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CALCULATION OF ORBIT DISTORTIONS FOR THE APS UPGRADE DUE TO GIRDER RESONANCES*

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Abstract

Maintaining sub-micron-scale beam stability for the APS-U Multibend Achromat Lattice places strict requirements on the magnet support system. Historically, magnet vibration requirements have been based on physics simulations which make broad generalizations and assumptions regarding the magnet motion. Magnet support systems have been notoriously difficult to analyze with FEA techniques and as a consequence, these analyses have been underutilized in predicting accelerator performance. The APS has developed a procedure for accurate modeling of magnet support systems. The girder mode shapes are extracted from these analyses and exported to accelerator simulation code *elegant* to calculate the static beam amplification factor for each mode shape. These amplification factors, along with knowledge of damping coefficients and the character of the tunnel floor motion, may then be used to predict the effect of girder resonances on beam stability and validate the magnet support designs.

INTRODUCTION

Typical magnet support stability requirements for light sources are specified by physicists with a girder-to-girder motion specification and a magnet-to-magnet motion specification (for elements mounted on a common girder) as shown in Table 1 for the APS Upgrade (APS-U). As the required stability of fourth-generation light sources becomes more stringent, so too do the requirements for support systems. The goal for APS-U is to limit mechanical sources of beam motion to less than one micron in each direction, without orbit feedback.

Table 1: APS-U Vibration Tolerances [1]

Specified over 1-100 Hz	X (rms)	Y (rms)
Girder Vibration	20 nm	20 nm
Quadrupole Vibration	10 nm	10 nm

Although the tolerances in Table 1 are useful to provide engineers with simple design requirements, they are based on broad generalizations regarding the character of the magnet motion which may be inaccurate. For instance, magnet-to-magnet vibration within a girder is simulated by physicists as uncorrelated motion, when in reality, this motion is mostly correlated and due to girder deformations (which can be simulated). In addition, the specifications are based upon a particular magnet grouping arrangement, making it difficult to accurately evaluate alternate magnet grouping arrangements in terms of beam dynamics.

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The APS has developed a procedure for modeling of magnet support system dynamics which has proven to be accurate in predicting modal response within 10%, as shown in reference [2]. The paper below describes a procedure for utilizing these modal analyses in order to predict the effect of measured ground motion and simulated magnet support system dynamics on beam motion. The procedure has been used to evaluate a previous magnet support grouping, as described in reference [3] and the results here are used to evaluate a new magnet support grouping.

APS-U MAGNET GROUPING

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. The middle module containing focusing and defocusing quadrupoles and dipoles is called “FODO”, and the side modules, which contain the quadrupole doublet, longitudinal gradient dipole, and multipoles, are called “DLM-A” and “DLM-B”.

The tolerances listed in Table 1 assume a magnet grouping arrangement where all quadrupoles between dipoles are located on a common girder. This arrangement does not allow for bellows in between modules, which makes fabrication, installation, and alignment of the accelerator components infeasible given the short period of time allotted for installation. The new magnet grouping arrangement places the quadrupoles adjacent to the dipole magnets on a common support with bellows on either end, called “QMQ”. Since the tolerances in Table 1 do not reflect this grouping, the strategy described in this paper is used to evaluate the magnet support design. The new and old magnet grouping arrangements are shown in Figure 1.

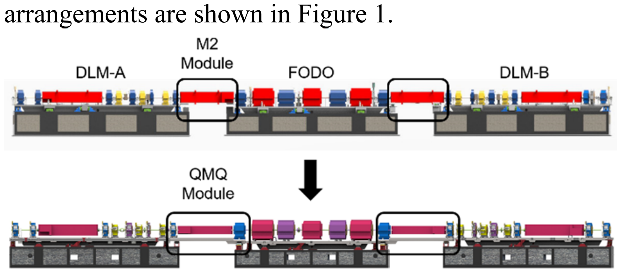

Figure 1: Previous (top) and current (bottom) APS-U magnet grouping arrangement.

GIRDER VIBRATION MODES

The girder modal analysis is performed using ANSYS Mechanical, Release 18.1 [4]. In order to accurately predict the modal response of the modules, dynamic stiffness testing is completed on the support components. Each support component is preloaded between two weights, hung from

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a crane, and an experimental modal analysis is performed. 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 is determined. This stiffness matrix for each support component is input into the ANSYS modal analysis along with the geometry of the magnets, girder, and plinth. During R&D, it was found that the storage ring concrete floor can be a considered a rigid boundary condition. All modules in the arcsector are included in the same analysis.

The analysis is limited to modes with resonant frequencies below 100 Hz due to the rapid drop in ground vibration amplitude at higher frequencies. Figure 2 shows the mode shape and a plot of magnet displacements corresponding to one of the modes of the DLM module.

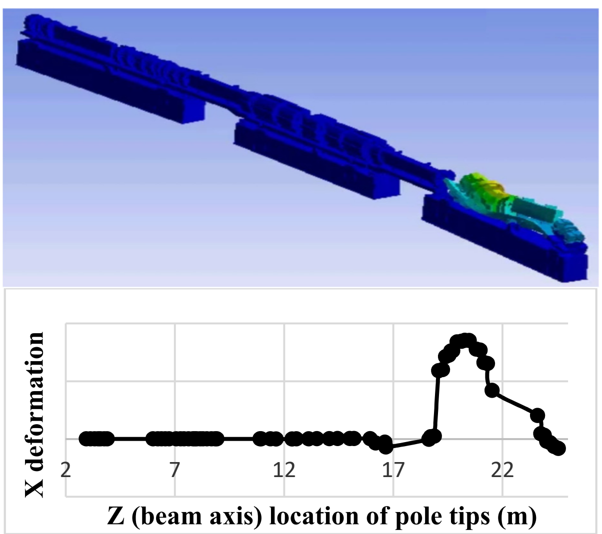

Figure 2: Mode shape illustration and plotted X-direction deformation for mode #10 – a mode which causes a relatively large orbit distortion.

LATTICE AMPLIFICATION FACTORS

Analysis shows the modes are lightly coupled and damped. This allows for the assumption that the modes can be assumed to be non-coupled, single-degree-of-freedom systems. Then, 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 quadrature. An *elegant* [5] parameter file is generated that contains the displacements and tilts of each magnet for every mode, like the one shown in Fig. 2. 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*.

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

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

where q stands for x or y, u is the girder mode displacement amplitude and $\emptyset_q$ 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 [6], therefore, we can add the rms motion caused by each girder in quadrature. The total motion Q due to all N girders for one mode is:

$$Q^2 = \sum f^2 u_i^2 cos^2(\emptyset_i - \pi\nu) = f^2 N \langle u_i^2 cos^2(\emptyset_i - \pi\nu)\rangle$$

$$= f^2 N \langle u_i^2\rangle\langle cos^2(\emptyset_i - \pi\nu)\rangle = 0.5 f^2 N u_{rms}^2 ,$$

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 a single girder is the rms of a sine function, or urms = 0.7umax, where umax is the ground motion amplitude at the frequency of interest. Therefore, the amplification factor of N girders vibrating at a resonance mode is:

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

To make amplification factors independent of beta function values at the ID locations, we divide the amplification factors by $\sqrt{\beta_{ID}}$.

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 [6] and are used in the calculations below.

For frequencies close to widely spaced resonances, the response amplitude x can be described by the resonance curve:

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

where X is the driving motion amplitude (amplitude of the ground motion), ω_0 is the resonant frequency, and Q is resonator quality factor. A value of 50 is used for the quality factor (damping ratio = .01) based on measurements of prototype girder resonances. The process of calculating the contribution of one mode is as follows. First, the driving motion PSD is multiplied by the resonance curve. Then, the resulting PSD is multiplied by the square of the corresponding mode amplification factor to get the PSD of the

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Table 2: Effect on beam motion from each girder mode below 100 Hz considering ground motion, girder dynamics, and amplification factors (some rows hidden).

Mode	Freq. (Hz)	Description	Amp. Factor (X)	Amp. Factor (Y)	Beam Motion (X)	Beam Motion (Y)
1	37.3	QMQs rocking, in-phase	2.0	0.7	46	18
2	37.4	QMQs rocking, opposite phases	9.9	0.3	228	6
3	41.9	FODO rocking	15.4	0.3	180	6
4	43.6	Upstream QMQ vertical buckling	2.0	0.9	20	16
5	43.6	Downstream QMQ vertical buckling	1.2	1.0	12	16
6	47.9	FODO twisting	8.4	1.3	97	13
7	53.3	Downstream DLM twisting-buckling	12.8	6.2	144	107
8	53.5	Upstream DLM twisting-buckling	20.6	5.6	227	94
9	56.5	Upstream DLM twisting-buckling	6.7	5.1	104	98
0	57.5	Downstream DLM twisting-buckling	22.3	11.8	468	270
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27	97.9	FODO wave-like distortion	0.5	20.1	2	111
Total					**680**	**610**

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.

A summary table of each girder mode, amplifications factors, and resulting beam motion is shown in Table 2. This table is extremely useful to determine the relative importance of each mode in inducing beam motion. For example, mode 10 contributes significantly to the total beam motion.

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 all six girder displacements and rotations. These amplification factors were calculated similarly to what was described above for the mode amplification factors. The obtained amplification factors are 58 and 63 for the X and Y directions.

RESULTS

The total beam motion due to girder resonant modes is 680 nm and 610 nm in the horizontal and vertical directions respectively, assuming no orbit correction is applied. Including the effect of non-resonant girder motion, the total open-loop beam motion due to ground motion and girder dynamics is 0.8 microns in both the x and y directions. A PSD plot of the measured ground motion and calculated beam motion is shown in Figure 3.

Using this analysis, the effect on rms beam motion of artificially changing the resonant frequencies of all girder modes by the same value may be explored (assuming modal order is unchanged), as shown in Figure 4. This plot shows the trend with frequency shift as larger amplitude floor motion in the lower frequency band is amplified, and also as narrow-band peaks in the floor motion are amplified. In general, one can see that designing for higher girder resonant modes is preferred. Since the goal is to keep the total beam motion in each direction below 1 micron, the current girder design is acceptable as long as modal frequencies are within roughly 5 Hz of the predicted values.

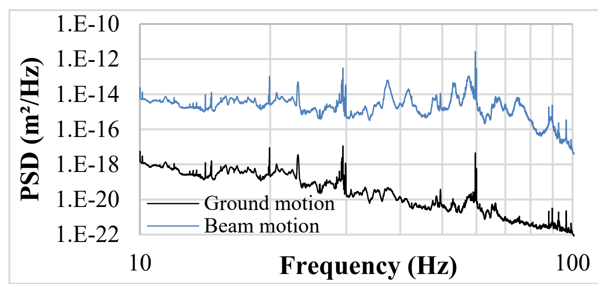

Figure 3: Measured X-direction ground motion (black) and expected X-direction beam motion (blue) including resonant and non-resonance girder vibration effects.

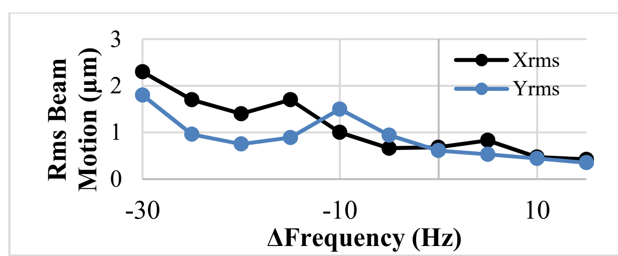

Figure 4: Rms beam motion vs. artificial frequency shift of all girder resonances.

CONCLUSION

A process has been developed which uses modal FEA data for a given magnet support design to predict the contribution of measured ground motion and girder dynamics to beam motion. The results are then used to evaluate the performance of the support system and determine a lower bound on modal frequencies, as well as provide useful information on the relative importance of higher order modes which may be used to further optimize the support system.

A new magnet support scheme is evaluated using the method presented above. The results show that the open-

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loop beam motion caused by the new support scheme is 0.8 µm in the x and y directions, which is larger than for the previous support design, but acceptable.

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