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A STUDY INTO THE LONG-TERM STABILITY OF FRONT END X-RAY BEAM POSITION MONITOR SUPPORT COLUMNS AT DIAMOND LIGHT SOURCE

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Abstract

Sand-filled steel columns are used at Diamond Light Source to support front end X-ray beam position monitors. This approach is chosen due to the relatively large thermal mass of the sand being considered useful to reduce the rate at which expansion and contraction of the column occurred as the storage ring tunnel temperature varied, particularly during machine start-up. With the higher requirements for mechanical stability for the upcoming Diamond-II upgrade, there is now a need to assess and quantify the current system's impact on X-ray beam movement. A study of thermal and mechanical stability has been carried out to quantify the stability performance of the front-end X-ray beam position monitor's columns and the impact that column motion may have on the X-ray beam position measurement. Measurements have been made over a range of different timescales, from 250 Hz up to 2 weeks. The measured stability of the support column is presented, showing that it meets our Diamond-II stability requirements. A comparison of the stability of the column with and without a sand filling is presented.

INTRODUCTION

To monitor and improve the stability of the photon beams, Diamond Light Source utilises X-ray beam position monitors (XBPMs) on most insertion device (ID) front ends. Each XBPM is mounted on a steel support column bolted to the synchrotron floor. Currently, the XBPMs are used as a diagnostics tool, monitoring long-term trends and in some cases for slow (0.2 Hz) beam position feedback [1]. After the Diamond-II upgrade, it is proposed that the front end XBPMs could be included in more critical orbit feedback systems. Therefore the mechanical stability of the XBPMs needs to be assessed. Motion of the steel columns arises from various sources, the largest contribution coming from the vertical thermal expansion of the steel over time, correlated with ambient temperature changes in the tunnel.

Each column is constructed from a hollow square tube with external dimensions of 200 mm x 200 mm and a wall thickness of 10 mm. The manufacturer, FMB Berlin GmbH, specifies that the column is produced using S235JR steel, with a coefficient of linear thermal expansion of $12 \times 10^{-6}\,\mathrm{K}^{-1}$.

The columns are bolted to the concrete floor using four 50 mm long M12 bolts. One of the open questions this work is intended to answer was whether the steel base of the XBPM pressed into the floor by the tension of these four bolts is sufficient to thermally couple the column to the thermal mass of the synchrotron floor slab, or if the column temperature is more correlated with ambient air temperature.

Each column is filled with fine sand intended to improve the thermal stability of the column by increasing its thermal mass. Experimental data was first acquired with the column in its original state, filled with sand. Then, during a machine shutdown, the sand was vacuumed out of the column (approximately 30 kg of dry sand), leaving it hollow, and the experiments were repeated.

EXPERIMENTAL SET-UP

Laser Interferometry

In this experiment a laser-interferometry system[1] was utilised to track variations in the height of the XBPM support column. The setup involved positioning one of the detector heads on the top of the XBPM vessel using a mounting bracket. A plane mirror was positioned on the ground and aligned to the laser beam such that the light is reflected back along the incident path. Figure 1 presents a sketch of this system.

Interferometry, the principle underlying this setup, exploits the wave nature of light. When the laser beam splits and travels different paths – one directly to the detector and the other along the length of the column to the mirror and then to the detector – they recombine, forming an interference pattern. By analysing this pattern, a measurement of the column height variation over time periods of 1 s to days is acquired. For background information on the various principles behind modern interferometry measurements, a useful introduction can be found in [2, 3].

Thermal Monitoring

The temperature of the column, the air, and the concrete floor upon which the column was bolted were measured in order to correlate any variation in column height to the temperature of the column and its surroundings.

A total of five temperature sensors, with a thermal resolution of 0.025 °C, were attached to the support column, on different faces of the column and at different heights. The intent of this was to determine if there were any temperature gradients across the column, or if non-uniformity of the column temperature could lead to bending or twisting of the column as different sides of it expanded or contracted at different rates. One temperature sensor was bolted into a

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[1] *Renishaw* RLE10.

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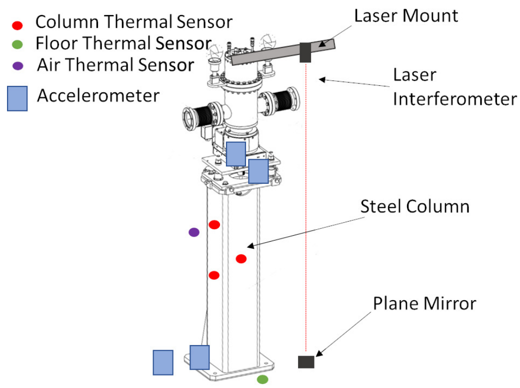

Figure 1: A drawing of the XBPM and its support column, with the locations of the different devices. Piezoelectric seismic accelerometers are shown by blue squares. Circles highlight the locations of the thermal sensors; red for column thermal sensors, purple for air thermal sensors and green for a sensor bolted to the floor. Two thermal sensors which were installed on the back and right side of the column are not shown in the schematic.

25 mm deep hole drilled in the concrete floor at the foot of the XBPM, at an equidistant location between two of the floor bolts of the support column which are separated by 200 mm. This sensor had a low-density packing-foam cover placed over it to insulate it from the ambient air temperature. This way, the sensor measured the long-term temperature stability of the floor slab, without detecting short-term fluctuations in ambient air temperature.

Accelerometers

Piezoelectric seismic accelerometers[2] were used to measure the horizontal and vertical stability of the support column over the frequency range of 10 Hz to 250 Hz with a broadband resolution of 9×10^{-4} m/s^2 rms. Piezoelectric accelerometers use the piezoelectric effect to measure forces induced due to the acceleration of the material. A seismic mass is attached to a sensing piezo-crystal. When under acceleration the seismic mass causes stress on the sensing piezo-crystal which outputs a proportional electrical signal [4]. Four piezoelectric accelerometers were used to measure the support column and the surrounding area, measurements were taken simultaneously. The accelerometers were placed on the floor next to the support column, on the base of the support column, on the top of the support column, and on the stepper motor to which the XBPM vessel is mounted referred to as the XBPM mounting plate, see Fig. 1.

RESULTS

Temperature Stability

Figure 2 shows the variation in the thermal sensor measurements installed on and around the support column over a 50 h period. The air temperature is seen to oscillate by about 0.4 °C peak-to-peak. However, the column has a significantly larger thermal mass, and is to some extent thermally bonded to the concrete floor slab. Thus, the temperature variations of the column are damped relative to the air, and vary over much longer timescales. The column temperature variation is broadly seen to follow the pattern of air temperature variation, albeit low-pass filtered. In addition, the location of the different sensors placed on the column does not make a significant impact on the temperature variation. This suggests that the thermal conductance of the support column is uniform across all faces. This relationship does not change when the sand is removed, see the bottom graph of Fig. 2. This is to be expected, given the thermal conductivity of steel and the timescales over which measurements were made. Over the full 11 day data collection period the standard deviation of the average column temperature was 0.064 °C with sand increasing to 0.071 °C when the sand is removed.

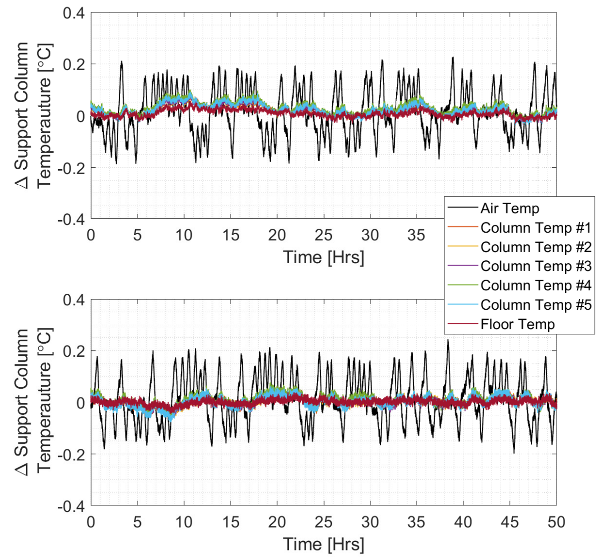

Figure 2: Graph showing the change in air, column and floor temperature over a 50-hour period with sand (Top) and without sand (Bottom).

Short Term Stability

The short-term stability was measured using accelerometers. There are two useful metrics by which the overall stability of the support column and the effect of the internal sand, can be compared: the transmissibility ratio of displacement transmitted through the column, and the power spectral density (PSD) of the motion of the support column.

The transmissibility ratio is the measure of the physical displacement transmitted through a system (i.e. the support column). This was obtained by measuring the motion using the accelerometer mounted at the bottom of the column and comparing the results to the XBPM support column stability using the accelerometer mounted at the top of the column. In the results presented here the ratio was taken from the base plate at the bottom of the support column to the XBPM mounting plate.

Typically, at low frequencies the whole system will move as one body, as all motion is transmitted through the column

[2] *PCB Piezontronics* model 393B31.

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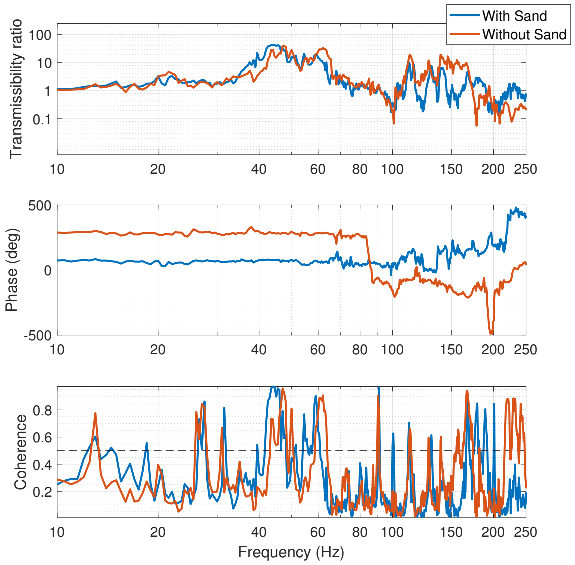

Figure 3: The horizontal transmissibility ratio of the XBPM support column bottom plate to the XBPM mounting plate.

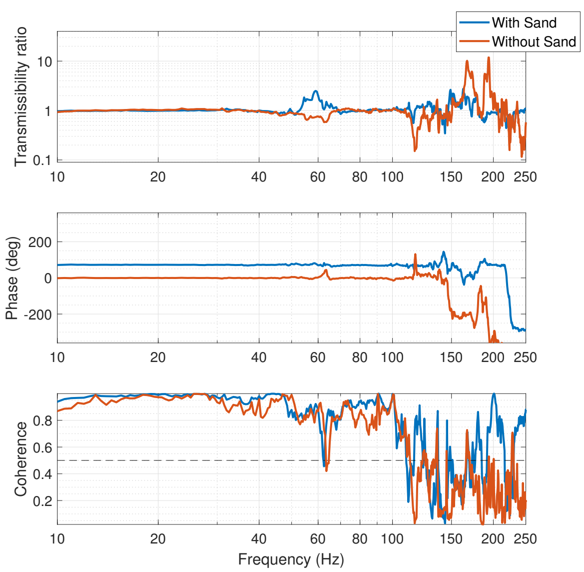

Figure 4: The vertical transmissibility ratio of the XBPM support column bottom plate to the XBPM mounting plate.

(i.e. transmissibility ratio = 1). A transmissibility ratio equal to one means a perfectly rigid system [5]. At higher frequencies the ground motion may no longer be transmitted through the column and is damped (i.e. transmissibility ratio < 1) or ground motion can even be amplified by the column at resonant frequencies (i.e. transmissibility ratio > 1). This enables the amplification, resonances and damping from the column to be seen.

Horizontally, the transmissibility ratio was similar both with and without sand up to ~ 120 Hz, see Fig. 3. There is an amplification of ground motion above 30 Hz in both datasets, with and without sand. The transmissibility ratio without sand shows fewer damping ‘troughs’ between 140 Hz and 166 Hz suggesting an overall larger amplification in this range of frequencies. There is a relatively large damping trough at 178 Hz in the without sand data which is not present in the column when there is sand. The vibration of the bottom of the column and top of the XBPM mounting plate go out of phase at 84 Hz, likely indicating a resonance of the system. The coherence of the system also has similarities between the two datasets, with slight changes in the peak frequencies. Removing the sand does not make the column more incoherent.

Vertically, the removal of sand has a larger impact on the transmissibility ratio, see Fig. 4. When sand fills the column the transmissibility ratio is close to one across the frequency range, except for a peak at 50 Hz - 70 Hz. New relatively large peaks at 167 Hz and 193 Hz were present once the sand was removed this suggests that the sand works to damp these resonances. Without sand the drop out of phase is shifted from 215 Hz to 144 Hz.

Overall, it is found that there are not significant changes to the short-term stability of the column as a result of the sand. The changes that are present could be explained simply as an effect of small differences in the bolt tightness following the unbolting and re-bolting of securing screws during the sand removal process.

The second metric by which the support column stability can be compared is the power spectral density for the horizontal and vertical motion of the XBPM mounting plate, seen in Fig. 5 and Fig. 6 respectively. The results here are similar to the transmissibility figures, in that they show very similar frequency responses both with and without sand.

Long Term Stability

During a typical week at Diamond Light Source, the electron beam is turned off to allow for machine development and maintenance. During this time the ambient air temperature in the tunnel typically drops as the thermal heating from the accelerator is removed. This temperature drop causes a contraction in the height of the XBPM support column. This can be seen clearly in a relatively large change in the column height in Fig. 7, highlighted by the black dashed line. The beam is returned to users at 9 AM the following day. The maximum change in height of the column during this beam-off period was 6.5 μm for the column with sand and 8.4 μm without sand. The standard deviation of the support column height variation over the 11 day measurement increases from 3.26 μm to 6.3 μm when the sand is removed. This variation is still below the 9.6 μm long-term stability needed for the planned upgrade to Diamond-II.

The correlation between the support column height and the temperature of the column can be seen in Fig. 8. At the start of both datasets the storage ring was not running. For the data set taken with sand, the electron beam was injected up to the user current, 300 mA, within 4 h. However, for the data taken without sand, the current did not reach 300 mA for close to 24 h. Therefore, the time for the column to reach an equilibrium temperature was longer. User current was returned to the machine at ~ 200 h in both runs. The column temperature takes 5 h longer to return to the level prior to the beam dump when it was filled with sand.

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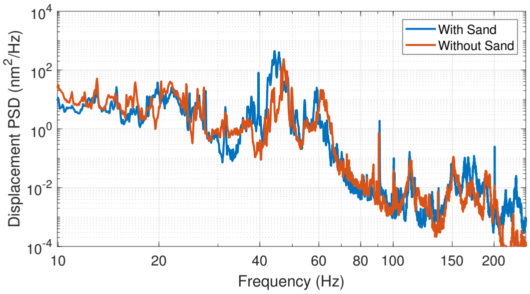

Figure 5: The power spectral density of the horizontal motion taken on the mounting plate of the XBPM.

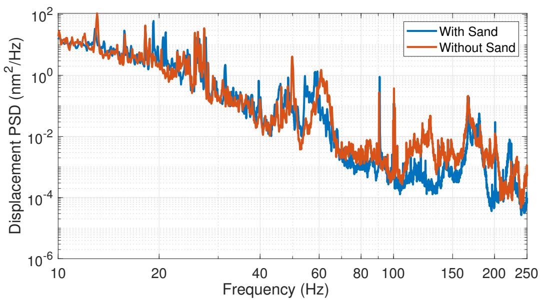

Figure 6: The power spectral density of the vertical motion taken on the mounting plate of the XBPM

Taking into account the expansion of steel, $12 \times 10^{-6}\,K^{-1}$, the column height change is larger than expected given the average column temperature variation. For example, in the top plot of Fig. 8, when the beam is turned off the column temperature drops by ~ 0.1 °C, which should give a change in height of ~ 2.9 µm. The actual measured change in height is around double this. This difference could be due to the XBPM being twisted by neighbouring vacuum vessels also warping or changing as the temperature changes. While the column height is correlated with temperature, it is a complex system that cannot be simplified down to just a steel support column existing in isolation. The column cannot be assumed to be completely vertically rising and falling with the temperature but could be 'bending' due to the tension in the bellows. It is a reasonable assumption that the column itself is not responsible for all the motion that is seen.

CONCLUSION

The mechanical stability of an XBPM support column has been assessed and results show that sand-filled steel columns effectively maintain the required thermal and mechanical stability for supporting front-end X-ray beam position monitors at Diamond Light Source. Through laser interferometry and accelerometer measurements, both short-term and long-term stability were examined, highlighting the negligible impact of sand on high-frequency mechanical stability and its beneficial role in reducing vertical column variations over extended periods. The standard deviation of the column height at a rate of 1 Hz over a period of 11 days was 3.26 µm with sand and increased to 6.3 µm when the sand was removed. These findings verify the stability of the column for the upcoming

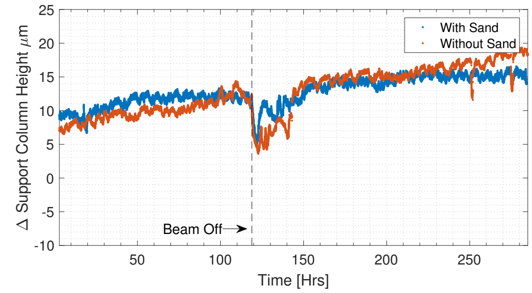

Figure 7: The change in the support column height measured with and without sand filling the column.

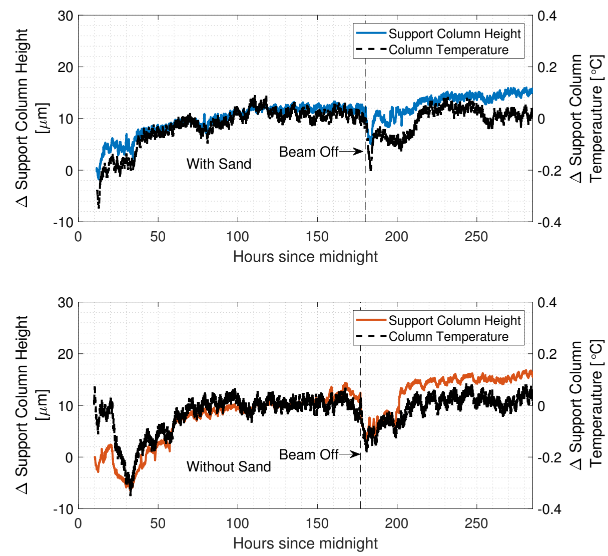

Figure 8: The change in the support column height and the average column temperature measured with (top) and without (bottom) sand filling the column.

Diamond-II upgrade, ensuring accurate and reliable X-ray beam position measurements. Removing the sand improves low-frequency vibrations slightly, but the impact of this is not significant. The current sand-filled steel columns are sufficiently stable to meet the Diamond-II requirements and therefore will remain during the upgrade.

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