Ground Vibration Model Studies For APS Storage Ring.*

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Abstract

An analytical ground vibration model is developed for study of the vibration effects on the beam motion in the Advanced Photon Source (APS) storage ring. The different physical parameters associated with the wave characteristics and the vibration modes needed for the study are taken from the vibration studies carried out at the APS site. The implementation has been carried out using Mathematica^{TM}. The study is carried out for the frequency range 1-35 Hz, with a number of sources changing from one through ten. The program written in Mathematica^{TM}, calculates orbit distortion, beta wave change, tune change, dispersion change, and chromaticity change. However, the main parameter studied for the APS storage ring has been the orbit distortion. The merit factor associated with different modes excited by the vibrations has been calculated.

1 INTRODUCTION

The issue of the ground vibration-induced effects on the APS storage ring beam is important because of the sensitivity of the storage ring beam to the quadrupole displacement errors. Quadrupole displacement errors which occur due to vertical movement of the ring, i.e, movement in which the relative placement of the quadrupoles does not change, are relatively unimportant. Such a movement can be a result of tidal effects or long time period atmospheric pressure changes. This also suggests that the disturbances with wavelength, λ, greater than twice the diameter of the ring are not important. This means we must consider those vibrations having wavelengths less than or equal to the diameter of the APS storage ring.

Since the storage ring is 351 meters diameter, we are concerned with those vibrations with $\lambda \leq 351$ meters. In order to convert this wavelength range into the frequency range, we will consider two types of the sources: (1) far off sources and (2) local sources. Waves from local sources travel only short depths, usually in the top 100 meters or so, before they are reflected and cause girder motion. Waves from far off sources will travel to much greater depths, thus acquiring wave velocities of ($\sim$ 3km/sec), before emerging and causing girder motion. Therefore, the relevant frequency for such waves is greater than 10 Hz. These frequencies are quite high and are mostly associated with earthquakes. Barring earthquakes, two other far off sources of vibrations are ocean waves and micro-seismic activity. These waves fall into the frequency range less than 0.2 Hz and are not really a source of concern for the storage ring.

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Local sources are a different matter. The approximate velocities measured at the APS site for three types of waves, namely body waves/P-waves, shear-waves/S-waves, and surface waves/R-waves, are, 541 m/s, 216 m/s and 206 m/s, respectively [1]. The relevant frequency ranges for these waves are as follows: P-wave frequency $\geq$ 1.8Hz, S-wave frequency $\geq$ 0.8Hz and R-wave frequency $\geq$ 0.6Hz. Therefore, barring any major earthquakes, the main sources of concern are the local sources of ground vibrations

It can be shown [4] that if r is the distance from a given source, then the energy of the P-waves and S-waves from a point source falls off as $\frac{1}{r^2}$, whereas the R-wave amplitude falls off as $\frac{1}{r}$. This fall off is over and above the wave attenuation, with distance depending on frequency ν and characterized by, say, α. The frequency dependence of the α at APS is given by $\alpha = 0.10958 - .00135171 * \nu + 6.33202 * 10^{-5} * \nu^2 + 1.2303 * 10^{-6} * \nu^3$ [2], where α is in units of m^{-1}. Since the geometric fall off rate of the amplitude for P-waves and S-waves is higher than the surface waves, the major contribution to the vibrations comes from the surface waves generated in the neighborhood of the storage ring. Therefore, in our calculations we have used the surface waves starting from a point source as the main source of the ground vibration, lying in the frequency range from 1 Hz to 35 Hz.

In the following we will outline the fields characterizing the deformation of the ground due to the passage of a surface wave [3]. Then we will use these fields to obtain the distribution of the ground-displacement around the ring associated with the passage of a wave starting from a point source. This displacement affects the motion of the quadrupoles and other elements in an accelerator ring. In general, the translation from the ground motion to the motion of the magnetic elements depends upon which modes are excited for a given girder in the ring. Since one does not know all the possible modes, we have simulated several different modes. Some of these have been measured and others are given as rigid body modes proportional to the ground motion. Finally we will give the tables containing the merit factors for orbit distortion for several different girder modes.

2 WAVE-VIBRATION MODEL

Consider an accelerator ring of radius r. Let R_0 be the radial distance from the center (A) of the accelerator ring to the source (B) of the surface wave. Consider some point (C) along the accelerator ring. Angle ϕ is the angle at the center of the ring formed by lines CA and AB and angle θ is the angle at the source formed by lines CB and BA. In terms of r and ϕ the distance R from the source to the point on the ring under consideration is given by $R = [R_0^2 - 2rR_0\cos\phi + r^2]^{1/2}$ and $\tan\theta = \frac{r\sin\phi}{(R_0 - r\cos\phi)}$. One can then express the ground deformation in terms of these coordinates. Note that s is the direction of the beam motion, r is the horizontal direction and y is the vertical direction of the accelerator coordinates. In terms of these coordinates the ground displacement components are [3] [4]:

$$\begin{aligned} u_r &= \frac{b(r - R_0\cos\phi)}{R}[\frac{ke^{k_ty}}{2}(J_{-1}\cos\omega t + Y_{-1}\sin\omega t) + \\ &\quad (\frac{ke^{k_ty}}{2} + k_the^{k_ty})(J_1\cos\omega t - Y_1\sin\omega t)], \qquad (1) \\ u_s &= \frac{bR_0\sin\phi}{R}[\frac{ke^{k_ty}}{2}(J_{-1}\cos\omega t + Y_{-1}\sin\omega t) + \\ &\quad (\frac{ke^{k_ty}}{2} + k_the^{k_ty})(J_1\cos\omega t - Y_1\sin\omega t)], \qquad (2) \\ u_y &= b[k_te^{k_ty}(J_0\cos\omega t + Y_0\sin\omega t) + \frac{e^{k_ty}}{R}(J_1\cos\omega t + \\ &\quad Y_1\sin\omega t) + \frac{ke^{k_ty}}{2}\{(J_0 - J_2)\cos\omega t + \\ &\quad (Y_0 - Y_2)\sin\omega t\}]. \qquad (3) \end{aligned}$$

u_s, u_r, and u_y give expressions for the different components of the ground displacement around the ring as functions of r and the angle ϕ. If we know the response of the magnetic elements to this ground motion then the ground motion can be translated into magnet displacement errors. Knowing these errors, we can use the standard expressions for orbit distortion, orbit dispersion, beta function change, tune change, and chromaticity change [5].

3 APPLICATION TO THE APS STORAGE RING

For the APS storage ring the main concern is the effect of vibrations on the orbit distortion. Given the quadrupole displacement error as function of the phase, say $F(\phi)$, we can write the amplification factor for orbit distortion characterized by $I_{\delta x}$ [5], as

$$\begin{aligned} I_{\delta x} &= (\frac{1}{2\nu\sin(\pi\nu)})^2 \sum_{i=1}^{i=n}\sum_{j=1}^{j=n}[\frac{L_iF(\phi_i)}{\nu\beta_i}\frac{L_jF(\phi_j)}{\nu\beta_j} \\ &\quad \cos[\nu(\phi_i - \phi_j)]]. \qquad (4) \end{aligned}$$

The implementation of the above model is carried out by a computer program written in Mathematica^{TM}. The program randomly picks the position of the source of the disturbance, with the number of disturbances varying from one to ten. The program evaluates Eq.(1) through Eq.(3), multiplied by the attenuation factor $e^{-\alpha R}$ at the position of the girders around the ring for every given source. This is done for each source at a given frequency for some fixed time. Then the contribution at a girder is computed by superimposing the contributions of different sources and normalizing by the number of sources. This gives the displacement of the girders, which is transformed into the displacement of the quads, according to some specified prescription. In the present case, one of the prescriptions used was that quads vibrate according to the girder vibration modes given by [6] [7], such that their maximum displacement agrees with the mode specified in [7].

We next evaluate Eq.(4), which gives us the amplification factor $I_{deltax} = \frac{\Delta x}{\sqrt{\beta}}$. Having thus obtained the orbit distortion, we calculate a quantity merit factor given as the ratio of the orbit distortion to the maximum quad displacement. In Tables 1 through 13 this quantity is given in the last two columns of each table. The frequency of the wave considered is given at the top of the table. The first column specifies whether the girder carries four quads or three quads. The second and the third columns give the ratio of the maximum displacement of that particular quadrupole to the maximum displacement for the quad on that girder. The two columns refer to the horizontal and vertical motion. The merit factor for the horizontal motion for these modes varies from a factor of 10 to a factor of 24. That means the orbit distortion equals the merit factor multiplied by the maximum quadrupole displacement. Similarly, the merit factor for the vertical direction varies from a factor of two to a factor of seven; this does not seem to be of any particular concern. For the modes considered here, the horizontal orbital distortion also seems to be within tolerable limits. It may be mentioned however, that in our study we encountered modes at lower frequencies, falling between 1 Hz and 4 Hz, for which the merit factors were significantly larger. However those frequencies were not reported in [6][7].

4 REFERENCES

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[2] J. Jendrzezejczyk, private communication.

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[5] R. K. Koul, F. E. Mills, "Linearized Error Analysis for an Accelerator and Application to the APS Injector Synchrotron," Submitted to Nuclear Instruments and Methods.

[6] Jack Henderson, private communication.

[7] Jack Henderson, private communication.

Table 1: 10.13 Hz, $x_{max} = 5.1 \times 10^{-8} m$, $y_{max} = 1.61 \times 10^{-9} m$

Magnet	$\frac{\Delta x}{x_{max}}$	$\frac{\Delta y}{y_{max}}$	x_{merit}	$y_{meritfactor}$
1	0.95	0.66		
2	1.00	1.00	16	
3	0.84	0.42		2
4	0.60	0.04		

Table 2: 11.63 Hz, $x_{max} = 1.4 \times 10^{-7} m$, $y_{max} = 5.4 \times 10^{-9} m$

Magnet	$\frac{\Delta x}{x_{max}}$	$\frac{\Delta y}{y_{max}}$	$x_{meritfactor}$	$y_{meritfactor}$
1	0.96	0.67		
2	1.00	1.00	10	2.5
3	0.59	0.41		

Table 3: 24.31 Hz, $x_{max} = 3.35 \times 10^{-9} m$, $y_{max} = -3.01 \times 10^{-9} m$

Magnet	$\frac{\Delta x}{x_{max}}$	$\frac{\Delta y}{y_{max}}$	$x_{meritfactor}$	$y_{meritfactor}$
1	1.00	1.0		
2	-0.58	0.61	14	3
3	0.84	0.42		

Table 4: 24.31 Hz, $x_{max} = -5.55 \times 10^{-9} m$, $y_{max} = -4.2 \times 10^{-9} m$

Magnet	$\frac{\Delta x}{x_{max}}$	$\frac{\Delta y}{y_{max}}$	$x_{meritfactor}$	$y_{meritfactor}$
1	-0.52	1.00		
2	-0.50	0.87	14	
3	1.00	0.60		3
4	-0.21	0.42		

Table 5: 24.69 Hz, $x_{max} = 1.0 \times 10^{-9} m$, $y_{max} = -3.01 \times 10^{-9} m$

Magnet	$\frac{\Delta x}{x_{max}}$	$\frac{\Delta y}{y_{max}}$	$x_{meritfactor}$	$y_{meritfactor}$
1	1.00	1.00		
2	-0.71	0.27	17	5
3	0.10	0.03		

Table 6: 24.81 Hz, $x_{max} = -8.55 \times 10^{-9} m$, $y_{max} = -5.11 \times 10^{-9} m$

Magnet	$\frac{\Delta x}{x_{max}}$	$\frac{\Delta y}{y_{max}}$	$x_{meritfactor}$	$y_{meritfactor}$
1	-0.39	1.00		
2	-0.27	0.76	17	
3	1.00	0.77		5
4	-0.75	0.56		

Table 7: 25.25 Hz, $x_{max} = 7.5 \times 10^{-9} m$, $y_{max} = -1.6 \times 10^{-9} m$

Magnet	$\frac{\Delta x}{x_{max}}$	$\frac{\Delta y}{y_{max}}$	$x_{meritfactor}$	$y_{meritfactor}$
1	1.00	1.00		
2	-0.93	0.13	18	5
3	0.20	0.18		

Table 8: 28.19 Hz, $x_{max} = -4.65 \times 10^{-9} m$, $y_{max} = -6.6 \times 10^{-9} m$

Magnet	$\frac{\Delta x}{x_{max}}$	$\frac{\Delta y}{y_{max}}$	$x_{meritfactor}$	$y_{meritfactor}$
1	-0.27	-0.13		
2	-0.01	1.00	24	7
3	1.00	0.99		

Table 9: 28.19 Hz, $x_{max} = -5.30 \times 10^{-9} m$, $y_{max} = -3.43 \times 10^{-9} m$

Magnet	$\frac{\Delta x}{x_{max}}$	$\frac{\Delta y}{y_{max}}$	$x_{meritfactor}$	$y_{meritfactor}$
1	0.34	-0.34		
2	-0.62	0.21	24	
3	-0.27	1.00		7
4	1.00	0.08		

Table 10: 29.75 Hz, $x_{max} = -4.80 \times 10^{-9} m$, $y_{max} = -2.15 \times 10^{-9} m$

Magnet	$\frac{\Delta x}{x_{max}}$	$\frac{\Delta y}{y_{max}}$	$x_{meritfactor}$	$y_{meritfactor}$
1	-0.53	-0.18		
2	-0.21	1.00	16	6
3	1.00	0.98		

Table 11: 29.70 Hz, $x_{max} = 1.13 \times 10^{-9} m$, $y_{max} = -0.4 \times 10^{-9} m$

Magnet	$\frac{\Delta x}{x_{max}}$	$\frac{\Delta y}{y_{max}}$	$x_{meritfactor}$	$y_{meritfactor}$
1	-0.82	-0.23		
2	1.00	0.70	16	
3	0.53	-0.48		6
4	-0.54	1.00		

Table 12: 42.40 Hz, $x_{max} = -5.30 \times 10^{-9} m$, $y_{max} = -3.43 \times 10^{-9} m$

Magnet	$\frac{\Delta x}{x_{max}}$	$\frac{\Delta y}{y_{max}}$	$x_{meritfactor}$	$y_{meritfactor}$
1	0.34	-0.34		
2	-0.62	0.21	24	
3	-0.27	1.00		7
4	1.00	0.08		

Table 13: 45.44 Hz, $x_{max} = -5.30 \times 10^{-9} m$, $y_{max} = -3.43 \times 10^{-9} m$

Magnet	$\frac{\Delta x}{x_{max}}$	$\frac{\Delta y}{y_{max}}$	$x_{meritfactor}$	$y_{meritfactor}$
1	0.34	-0.34		
2	-0.62	0.21	24	
3	-0.27	1.00		7
4	1.00	0.08		