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Achieving Vibration Stability of the NSLS-II Hard X-ray Nanoprobe Beamline

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Abstract. The Hard X-ray Nanoprobe (HXN) Beamline of National Synchrotron Light Source II (NSLS-II) requires high levels of stability in order to achieve the desired instrument resolution. To ensure that the design of the endstation helps meet the stringent criteria and that natural and cultural vibration is mitigated both passively and actively, a comprehensive study complimentary to the design process has been undertaken. Vibration sources that have the potential to disrupt sensitive experiments such as wind, traffic and NSLS II operating systems have been studied using state of the art simulations and an array of field data. Further, final stage vibration isolation principles have been explored in order to be utilized in supporting endstation instruments. This paper presents results of the various study aspects and their influence on the HXN design optimization.

Keywords: HXN beamline, vibration, stability, satellite building
PACS: 07.10.Fq, 07.05.Tp, 07.10.-h, 46.40.-f, 07.85.Qe

INTRODUCTION

The NSLS-II Hard X-ray Nanoprobe Beamline (HXN) and endstation instruments are designed to explore new frontiers of microscopy applications with the highest achievable spatial resolution. The HXN beamline aims for x-ray experiments achieving spatial resolutions ranging from the current level of 10 nm to the ultimate goal of ~1 nm. Spatial resolution at these desired levels, however, will require an extremely stable structural envelope. In an effort to arrive at a design of the endstation that will achieve stability levels that are in line with the spatial resolution requirements a comprehensive approach was adopted to identify the controlling parameters and thus influence the design of both the vibration-sensitive probe support floor and of its interface with the enveloping nanoprobe structure as well as the rest of the accelerator. The ground vibration environment in the vicinity of the nanoprobe endstation expected to influence the response of its floor and subsequently the probe itself supported on the floor is a combination of a number of modes, both stationary and transient, each of which is accompanied with wave types, amplitude and spectral content. These modes include the natural ground vibration measured at the nanoprobe endstation location, cultural noise stemming from mechanical sources that support the operation of the NSLS II accelerator, traffic-borne vibration in the vicinity of the HXN endstation and wind-induced ground vibration by its enveloping structure as well as the overall superstructure of NSLS-II.

Driven by the desire to meet wide-band and narrow-band vibration criteria established for the probe support floor, the location of the beamline station in reference to the overall accelerator as well as the structural [2]characteristics of the vibration-sensitive floor and its isolation from the surrounding structures were optimized and adopted into the design of the facility. The optimization of the nanoprobe endstation was achieved through the integration of (a) site-specific field measurements of natural ground vibration and of cultural sources such as heavy traffic in the proximity of the endstation, (b) quantification of the effect of accelerator-related operations and their potential impact on the nanoprobe station, and (c) the utilization of a large-scale, high-fidelity computational

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model/analysis that provided the means of vibration generation at the identified sources, propagation to and filtering by the nanoprobe structure. The effectiveness of the concept schemes explored in minimizing the ambient vibration of the substrate resulting from stationary and transient effects was assessed and feedback to the design of the integrated structure was rendered.

This paper summarizes all the elements of the multi-faceted effort that led to the adopted design of the NSLS-II HXN beamline. In particular, it discusses the rationale that led to the adoption of the HXN-specific stability criteria, the selection of key structural (such as the geometric dimensions of the probe-supporting floor slab) and isolating features, and the quantification of the expected vibration on the floor location where the sensitive probe will be supported both in terms of amplitude and spectral content. An overview of the complex analyses that enabled the latter is also presented. Finally, the coupling of the anticipated nanoprobe floor vibration to the dynamic response of the sensitive probe supported on it and the influence on the probe infrastructure is discussed.

HXN BEAMLINE DESIGN

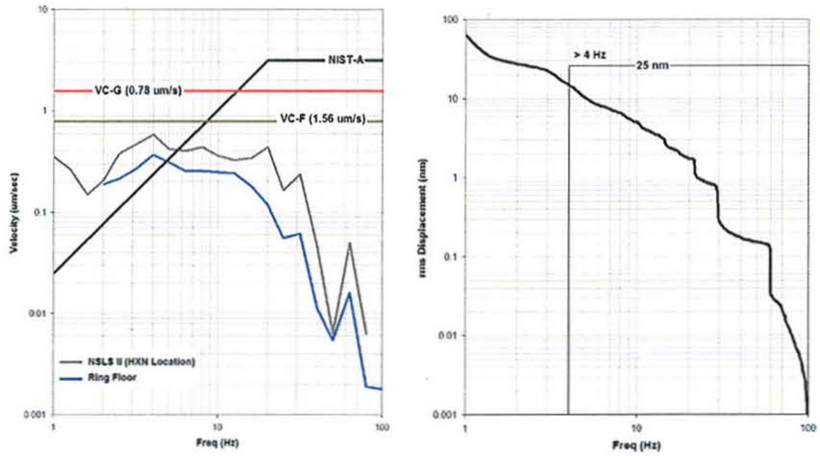
Natural and cultural ground vibration at the NSLS-II site which is expected to interact with the NSLS-II HXN endstation structure will inevitably filter through to the floor slab supporting the sensitive instruments. To achieve the intended spatial resolution of a few nanometers vibration on the floor must be kept at a minimum as well as the amplification of the floor vibration to the instruments supported on the floor. Therefore, there are two important vibration-related aspects that require both qualitative and quantitative assessment. The first is the full understanding of the HXN location's ground vibration environment both in terms of amplitude and content as well as the way the overall structure including the probe floor slab interact and filters ground vibration. The second, which applies to the instrument support infrastructure, is the coupling between the floor anticipated vibration spectra with the dynamic and vibration-isolating properties of the instrument and its support structure. To address the first aspect structural and dynamic features of the HXN structure are convoluted with the various spectra representing sources of vibration including natural ground motion, traffic-borne vibrations, operation-induced vibration and other external effects such as gust winds on the HXN and other structures in the vicinity. In addressing the second aspect, the spectra representing the combination of the source resultants on the endstation floor are convoluted with the dynamic properties of the probe-supporting structure and, by optimizing its design towards vibration isolating performance, the vibration levels at the probe can be minimized.

In conceptualizing and eventually designing the HXN endstation according to the stability requirements information on two controlling parameters are required namely the vibration stability levels or criteria that the endstation must satisfy and the site vibration characteristics the overall HXN structure must counteract and filter. Described below are the stability criteria the HXN design striving to meet on the floor supporting the sensitive instruments and the NSLS II site cultural and natural ground vibration characteristics.

Stability Criteria

Commonly used while designing vibration sensitive facilities, i.e. nanotechnology centers, microscopes, etc., velocity spectra on the supporting floor are used which are expressed in $1/3^{rd}$ octave band. This wide-band approach [2] is built on the principle that the vibration energy reaching the floor made-up of numerous modes is shared between closely placed frequencies and it does not lead to resonances of the system at a given mode. This is based on experience developed over the years of systems responding to wide-band noise. Figure 1(a) depicts the wide band criteria adopted for the HXN endstation floor in terms of velocity spectra according to the Vibration Criteria (VC) curves found in [2]. Also shown in Figure 1(a) are the NIST criteria which, while similar in concept to the VC curves they impose more stringent requirements on the lower frequency regime (< 20 Hz) which covers traffic-borne ground vibration. Such requirements for the low frequency range are typically satisfied by facilities below surface. The aim of the HXN design is to comfortably meet the VC-F criteria which translate into 1.52 μ/s floor velocity for the entire frequency range. The more demanding criteria expressed by the VC-G (0.78 μ/s) will be a desired level to operate at. Also shown in Figure 1(a) are field measurements at the location, do not include the NSLS II operation noise, of the HXN indicating that the VC-G criteria are within reach.

Given the sensitivity of the instruments to be supported on the endstation floor, however, narrow-band criteria where the individual vibration modes that arrive at the floor will be also important. This is because they will influence the design of the probe supporting structure in an effort to induce vibration isolation. Therefore criteria based on the power spectral densities and integrated *rms* floor displacements have been introduced to account for the vibration power contained within narrow frequency bands. The criteria shown in Figure 2(b) in terms of integrated floor displacement require that the for the frequency range above 4 Hz where ground motion tends to be incoherent the floor integrated displacement (*rms*) should remain below 25 nm. This value also represents the narrow-band vibration goal established for the NSLS II ring floor supporting the accelerator lattice.

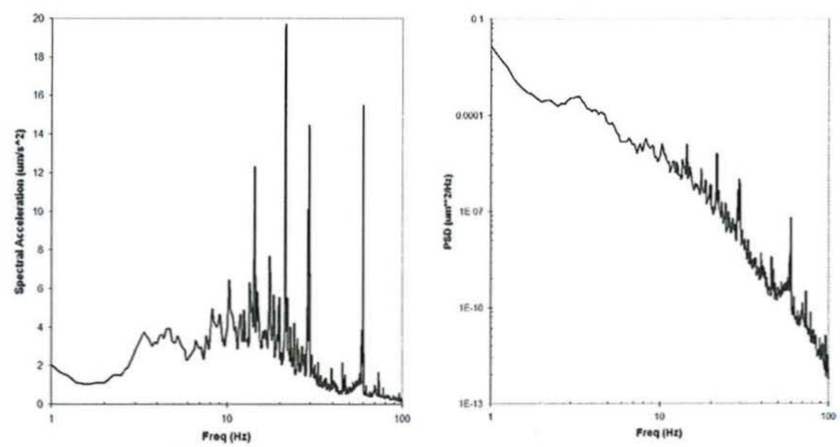


(a) (b)

FIGURE 1. Wide band (a) and narrow band (b) vibration criteria established for the HXN endstation floor.

NSLS II Site Characteristics

The ground vibration environment at the NSLS II site in general and the location of the HXN endstation in particular and the characteristics of the site substrate are important parameters and they must be considered towards the vibration-sensitive design. The NSLS II accelerator complex is build on a 900-foot quite uniform sand layer deposit overlaying the bedrock below. The sand deposit is inherently a stable medium and generally exhibiting attenuation properties. The presence, however, of a top dry sand layer above the water table (~10m below surface) forms a "wave-guide" for ground vibration wavelengths that can be trapped in the layer (> 8 Hz) thus allowing for ground disturbances to travel greater distances and arrive without undergoing attenuation at the site and the HXN location. Such disturbances are associated with the local and nearby highway traffic. Extensive site studies have been performed to both qualify and quantify the effects of vibration generation sources on the site and their impact on the desired stability levels. Through these studies it has been assessed that the ground vibration levels experienced at the NSLS II site will remain at levels which can lead to the satisfaction of both the accelerator ring criteria (narrow-band of 25 nm *rms* displacement above 4 Hz) and HXN VC-F criteria (wide-band, 1.52 μ/s spectral floor velocity in all frequencies). Figure 2 depicts ground motion spectra and power spectral densities obtained at the HXN location. Clearly depicted in Figure 2(a) is the highway effect registered in the frequency range of 3-12 Hz.

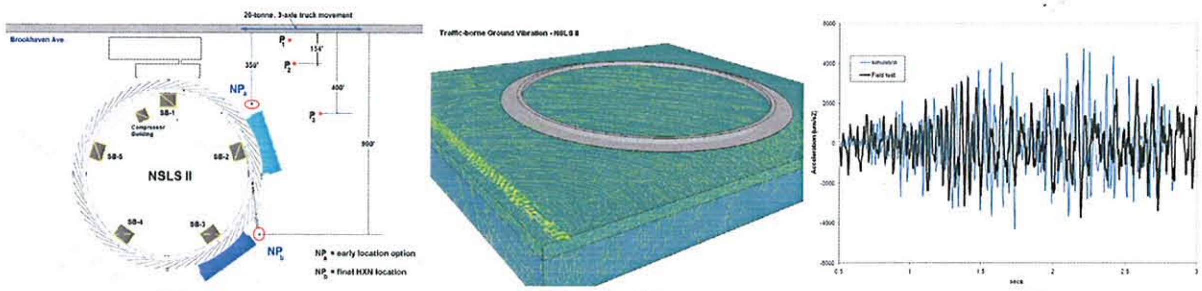


(a) (b)

FIGURE 2. Fourier spectrum (a) and power spectral density (b) of measured ground vibration at the HXN free-field site.

HXN Location Optimization

The design of the HXN endstation as well its interface with the rest of the NSLS-II accelerator complex was influenced by the quantification of vibration sources that currently exist at the site and anticipated ones that will surface when the accelerator is operational. To arrive at an optimal configuration a series of field studies accompanied by state-of-the-art ground motion propagation and interaction simulations were performed. Analyses performed in the early stages demonstrated that the HXN endstation can be designed as a satellite structure, totally detached from the NSLS-II experimental floor. While such an option removed the benefit of capitalizing on the "stiffness" provided by the monolithic accelerator ring structure, it provided for design freedom manifested in the structural isolating features that were finally implemented. One such benefit was the optimization of the HXN location relative to the ring and the spatial variation of ground vibration over the site. Shown in Figure 3 are the results of a field and simulation study that led to the adoption of the final location of the HXN relative to the ring. Shown in Fig. 1(a) is the footprint of the NSLS II ring along with a local traffic-borne vibration source. Field studies involving a 30-tonne truck traveling at 30 mph were performed to quantify the attenuating properties of the NSLS-II site and assess the minimum distance required for the HXN so it is unaffected from such disturbances. A ground vibration propagation model was developed (shown in Fig 3b) that included the characteristics of the site and in particular the top layer and water table interface and the monolithic ring structure. Comparison of field test and simulation results is shown in Figure 3c. By utilizing the benchmarked simulation model the optimal, and subsequently final location, was established (shown as location NP_b in Fig. 3a).



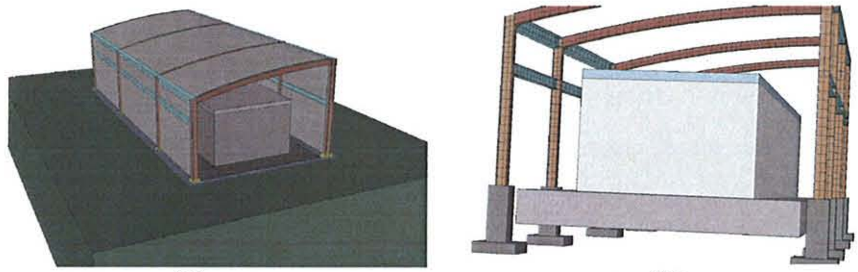
(a) (b) (c)

FIGURE 3. HXN Location Optimization relative to the NSLS II ring. (a) NSLS-II layout and field test parameters, (b) traffic-borne ground vibration propagation model used to validate the simulations against the field test and (c) comparison of field and simulation ground accelerations at a distance of 400' from the source.

HXN Structural and Vibration Isolating Features

In an effort to isolate the HXN floor that supports the sensitive probes, a number of structural and isolating features were implemented in its design. In particular, as shown in Figures 4a and 4b, the 1m-thick slab and the integrated instrument hutch enclosure is fully isolated from the endstation enclosure. The 1m-thick slab is "floating" on the sand substrate while the superstructure is supported by concrete footings and piers situated below the bottom surface of the slab. Detailed studies focusing on the optimization of the distance between the top of the footings and the bottom of the slab such that wind-induced transient rotations and impulses are attenuated as they propagate through the sand substrate and the HXN slab. A 36-inch separation distance was implemented into the final design. Intended also was the isolation of the endstation probe section from the HXN user area which was achieved by a complete separation of the user area 30 cm-thick slab-on-grade floor from the 1m-thick instrument floor. In addition, a top layer of special concrete (ConcreDamp) capable of dampening floor vibration induced by foot traffic and other impulse type loadings was introduced in the user area of the HXN. Figure 5 depicts a large-scale numerical model which was developed in order to analyze the response of the isolated HXN slab-hutch structure to vibrations borne within the accelerator ring and the lab office structure. In order to capture these effects, the detailed numerical model included all structural features of the structures that may influence the propagation of vibration toward the HXN floor. To enable the vibration analysis based on such large-scale model the explicit formulation of the finite element code LS-DYNA was utilized [3].

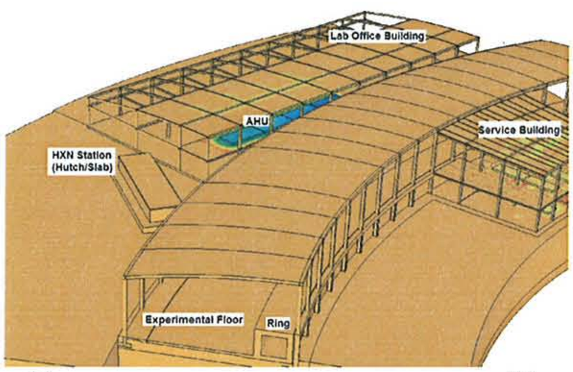
By adopting this isolated slab concept for the HXN floor, the independent response of the monolithic floor-hutch enclosure system to the various types of ground vibration (natural, cultural and wind) was assessed through an array of studies. Affecting the filtering potential and thus the vibration levels on the isolated slab floor are the dynamic properties of the monolithic structure and in particular its unique vibration modes. These were evaluated through numerical analyses which considered the interaction of the slab with the substrate according to the principle of a structure resting on an elastic foundation. Figures 6a and 6b represent the first two of the vibration modes the combined slab-hutch enclosure.



(a) (b)

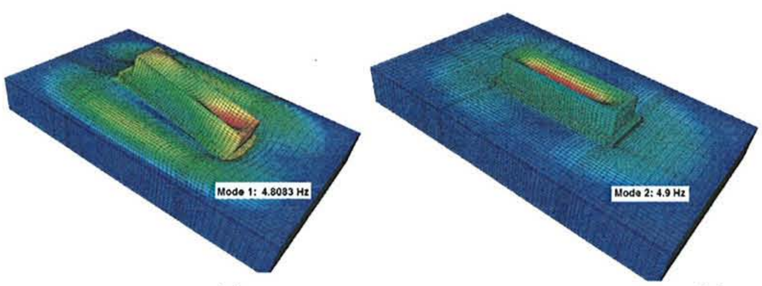
FIGURE 4. Design concept of the HXN floor and hutch enclosure isolated from the enveloping structure. (a) General HXN view depicting the substrate, the support floor and experimental hutch and the superstructure, and (b) detail of the structural isolation of HXN floor from the enveloping superstructure.

Regarding the superstructure, while isolated from the ring superstructure, it has for functionality reasons been structurally coupled with the LOB. The slab isolation however remained unaffected by this.



(a) (b)

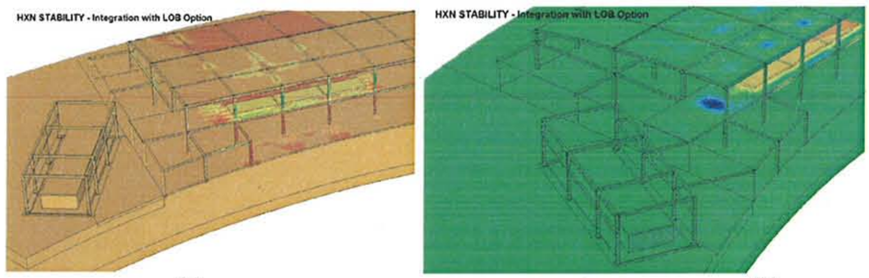
FIGURE 5. A detailed numerical model of the HXN floor and hutch enclosure and the NSLS II accelerator used in the simulations of vibration effects on the HXN from facility operations as well as external loads such as wind on the superstructures



(a) (b)

FIGURE 6. Vibration modes of the monolithic HXN floor and hutch enclosure structure.

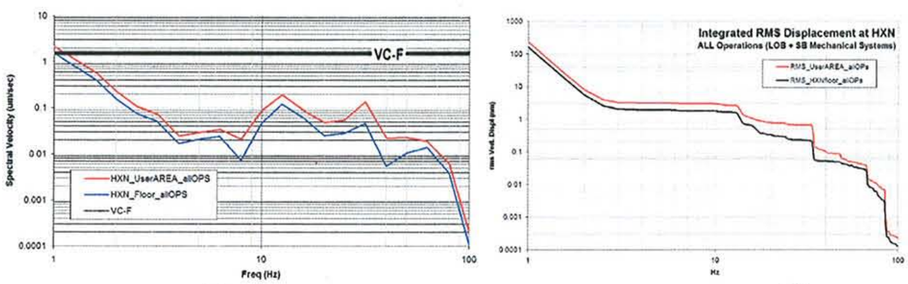
By utilizing the large-scale vibration propagation model cultural and natural vibrations expected to arrive at the HXN endstation were evaluated. These included (a) mechanical operations of the systems housed in the service buildings servicing the NSLS-II ring such as air-handling units, compressors and pumps, (b) operations in the lab office building that is adjacent to the HXN endstation, (c) traffic-borne vibration in the vicinity of the HXN, (d) surface ground motion waves arriving at the site in the form of Rayleigh waves as well as vertically propagating shear waves at the site, and (d) wind loads on the superstructures of the accelerator ring, the adjacent lab office building and the superstructure of the HXN itself. Of primary interest in all these studies was the quantification of the induced vibration on the HXN floor and comparison of the individual and combined effects with the intended stability criteria. The effect of the structural interface between the HXN superstructure and the adjacent Lab Office Building (LOB) was evaluated through a sensitivity study. Given that a physical structural connection, as shown in Figure 7b, would increase the functionality of the user area between the HXN and the LOB, the two alternatives were analyzed for wind effects and the vibration transmission from the operation of the large air-handling unit housed in the LOB. The studies confirmed that because of the complete isolation of the HXN slab from all surrounding superstructures physically connecting the HXN with the LOB structures (as shown in Fig. 7b) will not detrimentally increase the resulting vibration levels on the HXN slab. As a result the coupling of the two superstructures was implemented into the final HXN design.



(a) (b)

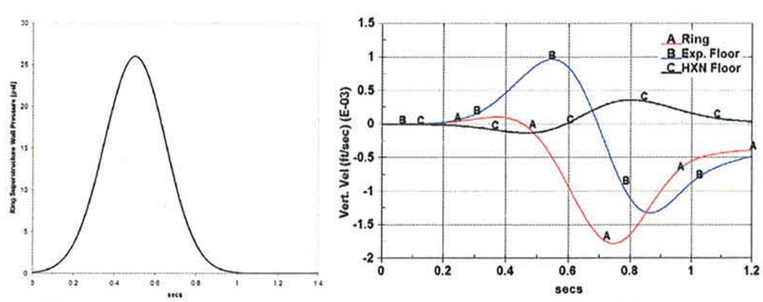
FIGURE 7. Structural interface options between HXN superstructure and adjacent Lab Office Building

Depicted in Figures 8a and 8b are HXN floor vibration levels predicted by simulations to be contributed by the operating systems of the NSLS-II and include the mechanical units of the nearest service building and the air handling unit of the LOB. The predicted contributions, which will add to the filtered by the structure ground vibration that is characteristic of the HXN site (as shown in Figures 1 and 2) are shown to be well within the desired criteria. Some results depicting the effect of extreme wind gusts on the ring superstructure and its implications on the different accelerator floors, including the HXN floor are shown in Figures 9a and 9b.



(a) (b)

FIGURE 8. Predicted effects of NSLS II operating systems on vibration levels on the HXN floor



(a) (b)

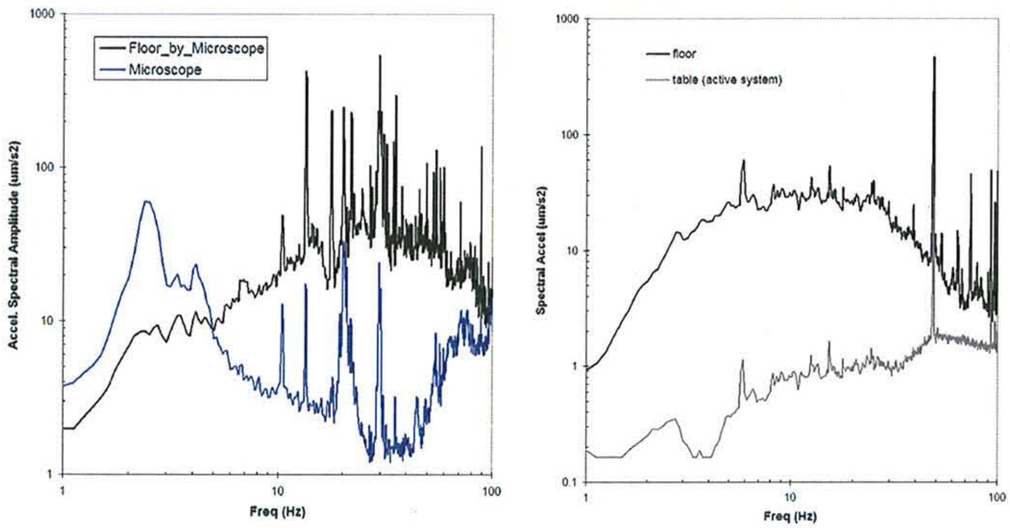
FIGURE 9. (a) Wind pressure impulse utilized in the wind analyses of NSLS-II ring and HXN endstation, (b) velocity transients computed on ring, experimental and HXN floors for a 50-mph wind gust on the ring superstructure.

HXN INSTRUMENT STABILIZATION

To ensure that the vibration stemming from all natural and cultural sources that will survive the isolating features and the "filtering" effect of the slab reaching the floor level where the sensitive instruments will be supported doe not undergo any further amplification a comprehensive study has been undertaken. In this study, the spectral as well as amplitude properties of the anticipated HXN floor vibration are considered along with the dynamic properties of the probe support structure in an effort to, either actively or passively or a combination of the two, design a system that will reduce the vibration signatures at the probe level.

In addition to the studies described in the previous section which deal with all the external sources that will contribute to the vibration environment on the HXN floor, isolating systems are being explored that will either minimize further amplification of the floor vibration levels or better yet reduce them to levels that will ensure that spatial resolution down to a nanometer level is feasible. As noted earlier, the criteria which govern the levels of vibration on the HXN floor are both wide-band (in terms of velocity spectra) and narrow-band in terms of power spectra of the vibration. While the wide-band will ensure of a stable environment (VC-F curve as the goal with VC-G as desired operational level) it is the narrow-band criteria which contain the narrow vibration peaks which will influence the design and isolating options of the probe support structure.

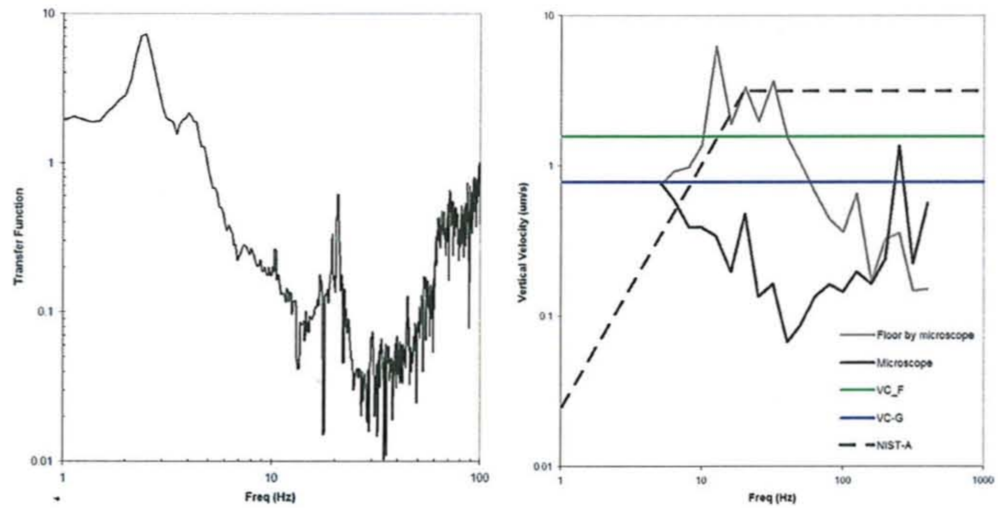
Given that different isolating principles are effective in different frequency regimes that may or may not cover the region of interest for the HXN sensitive probes, passive and active vibration isolation systems are being evaluated and their potential in being utilized at the HXN beamline endstation is being assessed. Shown in Figure 10 is measured vibration isolating performances of passive and active systems. As expected, and shown in Figure 10a, the isolation performance of a passive system is effective at frequencies greater that 5 Hz (a threshold governed by the natural frequency of the system) while at frequencies below 5 Hz it amplifies rather than reduces the floor vibration. The active system on the other hand shown in Figure 10b can affectively eliminate low frequency vibrations experienced by the HXN floor. Figure 11a depicts the transfer function of the passive system studied (transfer function is a property of the system irrespective of the floor vibration environment it operates at) and Figure 11b is a quantification of the isolation capacity of the passive system in terms of wide-band spectra.



(a) (b)

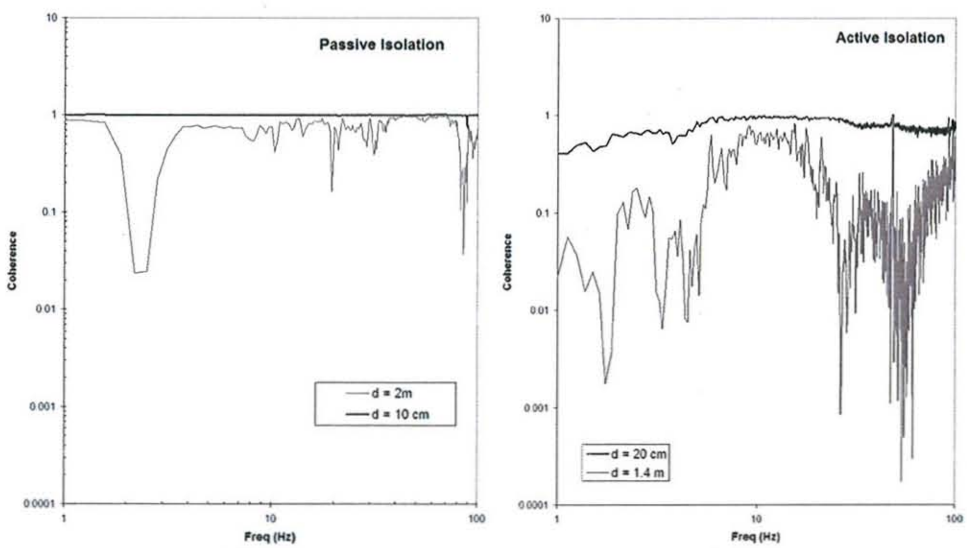
FIGURE 10. Measured vibration isolation capabilities of (a) passive and (b) active systems considered for the HXN endstation

In addition to the vibration stability at the final HXN experimental stage in terms of instant amplitude or integrated value, coherence of vibration on the plane of reference is also an important consideration and a parameter crucial towards achieving the desired nanometer-level spatial resolution. Shown in Figure 12 are coherence measurements on passive (Fig. 12a) and active (Fig. 12b) isolation systems.



(a) (b)

FIGURE 11. (a) Recorded transfer function of passive isolation system under study, and (b) passive system vibration isolation performance in terms of wide-band velocity spectra (1/3rd octave band)



(a) (b)

FIGURE 12. Coherence measurements on passive (a) and active (b) vibration isolation systems to support HXN probes

SUMMARY

Reported in this paper are results of a comprehensive study for the design and optimization of the HXN beamline endstation. The studies that have been undertaken are an integration of a wide array of field measurements with large-scale vibration propagation and interaction simulation models. The primary goal of these efforts was to verify that vibration stability criteria and levels can be met on the HXN endstation floor. These criteria are considered to be crucial in ensuring that x-ray experiments with spatial resolution down to a nanometer are within reach. In addition, of interest in this multi-faceted effort was the evaluation and feasibility of different types of vibration isolating systems in de-amplifying the HXN floor vibration further as it reaches the probe level.

The results of the studies, both experimental and simulation-based, revealed that the desired wide-band and narrow-band criteria established as stability goals for the HXN endstation floor can be met once the NSLS-II accelerator and HXN beamline come to operation. Further, it has been shown that de-amplification of HXN floor vibration is possible with the use of passive and, more promising, active vibration isolation schemes.

ACKNOWLEDGMENTS

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