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Dynamic Response of the APS Storage Ring Basemat: Preliminary Measurements

by

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Introduction

Successful operation of the Advanced Photon Source (APS) facility requires a positron beam of unprecedented stability. Stability of the beam is determined in large part by the vibrational stability of the quadrupole magnets. Any motion of the storage ring basemat will directly couple to the quadrupoles through the magnet support assemblies. As a consequence, the dynamic characteristics of the magnet/girder support assemblies and storage ring basemat and their response to ground motion are important.

Several studies have been performed on the response of various magnet/girder support systems [1-7], which, although they were not completely prototypical, were used to determine, among other things, system transfer functions. An unacceptable low-frequency response was exhibited in an early magnet support assembly design using conventional jackscrews for alignment [5]. The problem was eliminated by redesigning the support assembly using wedge-type alignment jacks [7]. From a vibration standpoint, the magnet/support system is very complex, consisting of many coupled subsystems. To obtain an accurate measure of response, the system must be prototypical. Toward this end, we plan to establish a vibration test bed for the magnet support assembly.

Ambient ground motion of the site was measured before construction of the APS began [8-10]. Predictive methods were used to calculate the dynamic response of the storage ring basemat and experimental hall [11]. The linac floor slab was the first slab-on-grade structure to be placed at the APS site. The vibration response of the linac floor slab, which was measured with the objective of gaining insights into the expected dynamic behavior of the storage ring basemat, is reported in Ref. 12.

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Based on the vibration study of the linac floor slab [12], it can be expected that slab-on-grade structures, such as the storage ring basemat, will generally follow ground motion in both the vertical and horizontal directions. In the study reported in Ref. 12, it was also observed that the large (linac) floor slab effectively filters out the higher-frequency (>15 Hz) components of ground motion, with the result that broadband magnification factors are <1 . However, the study also showed that magnification of particular frequency components was possible, suggesting a resonant system.

A feedback control system will be employed to ensure beam stability. Such a system, however, has limited dynamic range and frequency response. If a structural response frequency of the magnet support assembly were to coincide with a resonant frequency of the storage ring basemat or a dominant ground excitation frequency, the feedback control system may or may not be able to compensate, depending on the vibration amplitude and/or frequency.

When pile-driving at the vehicle tunnel took place on April 7-9, 1992, we recognized that it was a unique source of large-amplitude ground motion [13]. Taking advantage of the opportunity, we obtained measurements during the pile-driving operation that constituted a data base for characterizing the attenuation of surface waves in the ground [14]. As part of the effort, we instrumented the storage ring basemat and adjoining ground and measured the dynamic response of the basemat to ambient and forced (due to pile driving and/or construction) excitation. The results of these measurements, the first vibration measurements of the APS storage ring basemat, are the subject of this report.

Objective

To measure the dynamic response of the storage ring basemat to ambient and forced excitation, and to identify any dynamic characteristics and/or responses of the basemat that could result in excessive vibration coupling of the storage ring quadrupole magnets.

Technical Approach

The measurements were performed at the eastern sector of the storage ring. Two accelerometer triplets (an arrangement of three accelerometers oriented to measure response in the vertical and two orthogonal horizontal directions) were used. One triplet, Accelerometer Triplet A, comprised of Accelerometers 1-3 (see Fig. 1), was mounted on the top of a 2-ft-long steel stake driven into the ground at the location shown in Fig. 1 and used to measure

ground motion. The second triplet, B, comprised of Accelerometers 4-6 and was mounted on the storage ring basemat with a small aluminum plate which, in turn, was epoxied to the surface of the concrete. A single accelerometer that measured vertical response was placed on a basemat section where the inner-tunnel shielding wall was completed; see Accelerometer 7 in Fig. 1.

The measured accelerations were double-integrated to obtain displacements and were recorded on an FM tape recorder. Subsequent data analysis provided information on frequency content and amplitude.

Measurements and Results

The measurements were made on April 8, 1992, while (a) the pile driver was in use, (b) there was heavy construction activity, and (c) the site was quiet.

Pile driver in use

Typical displacement frequency spectra, obtained from the two accelerometer triplets while the pile driver was in use at $\approx 2:45$ pm, are shown in Fig. 2. Harmonics indicative of a Fourier series representation of a short rectangular pulse can be seen in both the ground and basemat displacement spectra. Attenuation of the harmonic components of the excitation source can be observed when the respective basemat/ground spectral amplitudes are compared. The 47-Hz component in the ground response spectra from the horizontally oriented accelerometers can be attributed to a resonance of the steel stake on which the accelerometers were mounted.

In Fig. 3, a measured displacement spectrum from the vertically oriented accelerometer of Triplet B is compared with the displacement from Accelerometer 7. The larger overall amplitude response at Accelerometer 7 can be attributed to the proximity of construction activities on the basemat, primarily operation of pneumatic chipping hammers. Attenuation of the vertical components of the pile-driver-generated harmonics can also be observed by comparing the Accelerometer 7 spectrum, given in Fig. 3, with the vertical-ground-motion spectrum of Fig. 2.

Heavy construction activity

Typical displacement spectra for a period of heavy site construction activity, but with the pile driver idle (3:24 pm), are given in Figs. 4 and 5. A large portion of the excitation was generated by a large soil compactor operating adjacent to the infield side of the storage ring basemat. A dominant 6.7-Hz response is observed

on all of the displacement spectra. Again, the basemat acts as a filter, providing attenuation primarily at frequencies >15 Hz.

Site quiet

Typical displacement spectra for a quiet period (5:48 pm) are given in Figs. 6 and 7. The basemat provides only limited attenuation of ground motion; for the northerly direction, a small amount of magnification is exhibited. With the exception of a 14.8-Hz component, the vertical amplitude at Accelerometer 7 is lower by a factor of ≈ 3 than the amplitude at Accelerometer Triplet B.

Dominant frequencies

A compilation of observed frequencies for several times is shown in Table 1. Two times, 3:24 pm and 3:46 pm, were during construction activity; the 5:09 pm time a quiet period. Most of the principal frequencies are between 6.7 and 7.6 Hz, indicative of a basemat resonant frequency in that range. In the study of the linac floor slab [12], a similar resonant-type behavior was observed, but at a frequency of 7.7 Hz.

Broadband (4-100 Hz) RMS displacements

Plots of broadband (4-100 Hz) RMS displacements from Accelerometer Triplets A and B, as a function of time for the northerly, easterly, and vertical orientations, are given in Figs. 8, 9, and 10, respectively. The northerly measurement (Fig. 8) indicates a large attenuation by the basemat of construction-related ground motion from the beginning of measurements to 3:46 pm. From 3:46 pm to the termination of measurements, both the ground motion and the basemat motion are approximately equal, with an RMS magnitude of 40 nm. The easterly direction displacement (Fig. 9) shows that the motion of the basemat follows that of the ground, with little attenuation by the basemat, during the construction time period. During the quiet time, the basemat response is approximately one-half that of the ground motion.

The measured vertical basemat displacements are given in Fig. 10. The response of the basemat is considerably higher than that of the ground during the construction period. This can be attributed directly to the fact that there was a considerable amount of construction activity on the basemat. For the quiet time (3:46 pm), the basemat follows the ground motion with the exception of several "spikes" at 3:45 pm, 4:25 pm, and 4:35 pm which are caused by light construction activity on the basemat. The average quiet-time RMS displacement of 40 nm is in good agreement with previous measurements of site ground motion [10]. A comparison of the measured vertical displacement at Triplet B with the vertical

displacement at Accelerometer 7 is presented in Fig. 11. Storage ring basemat displacement at Accelerometer 7 is considerably less than that at Accelerometer Triplet B. In Fig. 12, it can be observed that the vertical basemat motion at Accelerometer 7, follows the ground motion during the construction period, but is considerably less during the quiet time.

Figures 13 and 14 show the ratio of the horizontal-north basemat displacement to that of the ground and the ratio of the horizontal-east basemat displacement to that of the ground, respectively. During the quiet time period, the ratios, particularly that for the easterly orientation, are considerably <1 , which is indicative of the expected large damping characteristic of the basemat that leads to attenuation of ground motion. The ratio of measured vertical displacement at Triplet B to that at Accelerometer 7 is shown in Fig. 15. In this case, the displacements are considerably larger at Triplet B. It is postulated that this is due to the fact that the inner-tunnel shielding wall at Triplet B was not yet placed, with the result that the stiffening effect that the tunnel wall provides to the storage ring tunnel/basemat structure was not present.

RMS displacements in 10-100 Hz frequency band

Because the feedback control system can compensate, with a considerable degree of confidence, for vibrations at frequencies <10 Hz, RMS displacements within the frequency range of 10-100 Hz were studied and are presented in Figs. 16-24. Figures 16, 17, and 18 compare the ground and basemat displacements for the northerly, easterly, and vertical directions, respectively. In general, at frequencies >10 Hz, the storage ring basemat attenuates ground motion, especially for the case of the larger-amplitude contributions associated with heavy construction. In Fig. 19, it can be observed that, for the most part, the vertical basemat displacement at Accelerometer 7 follows the ground motion during periods of construction activity, but is attenuated during the quiet period. Vertical basemat response at Accelerometer Triplet B and Accelerometer 7 is shown in Fig. 20. The displacement amplitudes are considerably smaller than those measured over the broadband (4-100 Hz) frequency range and shown in Fig. 11. This indicates that most of the basemat motion occurs at frequencies of <10 Hz.

Figures 21, 22, and 23 show the ratio of basemat motion to ground motion for the northerly, easterly, and vertical directions, respectively. The average ratio for the northerly and easterly directions is <1 ; the average for the vertical is only slightly >1 . No large resonant response occurs at frequencies above 10 Hz. The ratio of vertical displacement of the basemat at Accelerometer Triplet B to that at Accelerometer 7 is shown in Fig. 24. As observed from the comparable wideband ratio data, the amplitude at Accelerometer 7 is less than that at Accelerometer Triplet B.

RMS displacements in the 20-100 Hz range

Inasmuch as it may be possible to extend the control range of the feedback system to 20 Hz, displacements in the range of 20-100 Hz for the northerly, easterly, and vertical directions were measured and are presented in Figs. 25, 26, and 27, respectively. For the northerly and easterly directions (Figs. 25 and 26) the ground response is greatly attenuated for the period of construction; for the quiet period it also exhibits attenuation, but of a lesser magnitude. In the vertical direction (Fig 27), the basemat tends to follow the ground motion for both the construction and quiet time periods; however, displacement values are very low. Vertical ground motion and basemat motion at Accelerometer 7 are shown in Fig. 28. With the exception of a time early in the construction period, the displacement levels can be considered approximately equal (i.e., the basemat motion follows ground motion) and of a very small amplitude during the quiet period. The RMS vertical displacements, given in Fig. 29, are similar.

Ratios of basemat displacement to ground displacement for the northerly, easterly, and vertical directions are given in Figs. 30, 31, and 32, respectively. The ratios are <1 for the northerly and easterly directions and only slightly >1 for the vertical direction. The ratio of vertical displacements at Accelerometer Triplet B to that at Accelerometer 7 (see Fig. 33) indicates that, for the quiet period, the high-frequency response at Accelerometer 7 is ≈ 1.4 times greater than that at Accelerometer Triplet B.

Discussion and Observations

Although the basemat itself was prototypical, the overall storage ring structure at the primary measurement location (Accelerometer Triplet B) was nonprototypical because the shielding walls had not yet been placed and, as a consequence, the structure was not as stiff as it eventually will be. Nevertheless, the measurements provided useful insights and the following observations can be made:

- The storage ring basemat appears to be stiffer and/or more highly damped in the horizontal direction.
- Motion of the storage ring basemat tends to follow that of the ground in the vertical direction.
- Vertical displacements of the storage ring basemat are a function of location, which implies the existence of a bending mode.

- Discrete frequencies in the 6-15 Hz range were considered indicative of a resonant system; however, no large basemat/ground amplification was observed, indicating that inherent system damping was large.
- The storage ring basemat effectively acts as a filter, attenuating high-frequency (>15 Hz) ground motion, primarily in the horizontal direction.
- The vertical displacement of the storage ring basemat (during the quiet period) was lower than that measured for the ground in May 1988 [10].

The dynamic response of the storage ring basemat is acceptable in the sense that 1. no resonant frequencies with associated large magnification factors were observed, and 2. the response to ground motion excitation was within the APS vibration criteria [15]. The measurement locations were selected on the basis of accessibility and site conditions at the time of measurement. The storage ring basemat and associated structure at the location of Accelerometer Triplet B was not prototypical, because the storage ring shielding tunnel walls were not yet placed at that location. Measurements are planned for a more prototypical section of the storage ring basemat (where the storage ring shielding tunnel is completed) .

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Table 1. Summary of observed response frequencies

Time and Location		Frequency, Hz			
3:24 PM					
Vert., Ground	6.7	7.2			13.5
Vert., Basemat	6.7				13.5
Vert., Basemat, 7	6.7	7.2		12.2	13.5
North, Ground	6.7				13.5
North, Basemat	6.7				
East, Ground	6.7				13.5
East, Basemat	6.7				
3:46 PM					
Vert., Ground		7.2		11.7	
Vert., Basemat		7.2	10.6		
Vert., Basemat, 7		7.2		11.6	13.5
North, Ground		7.2		11.6	
North, Basemat		7.2			
East, Ground		7.2		11.6	
East, Basemat		7.2		11.6	
5:09 PM					
Vert., Ground			9.4		14.8
Vert., Basemat			9.4		14.8
Vert., Basemat, 7		7.6	9.4		14.8
North, Ground		7.6			
North, Basemat		7.6			14.8
East, Ground		7.6			14.8 15.3
East, Basemat		7.6			14.8 15.3

NOTE: Bold type indicates principal frequency.

Fig. 1. Locations of storage ring basemat accelerometers

Ground

Basemat

Fig. 2. Typical displacement spectra resulting from pile-driving operation, 2:45 pm

Vertical

Basemat, Acc. Triplet B

Basemat, Acc. 7

Fig. 3. Typical vertical displacement spectra of the basemat at Accelerometer Triplet B and Accelerometer 7, obtained during pile-driving operation, 2:45 pm

Ground

Basemat

Fig. 4. Typical displacement spectra obtained during period of high site activity, 3:24 pm

Basemat, Acc. Triplet B

Basemat, Acc. 7

Vertical

Fig. 5. Typical vertical displacement spectra of the basemat at Accelerometer Triplet B and Accelerometer 7, 3:25 pm

Ground

Basemat

Fig. 6. Typical displacement spectra during quiet period, 5:48 pm

Basemat, Acc. Triplet B

Basemat, Acc. 7

Vertical

Fig. 7. Typical vertical displacement spectra of the basemat at Accelerometer Triplet B and Accelerometer 7 during quiet period, 5:48 pm

Fig. 8. Ground and basemat displacement, northerly direction, 4-100 Hz

Fig. 9. Ground and basemat displacement, easterly direction, 4-100 Hz

Fig. 10. Ground and basemat (at Accelerometer Triplet B) displacements, vertical direction, 4-100 Hz

Fig. 11. Vertical basemat displacements at Accelerometer Triplet B (basemat 4) and Accelerometer 7 (basemat 7), 4-100 Hz

Fig. 12. Vertical ground and basemat (at Accelerometer 7) displacements, 4-100 Hz

Fig. 13. Ratio of horizontal-north basemat displacement to northerly ground displacement, 4-100 Hz

Fig. 14. Ratio of horizontal-east basemat displacement to easterly ground displacement, 4-100 Hz

Fig. 15. Ratio of vertical displacement at Accelerometer Triplet B to vertical displacement at Accelerometer 7, 4-100 Hz

Fig. 16. Ground and basemat displacement, northerly direction, 10-100 Hz

Fig. 17. Ground and basemat displacement, easterly direction, 10-100 Hz

Fig. 18. Ground and basemat (at Accelerometer Triplet B) displacements, vertical direction, 10-100 Hz

Fig. 19. Vertical ground and basemat (at Accelerometer 7) displacements, 10-100 Hz

Fig. 20. Vertical basemat displacements at Accelerometer Triplet B (basemat 4) and Accelerometer 7 (basemat 7), 10-100 Hz

Fig. 21. Ratio of northerly basemat displacement to northerly ground displacement, 10-100 Hz

Fig. 22. Ratio of easterly basemat displacement to easterly ground displacement, 10-100 Hz

Fig. 23. Ratio of vertical basemat displacement at Accelerometer Triplet B to ground displacement, 10-100 Hz

Fig. 24. Ratio of vertical displacement at Accelerometer Triplet B to vertical displacement at Accelerometer 7, 10-100 Hz

Fig. 25. Ground and basemat displacement, northerly direction, 20-100 Hz

Fig. 26. Ground and basemat displacement, easterly direction, 20-100 Hz

Fig. 27. Ground and basemat (at accelerometer triplet B) displacements, vertical direction, 20-100 Hz

Fig. 28. Vertical ground and basemat displacements at Accelerometer 7, 20-100 Hz

Fig. 29. Vertical basemat displacements at Accelerometer Triplet B (basemat 4) and Accelerometer 7 (basemat 7), 20-100 Hz

Fig. 30. Ratio of northerly basemat displacement to northerly ground displacement, 20-100 Hz

Fig. 31. Ratio of easterly basemat displacement to easterly ground displacement, 20-100 Hz

Fig. 32. Ratio of vertical basemat displacement at Accelerometer Triplet B to ground displacement, 20-100 Hz

Fig. 33. Ratio of vertical displacement at Accelerometer Triplet B to vertical displacement at Accelerometer 7, 20-100 Hz

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