the Orion structure: 0·6 m and 0·9 m diameter bore piles and 3 m^2 pads. Hence all measurements recorded vertical and horizontal velocities at A2, C2 (test foundations) and at TP4 (TP indicates a ground spike), with the majority of measurements also recording at C3, B1, C1 (all test foundations), TP7 and either TP8 or B2. Only a few measurements were made of remaining ground spikes so the picture of propagation across the site was limited. The foundation response was also evaluated by forced vibration testing.

5. Vibration stability simulation approach and design signal selection

Several options were explored for simulating the effect of ground-borne vibrations on the Orion structure based on the vibration survey data. Ansys software had been selected for the structural vibration study, and one major factor in the approach was the transparency of the methodology.

While Ansys offers options for working in the frequency domain, which is an approach well suited to random vibration analysis requiring statistical properties of response, this is not well adapted for differential support excitation over the length of a structure and is also difficult for non-specialists to interpret. Due to the many organisations involved in the multiple review stages of the design process, a clear and simple presentation format was an essential component – time domain analysis was thus chosen, using carefully selected and optimally representative vibration signals.

5.1 Selection of 'design signals'

Due to the computational effort associated with time domain analysis, only two time series (signals) were sought from the large dataset of vibration recordings, but these would need to be representative of the site vibration character. The characteristics sought for these two 'design signals' were that they should

- be clear above background noise
- have a relatively short duration (around 10 s to limit simulation costs)
- have spectral content consistent with that observed during the 3 weeks of measurements
- show similar features in time and frequency between different measurement points indicating a common origin
- not include features such as mechanical (real) or electrical (instrumentation) transients from within the site (Figure 2) since these would be prevented during Orion laser firing.

The time series were derived from continuous measurements over the 14 separate working days, including periods of construction activity and at night but mainly during working hours. It was found that the most effective technique to check for the above criteria simultaneously was to scroll through sequential (262 s) spectrograms using bespoke MATLAB scripts. Spectrograms were found to represent the signals with sufficient detail in both time and frequency to identify candidates for further investigation of time series features and frequency domain relationships.

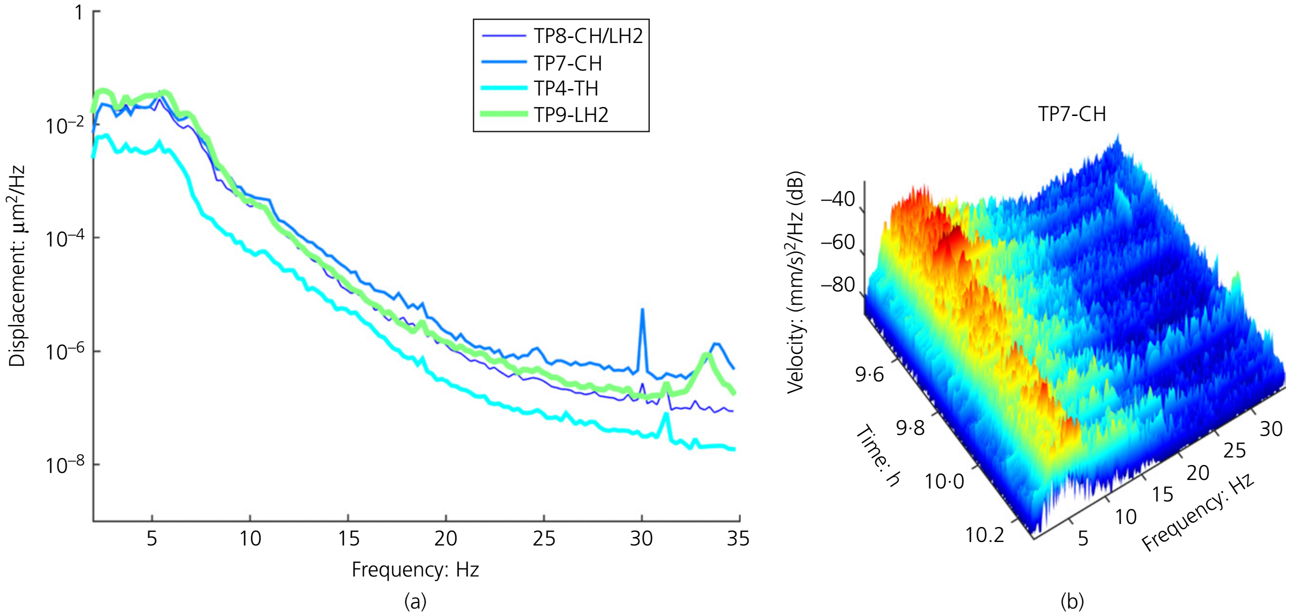


Figure 3. Vibration environment on 22 September 2005 for brownfield site: (a) 95th percentile PSD; (b) velocity spectrogram (reference 1 mm/s)

For the same data, statistical analysis was carried out by subdividing the velocity time series into 4 s frames, converting to the frequency domain (by discrete Fourier transform or fast Fourier transform (FFT)), converting to displacement through division by circular frequency, then assembling the FFT blocks into large three-dimensional arrays (record number versus frequency versus displacement amplitude) for each recording session, typically of one day or one night. Anomalies (mechanical or electrical overload) were automatically excluded. The sample size allowed for reliable evaluation of statistical distribution at a 0·25 Hz frequency spacing and evaluation of mean, median and 95th percentile values of displacement power spectral densities (PSDs) for each frequency bin as well as root mean square (RMS) over given frequency ranges, chosen as either 1–35 Hz or 2–35 Hz.

Figure 3 shows the 95th percentile displacement PSD and vertical velocity spectrogram from test point locations during a day with minimal construction activity (i.e. representative of operational conditions for the laser with ground-borne vibrations from local traffic and normal activities within AWE). Figure 3 also shows the TP7 signal as a spectrogram, indicating the variation of signal strength with time. The main observation here is that there were no exceptional events and that energy was concentrated around 5 Hz.

Extensive study of the data and discussions on the appropriate representative signals resulted in the selection of two example signals appearing to propagate from opposite ends of the site and also having different frequency content; these were labelled signal_02 and signal_89. The original time series for signal_02 recorded on 0·6 m diameter test piles either side of the runway are presented in Figure 4.

5.2 Signal generation and simulation

From the two signals, short periods (8 s and 12 s) were extracted and scaled to have RMS displacements matching the 95% values for the site determined by aggregating all the measurements.

The marching method developed by Hao *et al.* (1989) was used to generate time series for centre points of 12 groups of piles over the building footprint. This procedure generates a common ground motion propagating from a specific location,

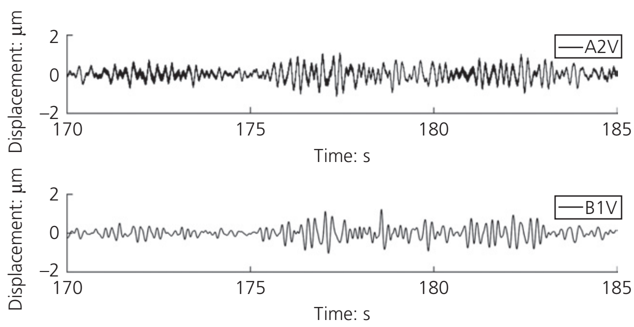


Figure 4. Signal_02 original time series

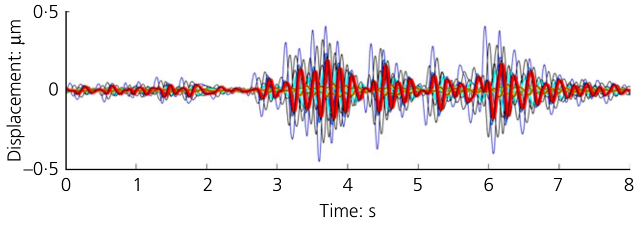


Figure 5. Set of generated input signals

allowing for attenuation, dispersion and delay. The analysis procedure makes use of frequency domain relationships (specifically coherence) between opposite ends of the site, determined from the full record from which the few seconds of time series were finally generated, those few seconds representing relatively strong parts of the 256 s signal showing commonality throughout the site. Consistent with the original signals, the derived inputs were taken to derive a signal propagating with spherical wave fronts from points on opposite corners of the site. Sample intervals of 0·004 s were retained from the original signals, and the set of 12 horizontal and vertical signals for signal_02 are shown in Figure 5.

5.3 Foundation performance studies and FE simulations

The Orion superstructure was straightforward to model due to the known properties and dimensions of the concrete, whereas the properties of the foundation required experimental studies using forced vibration such as with electro-dynamic shakers (Figure 6). Pile stiffnesses in each direction were estimated from reliable data at the lowest possible frequency points on the receptance frequency response functions (FRFs). In theory, receptance FRFs should be asymptotic to static stiffness at 0 Hz (DC) values but, for low frequencies with the shaker force dropping quickly due to the frequency squared force characteristic, values were chosen where H1 and H2 FRF estimators began to diverge. The H1 estimator is used where the input (force) signal is contaminated by noise and H2 where the output (response) is contaminated (Randall, 1987). The values were cross-checked by time series curve-fitting, giving stiffness values of 1·0 GN/m and 0·2 GN/m for the 0·6 m pile in vertical and horizontal directions respectively, and 5·0 GN/m and 0·5 GN/m for the 0·9 m pile in vertical and horizontal directions. For pads, the values were 0·2 GN/m and 1·0 GN/m (i.e. stiffer horizontally).

In practice, it has been found (Dobry and Gazetas, 1988) that pile stiffness is reduced in the presence of nearby piles, so reductions factors $1/(1+\alpha)$ are used; for Orion, the dynamic interaction factor for oscillating piles α is $0{\cdot}2 < \alpha < 0{\cdot}3$.

Using the experimental values, modal analysis of the structure and foundation system determined that the fundamental mode frequencies were 3 Hz using 0·6 m piles, 4·9 Hz for 0·9 m piles and 7·0 Hz for pad foundations. Given that the energy content of the ground displacement spectrum was concentrated in the range 2·0–4·5 Hz, 0·6 m piles were not viable. While pad foundations produced higher frequency modes, in the free vibration measurements they consistently showed the highest vibration levels in the ambient vibration measurements and they also picked up higher vibration levels than piles when foundations on the opposite side of the runway were driven by shakers. The 0·9 m pile was thus chosen and foundation construction could begin.

Performance simulations were carried out on the structure using pile group inputs generated from signal_02 and signal_89. Alongside the delayed and attenuated versions, analyses were carried out using common signals (i.e. the two signals were applied uniformly to each pile). After much discussion it was reasoned that because the free vibration signals had been measured at the tops of the sample piles, they

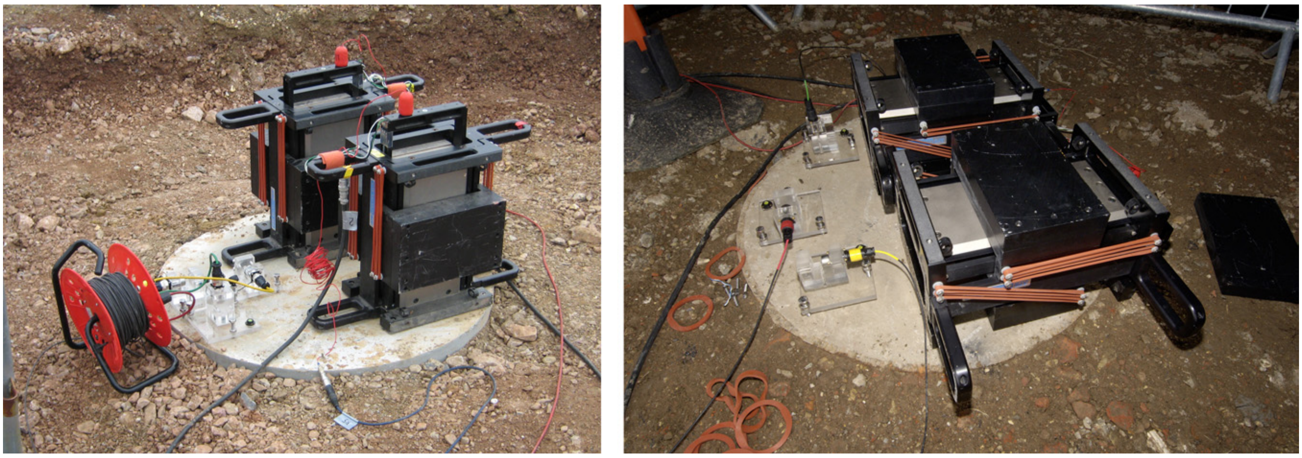


Figure 6. Shaker pile testing

already represented the behaviour of the piles and hence the signals were applied as imposed translations to the pile/structure interfaces. Although imperfect, the approach is one used elsewhere in simulations of the effect of traffic-induced vibrations (Hao *et al.*, 2001) and the method was expected to generate conservative predictions of translation; with the outputs from multiple Ansys simulations, the design of the superstructure converged to a system that allowed beam line precision within 2·13 μm.

5.4 Wind and vibration load case combination

Wind gusts were also a concern due to the varying pressures and resulting deformations possible in the 1 h alignment period. Eight years of wind data from the site anemometer were used to determine the range of wind speeds and were compared with data from Boscombe Down. Pressure changes over the 1 h period were calculated and the 95th percentile value was adopted for design.

In the initial design the envelope was partially supported on the massive target hall walls, which were separated from the target hall floor by a movement joint. This design resulted in unacceptable displacement of the laser hall so the design was modified to decouple the envelope steelwork from the target hall walls. Instead, the envelope is supported on double-sleeved piles that transfer the load deep into the ground. As vibrations experienced by Orion are primarily surface waves, the design should largely isolate the laser component support structure and target structure from wind effects. Optical modelling of the remaining effect of wind load alone showed beam accuracy to be within 0·84 μm for 95th percentile wind range.

To combine wind- and ground-borne vibration effects to get a 95th percentile value, 78th percentile values of each of the wind- and ground-borne vibration effects were combined (since 5% of the time 78th percentile values of both of each would be exceeded). The result obtained was 1·84 μm for the combination of load cases, hence ground-borne vibration alone governs dynamic stability.

6. Ground-borne vibration studies during construction

The vibration environment on the Orion structure was assessed twice during the construction phase, firstly in November 2006 when the majority of bore piles had been installed and part of the ground slab was in place and secondly in June 2007 when both the ground slab and the first-floor laser hall structures were structurally complete.

For the 2006 measurements, an array of 15 force balance accelerometers (FBAs) was deployed. Figure 7(a) shows the partial slab existing at the time of the measurements and the arrangement of measurement points. Points marked 1–5 along the diagonal, and points 6 and 7 indicate locations on the slab where accelerometers were mounted directly on the concrete surface of the slab (designated stp1–7), while points 1–4 on the corners indicate locations where accelerometers were attached to steel spikes driven into the soil (designated spk1–4). The x-axis and y-axis respectively correspond to gridlines 4–7 and B–G in Figure 2, with stp6 ≈ TP3 and stp1 ≈ TP2. A single Guralp CMG3-ESPD triaxial seismometer was used in parallel with one of the sensors at stp6 to corroborate the information

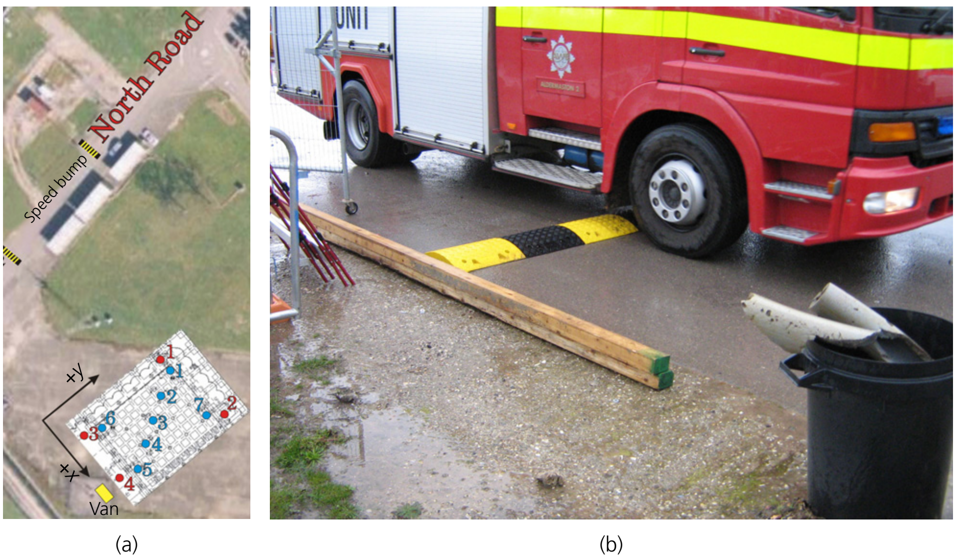


Figure 7. (a) Arrangement of measurement points on the partial slab and speed bump locations. (b) Heavy vehicle used on speed bump

from the accelerometer. The Guralp has a noise floor at least an order of magnitude below the FBAs.

For the 2007 measurements, 20 FBAs were arranged on the slab and partially completed upper level (laser and compressor halls), indicated in Figure 2 as LS1, GS1, LS3, GS3, GS4 and TH1 as well as on ground spikes (E1 and E2): GS represent (ground-floor) slab test points, LS are upper level (first-floor) test points and TH is the target hall.

For both sets of measurements, six accelerometers were arranged in triaxial sets and not moved for all of the 1 h recordings (six for 2006 and five for 2007) while other accelerometers were rotated to vertical and (two) horizontal directions. Recordings were made with construction activities shut down to represent typical conditions for operating the laser.

In addition, for both 2006 and 2007 slab measurements, ground vibration pulses were deliberately generated using a

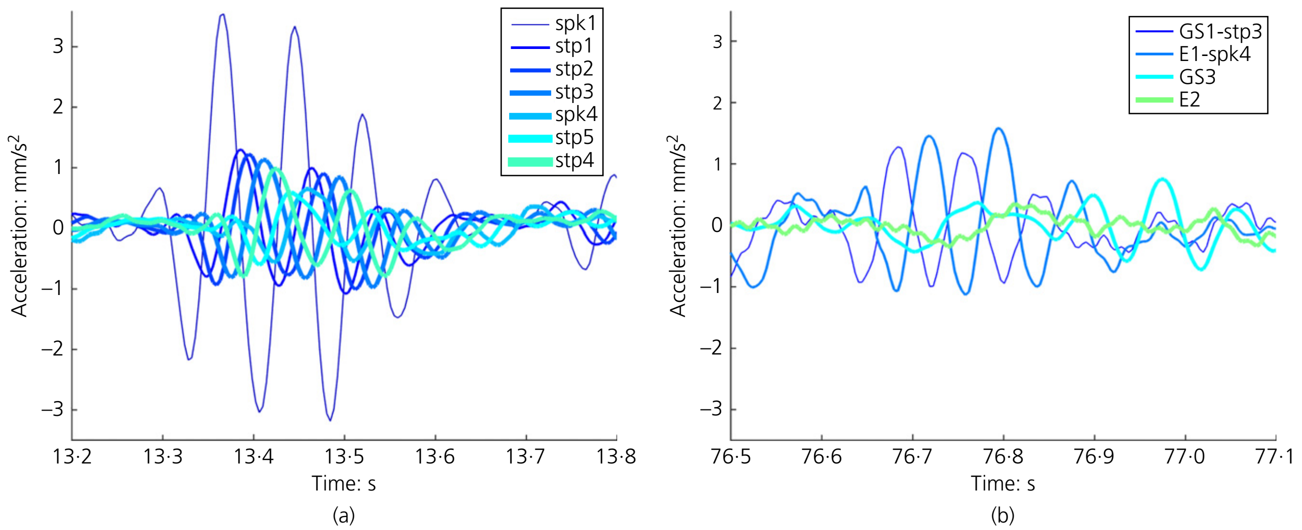


Figure 8. Speed bump time histories: (a) 2006 slab-only measurements; (b) 2007 measurements of slab and partial structure

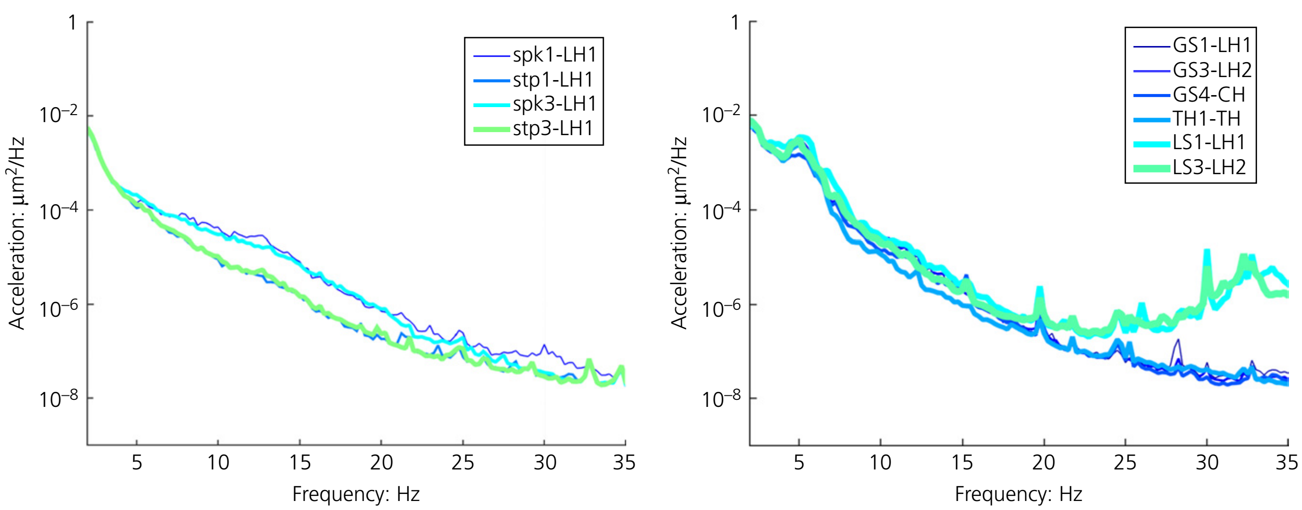


Figure 9. PSDs of vertical vibration with construction for (a) 2006 measurements and (b) 2007 measurements; stp3 (2006) compares with GS1 (ground-floor slab) and LS1 (first-floor slab) in 2007

heavy vehicle (a fire engine) driving over a speed bump (Figure 7). Simulations of the vehicle, its suspension and the bump profile (Al Dimashki, 2011) provided an estimate of ±60 kN for the reaction pulse for each axle and of the measured response in the alignment spk1–spk4, which were at opposite corners of the slab (Figure 8); stp1–stp5 are the points equally spaced along the spk1–spk4 interval. In Figure 8 there are two transients as the two axles of the vehicle pass over the bump with a speed of approximately 5 mph (8 km/h).

GS1 (2007) corresponds to stp3 (2006), while GS3 (2007) is at the far end of the structure from GS1. There is no obvious difference in the nature of the response of the structure between the two measurements, although both clearly demonstrate the delay and attenuation of the travelling vibration waves.

Corresponding to the measurements presented in Figure 3 for the brownfield site in 2005, Figure 9 shows corresponding levels for the 2006 and 2007 measurements, also as average values of displacement. The PSD for the 2006 measurement with the partial ground-floor slab shows a clear reduction of (vertical) response and no obvious resonance in the 5 Hz region. For the 2007 measurement with complete ground-floor and first-floor slabs, a clear resonance at 5 Hz has reappeared in all signals, suggesting a rigid body vibration of the whole building. The first-floor slab exhibits apparent resonance above 30 Hz, but the displacement levels are so small as to be of no concern. More detailed analysis of the signals from the three stages showed that vibration levels reduced overall by 2·0–2·5 μm (in terms of the 95th percentile displacement levels).

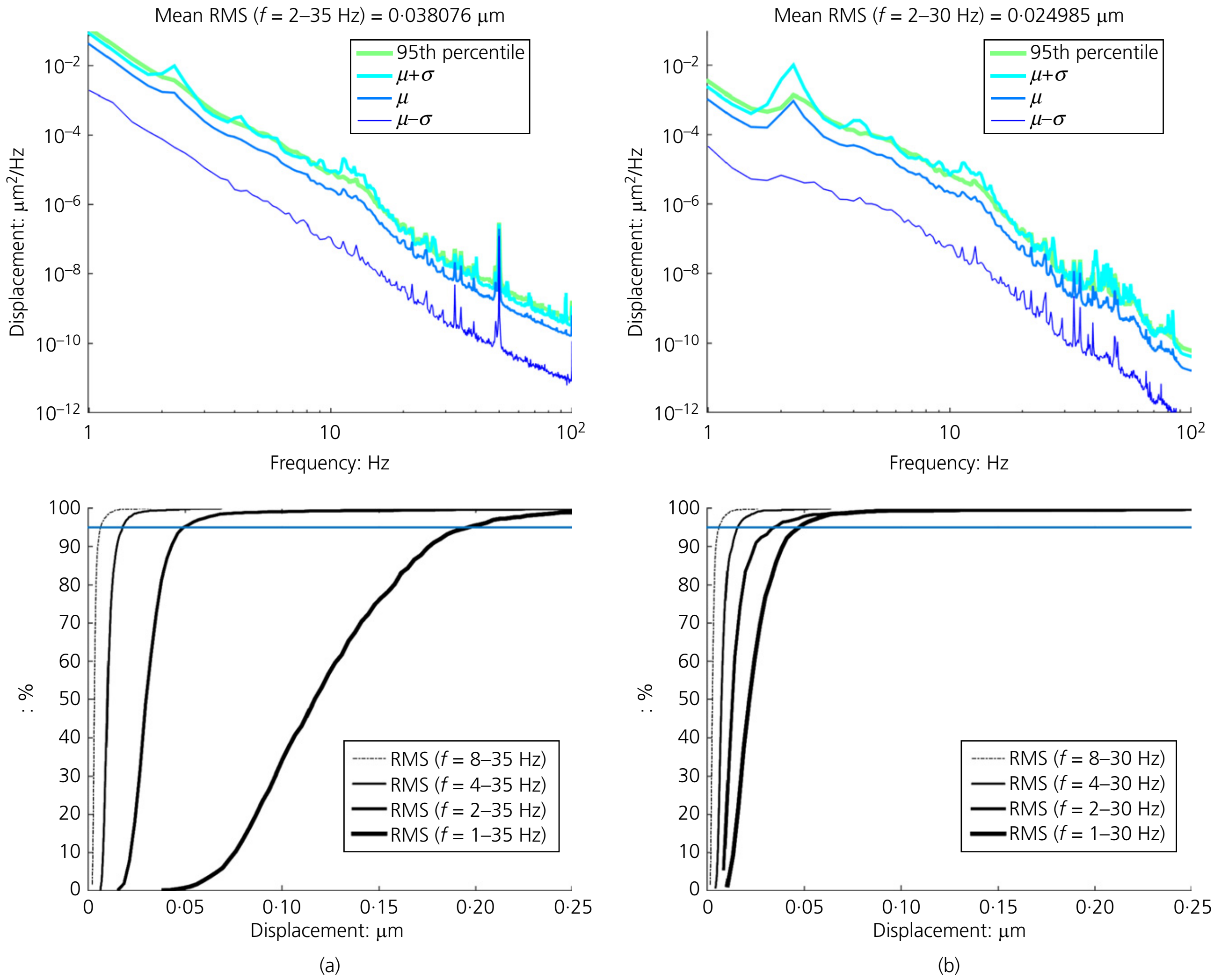


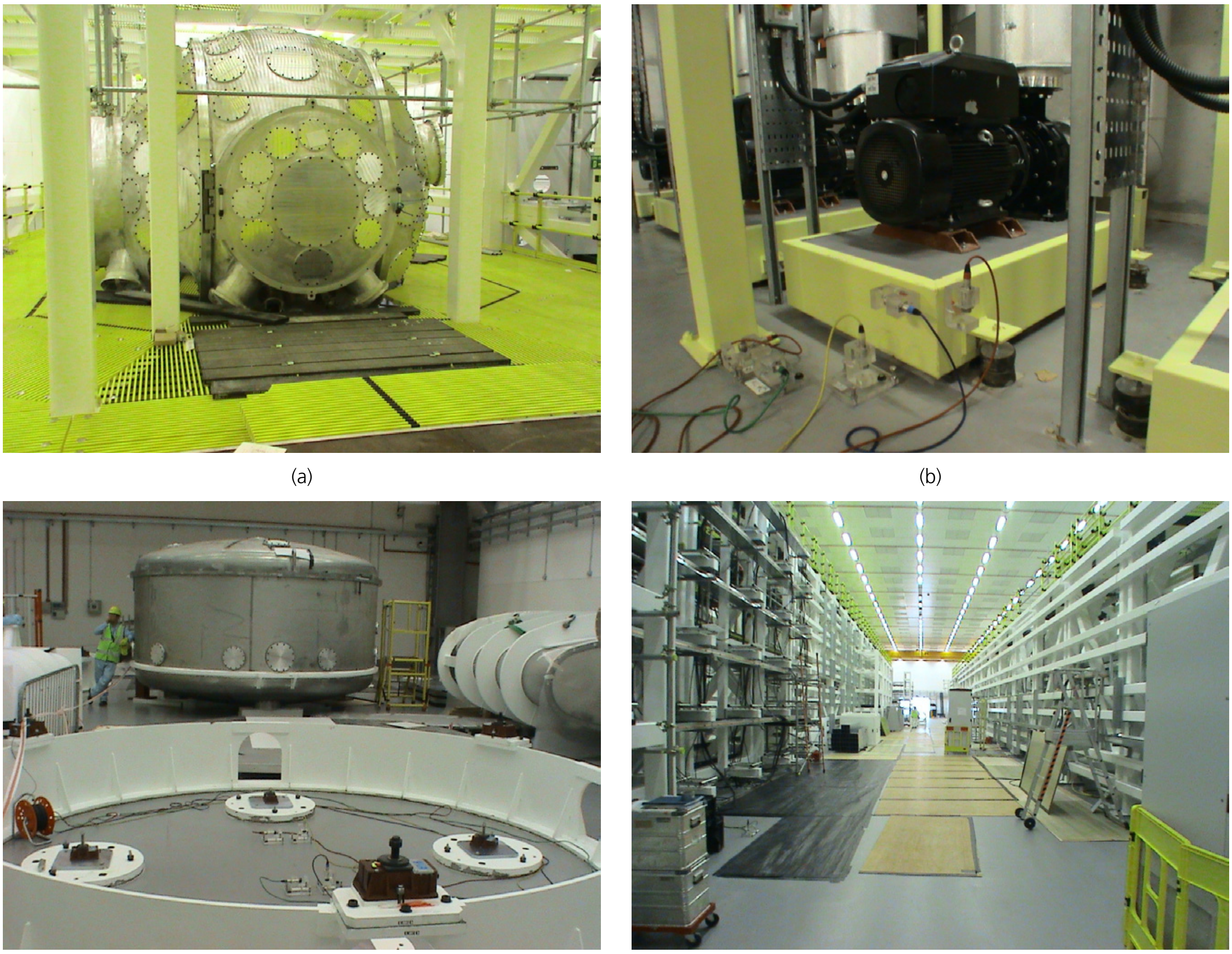
Figure 10. Comparison of ground-floor slab response using (a) FBA and (b) Guralp CMG-3ESP

7. Evaluation of percentile levels and performance of instrumentation

For the ambient vibration measurements in 2005, 2006 and 2007 the principal metric of ground and structural vibration levels was the 95th percentile of displacement response. Determining this value from measurements is complicated by the choice of appropriate recording conditions, instrumentation performance and selection of appropriate bandwidth. The 95th percentile criterion avoids the effect of extreme and unrepresentative transients in the analysed signals that can skew average values provided that the extended measurement, which lasts one or more hours, does not contain continued unusually strong signals, from temporary construction machinery for example.

Instrumentation performance is crucial. Accelerometers typically used for low-vibration measurements have a capacitive coupling to disconnect the power signal from the signal, resulting in poor performance and noise levels rising asymptotically towards DC (0 Hz). The FBA is a true DC accelerometer but has its own background noise levels, quoted by the manufacturer as 'resolution' of 1 μ***g*** or 9·8 $\mu m/s^2$. Tests by the first author in the quiet environment of the Diamond Light Source at night (Brownjohn, 2007) showed that, with high-quality acquisition equipment, background levels for the FBA can be as low as 1 $(\mu m/s^2)^2/Hz$, which sums to 1 μ***g*** over a 100 Hz bandwidth. The Guralp CMG-3ESP has superior performance, with noise levels below the US Geological Survey new low noise model (Ringler and Hutt, 2010). The Willmore seismometer is reported as having self-noise of 10^{-4} $(\mu m/s^2)^2/Hz$.

Figure 10 compares the FBA and the Guralp for vertical response of the partial ground-floor slab (2006 measurements).



(a) (b) (c) (d)

Figure 11. Optical and mechanical machinery: (a) target chamber; (b) chilled water pump in plant room; (c) optical compressor; (d) short/long-pulse laser frames

Subsequent measurements of extreme low-vibration facilities have shown that capacitor-coupled accelerometers have unacceptable performance for this type of measurement. The PSD plots show clearly that the Guralp performs better across the whole frequency range, but the critical part of the response between 2 Hz and 20 Hz is well represented in the 95th percentile curves. The plots also show that mean values enhance resonances due to short-lived transients.

The cumulative distribution functions show the effect of the lower limit of the range for calculating broadband RMS. When including only contributions above 4 Hz there is little difference between results for the two sensors but, when including components above 2 Hz, the FBA overestimates levels by approximately one-third due to the higher levels of low-frequency noise.

8. As-built structure performance with plant operation

In the last phase of measurements in June 2009, separate from the design process and commissioned by the operator (AWE), vibration levels on the floors of the laser, compressor and target halls were checked to show that vibrations generated by rotating machinery and piping did not cause the stability limit to be exceeded. Machinery included a range of air compressors, water pumps and air handling units located on the plant room floor below the compressor hall. These machines have rotational speeds around 1450 rpm or 2850 rpm, so if detected would generate sharp peaks in vibration response just below 25 Hz and 50 Hz.

Measurement locations were the same as for the 2007 measurements (in laser, compressor and target halls) to permit comparison. Figure 11 illustrates the measurements in the three comparative locations, along with one of the additional measurements at a chilled water pump in the plant room (Figure 11(b)). The view of the compressor hall measurement (Figure 11(d)) shows that the accelerometers were arranged in groups of four, allowing measurement in two translational directions. By differencing signals and using a baseline of 1 m, rotations about two axes could be obtained. The remaining two degrees of freedom would be obtained by rotating the accelerometer arrangement 90° about the vertical axis.

Figure 12 shows 95th percentile PSDs for measurements in the laser and target halls. Compared with the 2007 measurements (Figure 9) the values in the laser hall are significantly reduced in the higher frequency range, as if the apparent amplification effect of the first-floor slab has completely disappeared, other than weak spectral peaks around 17 Hz. The effect of machinery is clear in the peak at 24 Hz but the displacement levels are trivial, with rotations at the noise floor; the overall conclusion was that displacements were well within the stability budget for any combination of plant machinery operation.

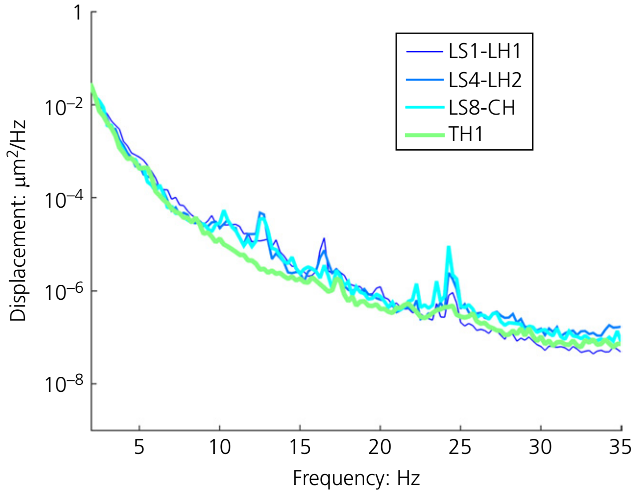


Figure 12. Displacement PSDs in laser hall and target hall from 2009 measurements

9. Summary and conclusions

A series of measurements and data analyses spanning a period of 5 years was undertaken with the aim of ensuring that vibration levels at components of the Orion laser facility would be within displacement stability budgets, ensuring that a beam line precision of 5 μm could be achieved at the 95th percentile level of vibrations during the 1 h pre-firing alignment procedure.

Time domain analysis was chosen for transparency and because it lends itself to multiple-support excitation. While the selection of foundation type was guided by site vibration measurements on the piles due to ambient and artificial excitation, simulations were carried out with direct drive of pile-caps. Simulations showed vibrations to be acceptable, and measurements of the structure at three stages during construction confirmed this to be the case. Finally, measurements on the as-built structure during worst-case conditions of machinery operation showed that the contribution of machinery to stability is negligible.

Despite vibration levels being close to noise levels for high-grade force balance accelerometers, the measurements were sufficiently clear to demonstrate the mitigating effects of the structure on vibration levels, the small resonance of the first-floor slab and, ultimately, the damping of the optical system support frames and other components on vibration levels.

Due to operational and commercial constraints, there were limitations on the range of vibration measurements. However, it is clear that the attention to optimisation of the foundation and structural design allowed for exceptional vibration performance to be achieved.

Acknowledgements

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