VIBRATION MEASUREMENT AND ITS EFFECT ON BEAM STABILITY AT NSLS2*

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Abstract

Vibration measurements have been carried out at NSLS2. The floor has more than 100 nm RMS vertical motion during workdays (>1Hz). This motion reduces to 30 nm RMS during nights and weekends. Traffic on the nearby expressway is considered to be the major source of ground motion. Weather (wind) and utility system induced vibrations are other possible factors on floor motion. Vibrations have been measured at various locations, like the tunnel and experiment floor, HXN long beamline satellite building floor, high stability BPM support, Quadrupole magnets etc. Assuming a typical un-correlated motion of Quadrpole magnets of 100 nm, beam orbit jitter is around 4-7 microns. Fast orbit feedback will control the orbit stability within 10% of beam size.

INTRODUCTION

NSLS2 is an advanced third generation light source under construction at Brookhaven National Laboratory, with < 1 nm.rad horizontal emittance and 8 pm.rad vertical emittance. Minimum vertical beamsize in NSLS2 storage ring will be around 3 μm. Beam orbit needs to be measured and controlled with very high precision, typically within 10% of the beam size. For such a small beam size, any external excitations like the mechanical vibrations need to be well quantified.

The ambient floor vibration level of NSLS2 tunnel was expected to be 25 nm from 4-50Hz [1]. Ground motion below 4 Hz was expected to be correlated. Recent measurements on the constructed storage ring floor and experiment floor indicate that the floor motion is only correlated below 1-2 Hz, at distance of one cell length. Ambient floor motion is larger than specified.

To quantify the vibration level, two types of vibration sensors are used: geophones and accelerometers. The geophones have voltage output proportional to the velocity in the working frequency range while accelerometers measure the acceleration. High resolution low noise digitizers are used to record the sensor output voltages, DFT of digitized voltage signal reveals the vibration spectrum, as shown in Eq. (1), where *x(n)* is sampled voltage, *w(n)* is DFT window, *NFFT* is number of FFT points.

$$X(k) = \sum_{n=0}^{NFFT-1} x(n)\cdot w(n)\cdot \exp(-j2\pi kn/NFFT) \quad (1)$$
$$k = 0,1,2,\ \ldots (NFFT-1),$$

We define two parameters S_1, S_2 to normalize the spectrum.

$$S_1 = \sum_{n=0}^{NFFT-1} w(n) \qquad S_2 = \sum_{n=0}^{NFFT-1} w^2(n) \quad (2)$$

Normalized equivalent noise bandwidth NENBW and effective noise bandwidth ENBW of the Fourier spectrum are:

$$NENBW = NFFT\,\frac{S_2}{(S_1)^2}$$
$$ENBW = NENBW \cdot \frac{F_s}{NFFT} = F_s\,\frac{S_2}{(S_1)^2} \quad (3)$$

Where F_s is the digitizer sampling rate.

From the voltage spectrum, one can get the velocity spectrum for geophone, knowing the sensor sensitivity. Displacement spectrum is calculated from Eq. (4), by integrating velocity spectrum once. For accelerometers, two integrations are needed to get displacement spectrum from acceleration spectrum.

$$D(k) = \frac{Vel(k)}{j\omega_k}$$
$$\omega_k = 2\pi f_k = 2\pi k\,\frac{F_s}{NFFT} \quad (4)$$

RMS displacement power spectrum (PS) and power spectrum density (PSD) are:

$$PS(k) = \frac{2\cdot|D(k)|^2}{S_1^2},\ k = 1,2,\ldots NFFT/2$$
$$PSD(k) = \frac{PS(k)}{ENBW} = \frac{2\cdot|D(k)|^2}{F_s\cdot S_2} \quad (5)$$

In Eq. (5) PS calculation, the factor of 2 comes from converting double sided FFT to single sided FFT. The DC term ($k = 0$) is ignored. In real measurement, average of PS/PSD from many FFT frames can improve the measurement resolution. Amplitude spectrum and amplitude spectrum density are square root of the averaged power spectrum and power spectrum density.

Correlation of two channels' signals is defined as:

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$$Correlation \equiv \frac{\mathrm{Re}\langle PS_{12}\rangle}{\sqrt{\langle PS_1\rangle\langle PS_2\rangle}} \tag{6}$$

$$PS_{12} = \frac{2}{S_1^2} D_1(k)\cdot D_2^*(k)$$

Where PS_1 and PS_2 are power spectra of two channels, as defined in Eq. (5). PS_{12} is cross spectrum of Channel 1 and 2.

We define correlated difference spectrum, which gives the uncorrelated motion between these two channels:

$$CorrDiff \equiv 2(1 - Correlation)\sqrt{\langle PS_1\rangle\langle PS_2\rangle} \tag{7}$$

MEASUREMENT SETUP

Two types of sensors are used for NSLS2 vibration measurements. Sercel L4C seismometer [2] has open circuit electrodynamic constant ~270 V/(m/sec). It has resonant frequency of 1 Hz. By adding damping resistors, the sensor constant is:

$$G_d = \frac{R_s}{R_s + R_c} G \tag{8}$$

Where R_s is damping resistor, R_c is coil resistor and G is open circuit constant.

Typical measurements used two L4C vertical (or horizontal) sensors. Correlation information was obtained from two channels' cross spectrum. Sensors are connected to damping resistor boxes. The output signal is amplified before being fed into 8-channel 24-bit PXI 4472B digitizer. Another portable digitizer with USB interface USB-9234 is used for hard to access locations. Noise spectra of the digitizers are well below the sensor output spectrum.

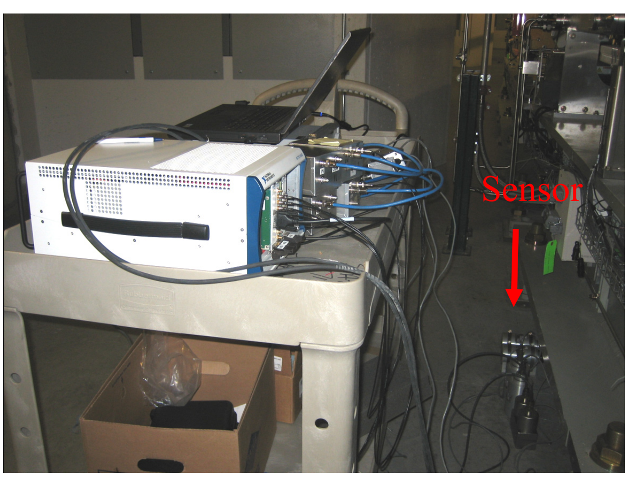

Figure 1: Vibration measurement setup in the NSLS2 storage ring tunnel.

Second type of sensor used is PCB [3] accelerometer. High sensitivity seismic accelerometer 393B31 has sensitivity ~ 1 V/(m/s^2) in the working frequency range 0.1Hz to 200Hz. Using digitizer integrated IEPE excitation, no extra signal conditioning is needed. Matlab scripts are prepared to do the data acquisition and signal processing.

Fig. 1 shows the measurement setup photo in NSLS2 storage ring tunnel. Two horizontal L4C seismometers, two vertical L4C seismometers and PCB 393B31 accelerometers are aligned on the tunnel floor, near one of the magnet supporting girders. Laptop running the Matlab scripts is communicating with the digitizers. Typical digitizer sampling rate was set to 5 kHz.

MEASUREMENT RESULTS

A typical floor motion spectrum in vertical plane is shown in Fig. 2. Compare the displacement spectrum results from seismometer and accelerometer. Both types of sensors have spectra in agreement between 0.5Hz and 200Hz. Above 200Hz, the vibration level is negligible. Peak ~30 Hz is induced by air handler. Peaks around 55Hz and 59Hz are coming from the cooling water pumps. Effects of utility system induced vibration on the beam may increase when the machine is fully operational. Vibration level at 1 Hz and above is around 130 nm during normal working days. The level is lower during night and weekends, as one can see later on the long term results.

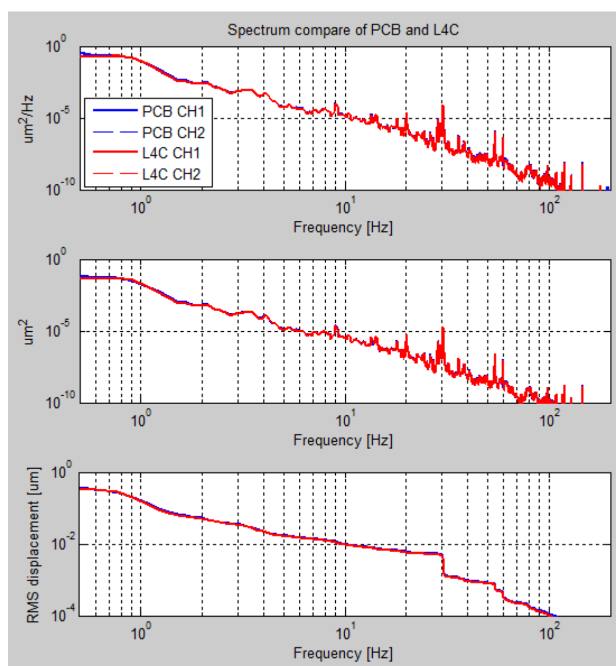

Figure 2: Typical ambient vibration spectrum measured on NSLS2 storage ring floor.

Locating two sensors at different separation, correlation of the two channel outputs are measured as described in Eq. (6). Shown in Fig. 3, when two sensors are sitting side by side (0.1m separation), correlation is good all the way

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up to 200Hz. As the sensors are moved apart, correlation at higher frequencies decreases. The correlation at NSLS2 site is good around 1.5Hz when two sensors are separated by one cell, which is about 26 meters. For NSLS2 storage ring lattice (Qx/Qy = 33.36/16.28), one horizontal betatron oscillation wavelength is about one cell distance, vertical betatron wavelength is even longer. Typically we integrate the motion 1Hz (or 2Hz) and above, to reflect this correlation spectrum.

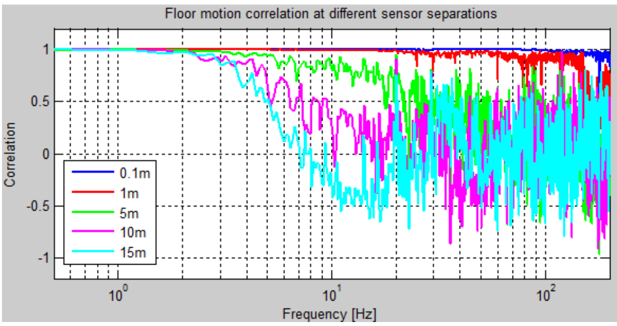

Figure 3: Two channel correlation at various sensor separations.

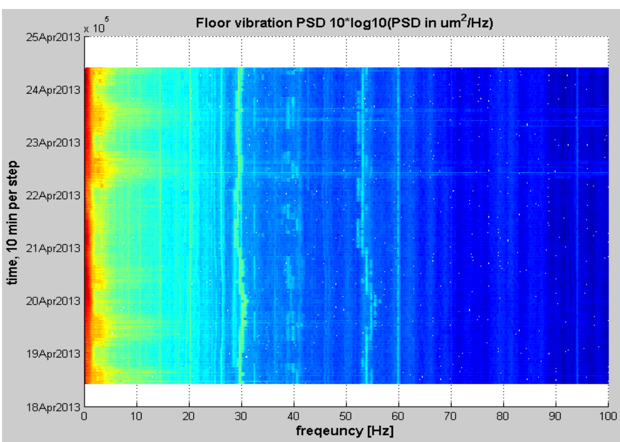

Figure 4: PSD spectrogram plot of NSLS2 tunnel floor motion during ~ 1 week period. Horizontal axis is frequency and vertical axis is the time at 10 minutes intervals. Color reflects the PSD spectrum amplitude.

Floor vibrations have been recorded for long period of time. Using a timer, Matlab script can collect and analyze vibration data for a given interval. Fig. 4 shows the floor vibration PSD spectrum during ~ 1 week period. From the PSD spectrogram, diurnal pattern was clearly observed, especially for the motion below 10 Hz. Air handler induced vibration peak (~30 Hz) and water pump skids induced peak (~ 60 Hz) exist although the levels are low. Our utility system has dynamic flow rate adjustments, which is why utility induced vibration peaks vary during this long period of time. Fig. 5 plots the integrated RMS motion level in three different frequency ranges. For 2 Hz and above, the motion has clearly day/night difference. Floor vibration level is lower on weekends. Freeway traffic about one mile south of NSLS2 site is suspected to be a major cause of this diurnal pattern. Large trucks are believed to be the dominant source of ground borne surface waves.

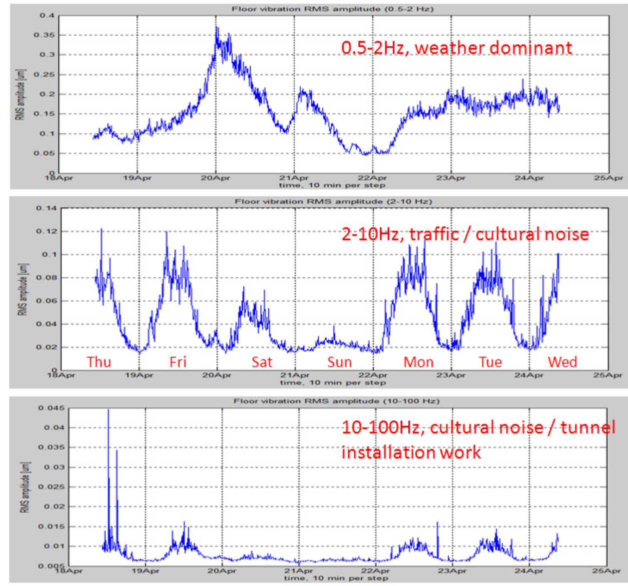

Figure 5: Integrated RMS motion in different frequency ranges for ~ 1 week period.

Green field measurements were carried out at different locations on BNL campus. Closer to the freeway, vibration level is higher at similar times of working days. These measurements confirm the traffic is major source of NSLS2 site vibration. There are some high frequency spikes on working days, coming from the installation work inside the tunnel and on the experiment floor.

If we integrate the RMS motion from 1 Hz and above, the diurnal pattern is not obvious for this particular week. Further investigation reveals weather, especially wind speed, affects the floor motion near 1 Hz range. Lower frequency motions are correlated to the wind speed.

To further understand the wind induced ground motions, floor motion measurements were carried out on the HXN (Hard X-ray Nanoprobe) beamline satellite building. HXN beamline is a long beamline that extends outside the NSLS2 ring building. Its floor motion requirement is even more stringent than NSLS2 experiment/tunnel floor. The satellite building floor has a thickness of one meter and is isolated from the rest of the building. Fig. 6 compares the vibration spectrum on HXN satellite building floor at three different times, with different wind speed and traffic volume. Red curve shows the spectrum during a windy midnight, when the traffic induced motion is low. Blue curve is a typical daytime with quiet weather and Green is midnight data without wind. Comparing the red and green, we can see motion around 1Hz was elevated due to the wind. During gust of wind, the building may excite several Hz resonant peaks and couple to the floor. Compare the blue and green curves, it is clear that daytime traffic induced motion is in 2-10Hz range.

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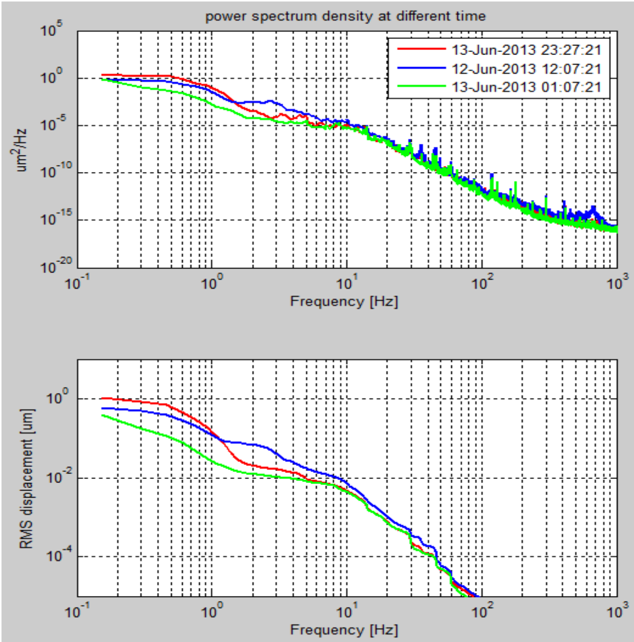

Figure 6: HXN satellite building floor vibration spectrum and cumulative RMS displacement at three different times.

Preliminary measurement for one high stability BPM support shows the support has no vertical amplification. Horizontally the support has resonant peak around 42 Hz, which agrees with the mechanical design. Fig. 7 compares the horizontal spectrum of high stability BPM stand, where Ch0 is ground motion near the support and Ch1 is sitting on top of the stand.

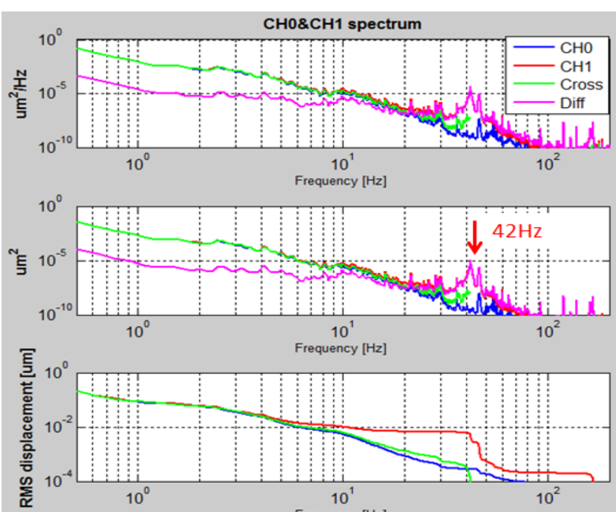

Figure 7: NSLS2 high stability BPM horizontal motion spectrum. Ch0- sensor sits on the floor; Ch1- sensor sits on top of the BPM stand.

BEAM EFFECT

Misalignments in the storage ring elements will introduce beam closed orbit errors. Vibration of magnets deflects the electron beam in the same way as misalignment. The difference is vibration is a transient effect, while misalignment is "static". With ground motion, the dominant effect will produce transverse offset of elements (Quadrupoles). This transverse offset will introduce a kick angle to the beam:

$$\theta = \frac{P_x}{P_{//}} = \frac{e \cdot k \cdot x \cdot L}{E/c} = \frac{ec}{E} kxL \qquad (9)$$

Where k is Quadruple strength in T/m; x is beam offset to the Q-center; L is Quadruple length and θ is kick angle introduced by offset x in Quadruple magnet.

Closed orbit variation at i-th BPM Δx_i with j-th kick angle θ_j can be expressed in Eq. (10)

$$\begin{aligned} \Delta x_i &= \theta_j \frac{\sqrt{\beta_i \beta_j} \cos(|\mu_i - \mu_j| - \pi Q)}{2\sin(\pi Q)} \\ &= a_j k_j l_j \frac{\sqrt{\beta_i \beta_j} \cos(|\mu_i - \mu_j| - \pi Q)}{2\sin(\pi Q)} \end{aligned} \qquad (10)$$

Where β_i, β_j, μ_i, μ_j are beta function and phase at BPM and Quadruple magnets. Q is the ring betatron tune.

Based on the NSLS2 vibration measurements, assuming each Quadruple magnet has 100nm un-correlated motion, simulation of NSLS2 storage ring lattice shows orbit variation of 4-7 microns at BPM locations. This is about 45% of vertical beam size, which exceeds the 10% beam size stability requirement. The real machine is more complicated since nearby magnets vibration has less un-correlated motion. Measurement shows un-correlated motion is less than 20 nm between quadruples on the same girder. Storage ring global orbit feedback system is expected to reduce the orbit motion by at least 20 dB. This will ensure that the orbit variation is within 10% of beam size.

SUMMARY

Vibration measurements have been carried out at NSLS2. Ambient floor motion level exceeds the 25 nm specification. Long term floor motion shows diurnal pattern, which indicates nearby freeway traffic is the dominant source. There is clear evidence that weather (wind) increases the floor motion at low frequency in several Hz range. With help of global orbit feedback system, 10% beam size orbit stability shall be achievable.

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[1] NSLS2 Conceptual Design Report, Dec 2006
[2] Sercel seismometer, http://www.sercel.com/
[3] PCB accelerometer, http://www.pcb.com/

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