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CALCULATION OF EXPECTED ORBIT MOTION DUE TO GIRDER RESONANT VIBRATION AT THE APS UPGRADE*

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Abstract

The Advanced Photon Source (APS) is pursuing an upgrade to the storage ring that will provide electron beams with extremely low emittance. To allow users to take advantage of this small beam size, the beam orbit has to be kept stable to within a fraction of the beam size. To keep the beam orbit stable on a sub-micron level, one needs to carefully design magnet supports/girders so that the ground motion does not lead to excessive orbit motion due to resonant modes of the magnet supports. In this paper, we will describe the process of calculating the expected orbit motion due to girder resonant vibration. First, we will present the simulation results for the girder resonant modes, then we will calculate the orbit amplification factors for the girder deformation modes, then calculate the expected orbit motion using measured ground motion spectrum. This process can be used to evaluate the design of the magnet supports.

INTRODUCTION

The Advanced Photon Source (APS) is planning an upgrade to the storage ring that will provide electron beams with extremely low emittance. The new lattice is based on hybrid seven-bend achromat [1] and utilizes reverse bend magnets [2, 3] to achieve natural emittance of 42 pm·rad [4]. The lattice has very strong focusing magnets with a maximum integrated quadrupole strength K_1L nearly five times that of the current APS lattice. Since the effect of quadrupole vibration on the orbit stability is proportional to K_1L, it is expected that the ground vibration will have a stronger effect on the orbit in the new machine. Furthermore, the orbit stability requirements, which are defined as a fraction of the electron beam size, will be much more stringent. Careful prediction of the effect of ground vibration on the orbit stability becomes vital for the success of the upgrade project. In this paper we will describe the process that was used to calculate the effect of the girder resonant modes on the orbit stability.

GIRDER VIBRATION MODES

The APS-U magnets will be placed on three long and two short supports (girders) per sector. Three larger supports will rest on three concrete plinths, and two smaller supports will straddle between the three plinths. The plinths are used to effectively raise the floor and reduce the height of the girders. Figure 1 shows the magnet arrangement of one sector. The middle module containing focusing and defocusing quadrupoles and dipoles is called FODO [5], and the side modules, which contain quadrupole doublet, longitudinal-gradient dipole, and multipoles, are called DLM . The vibration mode analysis was performed using ANSYS Mechanical, Release 18.1 [6]. In order to accurately predict the modal response of the modules, dynamic stiffness testing was completed on the support components. Each support component was preloaded between two weights, hung from a crane, and a modal analysis was carried out. Using the equations of motions for this simple dynamic system along with the experimentally determined rigid body mode values, the 6×6 diagonal stiffness matrix of the component was determined. This stiffness matrix for each vertical and lateral support component was input into the ANSYS modal analysis along with the geometry of the magnets, girder, and plinth. Each module was simulated separately.

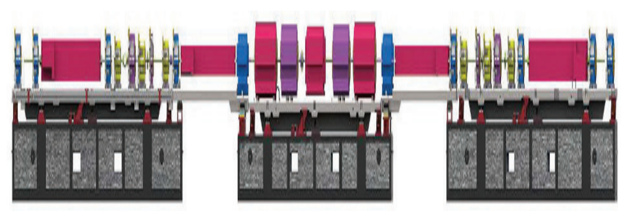

Figure 1: Layout of one APS-U sector.

At the time of writing this paper, the support design was slightly changed, and the new analysis is under way. The results presented here are obtained with the old support design. The new design will also be analyzed using the approach described in this paper. The analysis is limited to modes with resonant frequencies below 100 Hz due to the rapid drop in ground vibration amplitude at higher frequencies [7]. Table 1 gives the first five resonant frequencies. Figure 2 shows exaggerated magnet displacements corresponding to one of the modes of the DLM module.

Table 1: First five resonant frequencies (in Hz) for DLM and FODO girders.

Module	1	2	3	4	5
DLM	55.02	64.49	68.27	83.65	89
FODO	36.29	51.53	63.91	74.27	75.70

For each magnet, two vertically separated points are chosen on the upstream and downstream sides of the magnet, and ANSYS is used to calculate the displacements of these points for every mode. The displacement data are saved in an MS Excel spreadsheet and then converted to SDDS format [8]. Then, X, Y, and Z displacements and tilts are calculated for every magnet by averaging displacements of the

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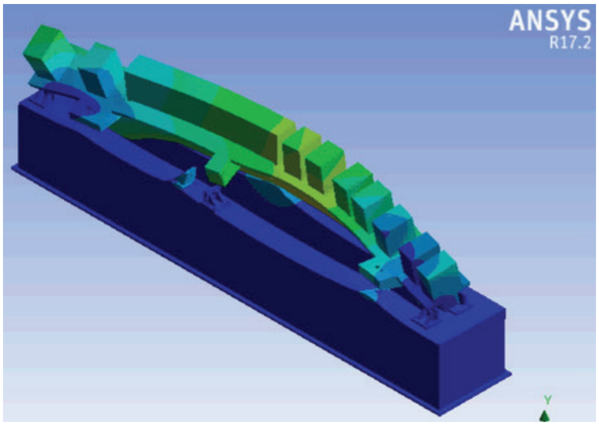

Figure 2: Example of the deformation mode.

upstream and downstream ends of magnets. Magnet pitch and yaw are ignored. Figure 3 shows transverse displacements of the magnets in arbitrary units for the first and third modes for the DLM module.

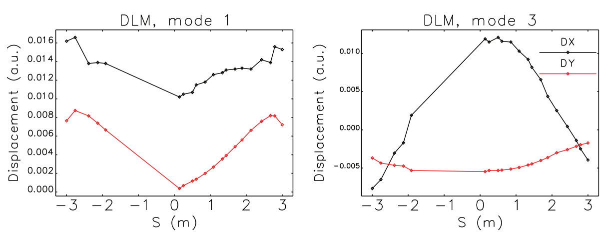

Figure 3: Example of displacement along the beam axis for some of the modes. The displacements are in arbitrary units, and points are located on both ends of magnets. The right-hand plot corresponds to the mode shown in Fig. 2.

LATTICE AMPLIFICATION FACTORS

Since all modes have different frequencies, the motion caused by different modes in one girder is independent. It means that the effect of the modes on the orbit can be considered separately and then the overall effect can be obtained by adding corresponding rms amplitudes of orbit motion in quadratures. An `elegant` [9] parameter file is generated that contains the displacements and tilts of each magnet for every mode, like the ones shown in Figure 3. To generate the parameter file, the modal displacements are normalized to make the maximum of all three displacements equal to 10 μm. Then `elegant` is used to calculate the closed orbit due to magnet displacements on a single girder for each resonant mode. The ratio of the maximum orbit distortion at the ID location to the maximum magnet displacement (10 μm in our case) is the single-girder lattice amplification factor f_m for a particular mode m.

Lets consider the orbit motion due to a single mode in all girders. The orbit displacement at the ID locations due to a single girder displacement in a resonant mode m is

$$q = f_m\, u\, \cos(\phi_q - \pi\nu_q),$$

where q stands for x or y, u is the girder mode displacement amplitude, and ϕ_q is the horizontal or vertical phase advance between the girder and the observation point. There is no beta function in this expression because the single-girder amplification factor f_m was calculated for orbits at ID locations only. The motion of every girder in the same mode is also independent because the coherence length of ground motion at frequencies above 30 Hz is less than 5 m [10], therefore, we can add the rms motion caused by each girder in quadrature. The total motion Q due to all N girders in one mode is

$$Q^2 = \sum f^2 u_i^2 \cos^2(\phi_i - \pi\nu) = f^2 N\left\langle u_i^2 \cos^2(\phi_i - \pi\nu)\right\rangle = \\ = f^2 N\left\langle u_i^2\right\rangle\left\langle \cos^2(\phi_i - \pi\nu)\right\rangle = 0.5 f^2 N u_{\mathrm{rms}}^2,$$

where we averaged $\cos^2$ to 0.5. The girder motion is driven by the ground motion, and since the ground motion spectrum is approximately the same at any location around the ring, the ground motion amplitude at some frequency is on average the same around the ring. The rms displacement of single girder is the rms of a sine function, or $u_{\mathrm{rms}} = 0.7u_{\mathrm{max}}$, where u_{max} is the ground motion amplitude at the frequency of interest. Therefore, the amplification factor of N girders vibrating in a resonance mode is

$$F = \frac{Q}{u_{\mathrm{max}}} = 0.7 f\sqrt{0.5N} \approx 0.5 f\sqrt{N}$$

To make amplification factors independent of beta function values at ID locations, we divide the amplification factors by $\sqrt{\beta_{\mathrm{ID}}}$. Table 2 gives the total amplification factors for resonant modes normalized by beta functions.

Table 2: Amplification factors of girder vibration modes summed over all girders and divided by $\sqrt{\beta_{\mathrm{ID}}}$. Units are $(1/\sqrt{\mathrm{m}})$.

Mode	DLM			FODO		
	F (Hz)	A_X	A_Y	F (Hz)	A_X	A_Y
1	55.02	8.3	4.3	36.29	2.3	0.9
2	64.49	13.4	1.0	51.53	0.5	3.3
3	68.27	19.9	3.9	63.91	13.4	0.2
4	83.65	4.5	5.1	74.27	3.1	1.4
5	89.0	6.4	2.3	75.70	1.6	7.4
6				80.37	7.6	2.6
7				95.87	15.5	8.2

GIRDER VIBRATION

It is assumed that the excitation for the girder vibration comes from the ground motion. The spectrum of the ground motion at APS was measured on several occasions, and the most recent measurement can be found in [10]. The wide-range Power Spectral Density (PSD) dependence on frequency is approximately $1/f^n$, where n is close to 4 [7].

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The exact response of a mode to the excitation, especially far from the resonant frequency, could be hard to calculate. But for frequencies close to resonance, its amplitude x can be described by the resonance curve

$$\frac{x(\omega)}{X} = \frac{Q}{\sqrt{(\omega-\omega_0)^2\left(\frac{2Q}{\omega_0}\right)^2+1}}, \tag{1}$$

where X is the driving motion amplitude (amplitude of the ground motion), ω_0 is the resonant frequency, and Q is resonator quality factor. The quality factor can be found using the damping constant ζ as $Q = 1/2\zeta$. The damping constant was measured by hitting a girder with a hammer and measuring the response. The measurements gave $Q \approx 50$. For this quality factor, which corresponds to a FWHM of less than $0.04 f_0$, the deviation of Eq. 1 from the actual response should be sufficiently small for $f : [0.5 f_0, 2 f_0]$.

The process of calculating the orbit-motion contribution of one mode begins by multiplying the ground motion PSD by the resonance curve from Eq. (1). Then, the resulting PSD is multiplied by the square of the corresponding mode amplification factor to get the PSD of the orbit motion caused by this mode. Finally, the orbit motion PSD is integrated between $0.5 f_0$ and $2 f_0$ to get the rms orbit motion due to this mode.

ORBIT MOTION CALCULATION

A short program was written that multiplies the ground motion PSD by the resonance curve and orbit amplification factor, then integrates the resultant PSD to obtain the rms orbit motion. The ground motion PSD was approximated as $1.6 \cdot 10^{-13}/f^{4.4}$ m^2/Hz for X and $8 \cdot 10^{-13}/f^{4.4}$ m^2/Hz for Y in the frequency range between 10 and 100 Hz. Table 3 shows the results. The total motion due to girder resonant modes is 180 nm in horizontal and 80 nm in vertical planes. This motion is rather small even before applying the orbit correction attenuation.

Table 3: Rms orbit motion due to girder resonant modes based on fitted ground motion. The number of girders is taken into account. Attenuation due to orbit correction is not included.

Mode	DLM		FODO	
	X (nm)	Y (nm)	X (nm)	Y (nm)
1	62	36	34	15
2	76	7	4	31
3	103	23	77	1
4	16	21	14	7
5	21	8	7	36
6			30	12
7			44	26
Total	144	48	101	58

The overall orbit motion due to ground vibration consists of non-resonant and resonant contributions. Non-resonant contribution can be calculated by simply multiplying the PSD of the ground motion by the girder amplification factors calculated assuming girders to be rigid bodies and considering girder displacements, pitch, yaw, and tilts. These amplification factors were calculated similarly to what was described above for the mode amplification factors. The obtained values are 20.3 and 16.5 for X and Y planes. Figure 4 shows the total expected orbit motion PSD due to ground motion above 10 Hz.

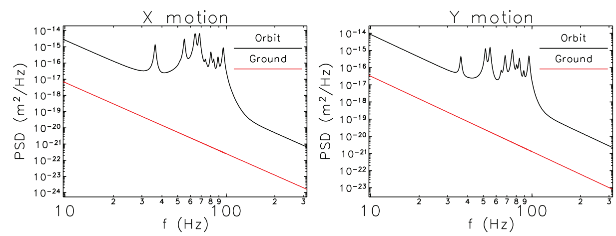

Figure 4: Total expected orbit motion (black) including resonant and non-resonant contributions due to ground motion shown in red.

CONCLUSIONS

We worked out a way to calculate orbit motion due to girder vibration modes driven by the ground motion. We took girder displacements due to resonance modes calculated by ANSYS and used them to calculate orbit motion amplification factors to obtain the expected effect of each mode on the orbit motion. Then we added all modes together in quadrature to get the effect of all modes. The estimate thus obtained of the expected contribution of the girder vibration modes into the orbit motion is about 200 nm in X and 80 nm in Y. Both the fitted ground motion PSD and the actual measured PSD give similar values. This contribution to orbit motion is rather small even without considering attenuation due to orbit correction and thus satisfies the orbit stability budget.

REFERENCES

[1] L. Farvacque et al. *Proc. 2013 IPAC*, 79 (2013).

[2] J. Delahaye et al. *Proc. PAC89*, 1611–1613 (1990).

[3] A. Streun. *NIM A*, 737:148 (2014).

[4] M. Borland et al. *NAPAC 2016*, 877–880 (2016).

[5] J. Nudell et al. *Proc. MEDSI 2016*, 83 (2016).

[6] www.ansys.com. ANSYS – Engineering simulations and 3D design software (2018).

[7] A. Sery et al. *Phys Rev E*, 53:5323 (1996).

[8] M. Borland et al. User's Guide for SDDS Toolkit (2014). Https://ops.aps.anl.gov/oagSoftware.shtml.

[9] M. Borland. ANL/APS LS-287, Advanced Photon Source (2000).

[10] V. Sajaev et al. presented at IPAC2018, TUPMF012.