VIBRATION MEASUREMENTS IN THE KEKB TUNNEL

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1. INTRODUCTION

KEKB is a double-ring collider with a circumference of 3016 m [1]. The two rings are placed side-by-side in the tunnel. The KEKB tunnel consists of four straight sections, four arc sections and four experimental buildings located in the middle of each straight section. The 8-GeV electron ring (HER) and the 3.5-GeV positron ring (LER) intersect at the interaction point (IP) in one of the Tsukuba experimental building. The BELLE detector [2] is installed at the IP and collects physics data. Figure 1 shows the layout of the beam line near the IP.

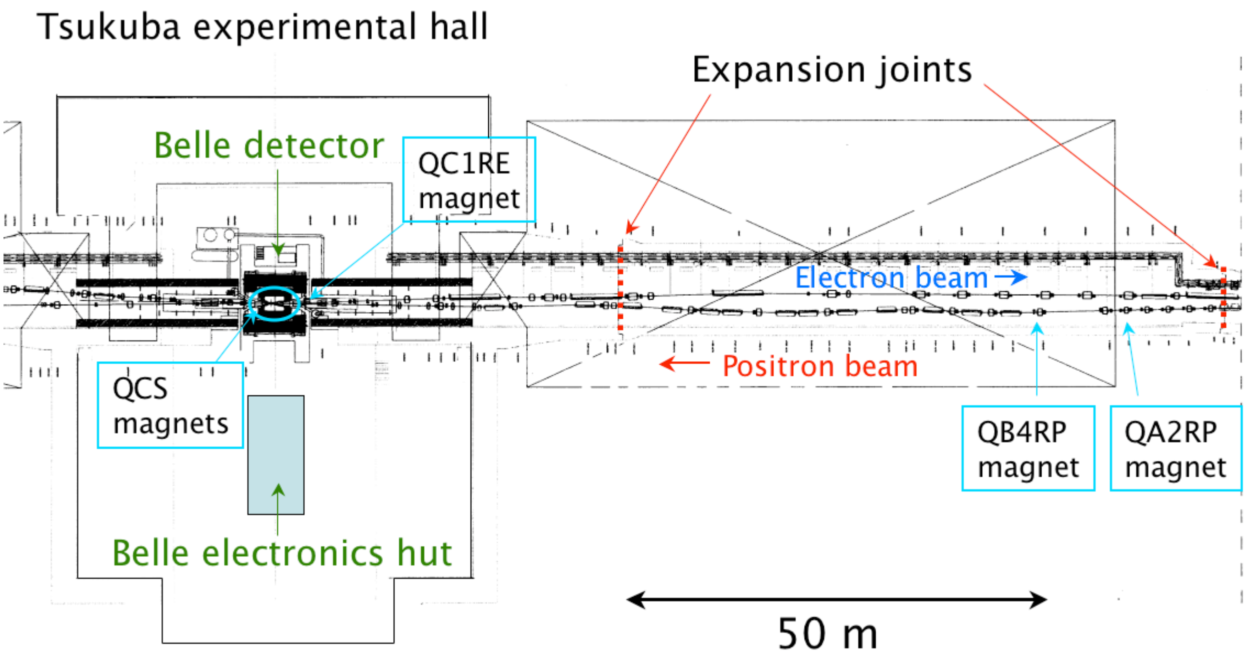

Fig. 1 The KEKB interaction region and the right side of the straight section.

A pair of superconducting quadrupole magnets, QCSL and QCSR, provide vertical focusing for the beam. An additional vertical focusing field is created by a pair of conventional magnets, QC1LE and QC1RE, for the HER beam. These magnets are called the IR (Interaction Region) magnets. In order to compensate for thermal expansion and contraction of the tunnel, expansion joints are placed every 50-60 m in the arc and straight sections. The motions of the IR magnets, the supporting table for the QCS cryostats and the non-IR magnets (QB4RP and

QA2RP in Figure 1) were measured. The floor motions near these components were also measured simultaneously. The measurement method and the data are presented in this paper.

2. SENSORS

The vibration data were measured by six acceleration sensors (MG-102S, Tokkyo-kiki Corporation). The data were amplified and then sent to the data logger (DS2000, Ono Sokki Corporation). The specifications of the sensors are summarized in Table 1. For the resolution of the sensors, see the huddle test results presented in the accompanying paper [3].

Table 1 Specification

Acceleration sensors: MG-102S (Tokkyo-kiki Corp.)	
Maximum Input	+/- 2 G
Sensitivity	0.5102 V s^2/m
Frequency range	DC-400 Hz
Cross talk	1/1000
Weight	160 g
Amplifier: OSP-06 (Tokkyo-kiki Corp.)	
Frequency range	0.1-400 Hz
Data logger:DS-2000 (Ono Sokki Corp.)	
A/D conversion	24 bit

Two sets of three sensors were used to measure along two horizontal axes and along the vertical axis. One set of sensors was always placed on the floor and the other set was placed on the magnet, for example. The axes of the measurement system are defined as in Table 2.

Table 2

x	Horizontal plane, perpendicular to beam direction
y	Horizontal plane, parallel to beam direction
v	Vertical

3. MEASUREMENT DATA

The vibration measurement was carried out at a sampling frequency of 512 Hz. The data recording time varied from 1 minute to 5 minutes in the following measurements.

3.1. Characteristic vibration of the quadrupole magnets

The vibrations of two different types of quadrupole magnets (QB4RP and QA2RP) in the straight section on the right-hand side of the IP (see Figure 1) were measured. The bore radii, lamination lengths and weights of QB4RP (QA2RP) are 166 mm (110 mm), 500 mm (400 mm) and 2.0 tons (1.5 tons), respectively. The heights of the magnets are different due to floor-level differences relative to the beam pipe. The sensors were placed on top of the magnets. The distances between the sensors and the floor were 1.9 m for QB4RP (the "tall" magnet) and 1.3 m for QA2RP (the "short" magnet). The magnets and the magnet supports are bolted together and the magnet supports are bolted to the tunnel floor. Figures 2(a)-(c) show the power spectral density (PSD) of the vibration of the floor and the magnets. The corresponding vibration amplitudes are plotted in Figures 2(d)-(f). The low frequency peaks at around 2-3 Hz observed in both floor and magnet motions were caused by human activities. The other significant peaks appear at around 13 Hz in all x,y and v directions. The amplitude of this peak is smaller for the "short" magnet. The 13 Hz vibration in the x direction of the "tall" QB4RP magnet shows the largest amplitude, about ~0.4 μm.

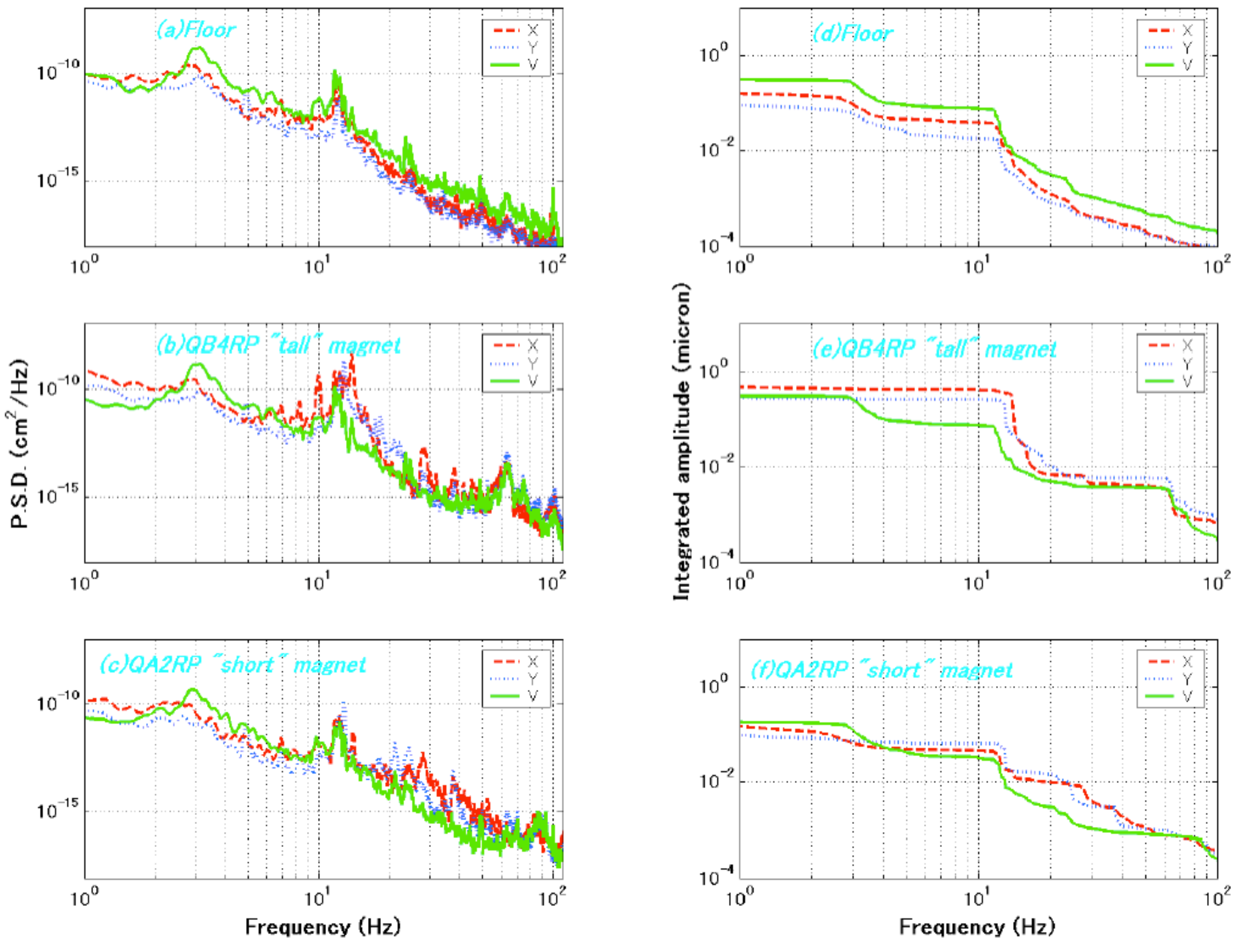

Fig. 2 Power spectra (a)-(c) and integrated amplitude curves (d)-(f) of the floor and the magnet motion.

A further analysis was carried out on the 13-Hz peaks in the QB4RP PSD plots. The amplitude spectrum of the magnet was normalized to that of the floor and plotted as a function of frequency as shown in Figure 3. The 13-Hz peak in the vertical direction disappears when normalized to the floor motion. Both the x and y horizontal peaks remain. In order to investigate the characteristics of these peaks, the normalized amplitude curves were fitted to the following function [4] where *a, b* and *c* are free parameters:

$$A = \frac{a}{\sqrt{\left\{1-\left(\frac{f}{b}\right)^2\right\}^2 + \left(2c\frac{f}{b}\right)^2}} . \quad (1)$$

Eq. (1) represents the amplitude of the solution of the equation of motion when there is a damping force proportional to the velocity. The parameters *a, b* and *c* correspond to the amplitude at zero frequency *(f=0),* the natural frequency of the magnet system and the damping factor of the vibration, respectively. The fitting results are summarized in Table 3.

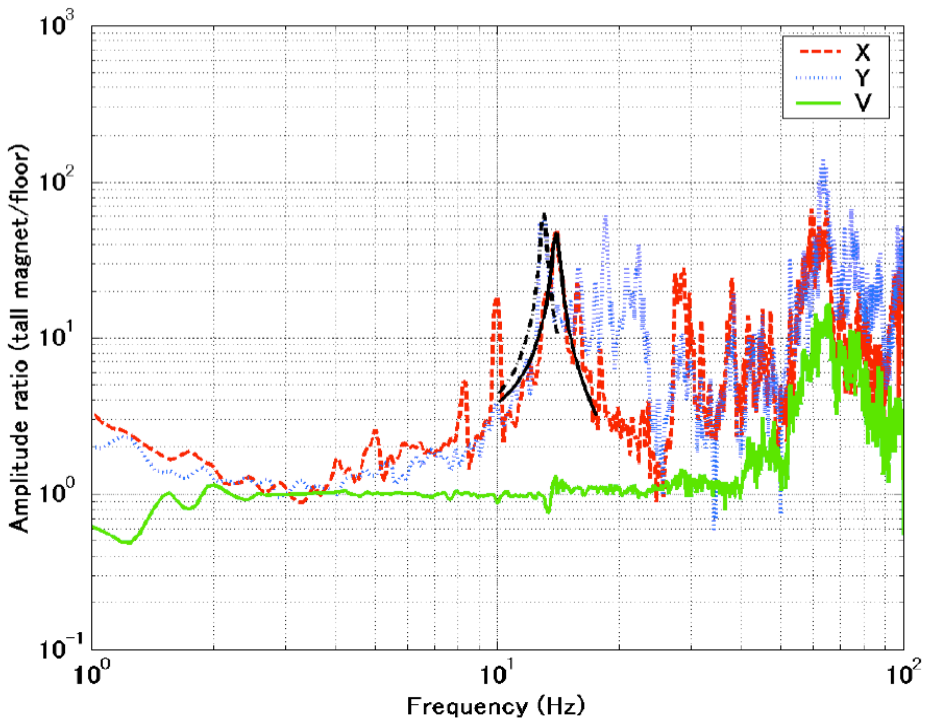

Fig.3 Normalized amplitude of the QB4RP "tall" magnet system. The solid and dotted curves are the fitting results for the 13-Hz vibrations in the x and y directions.

Table 3 Fitting results for the QB4RP magnet system.

Direction	Natural frequency (Hz) and fitting errors	Damping factor (%)
X	13.95 +/- 0.01	1.9
Y	13.00 +/- 0.01	1.4

The 13-Hz peaks are significant primarily in the x and y directions, and have a damping factor of about 2%. The damping factor obtained from fitting agrees well with the typical damping factor for bolt-supported structures as shown in Table 4 [5]. The fitting results of the "short" magnet system also give similar numbers for the damping factor. Therefore we conclude that the non-IR magnet systems have a 1st-order natural frequency of around 13 Hz. The effects of these magnet motions on the KEKB beam operation need to be evaluated.

Table 4 Typical damping factors for different structures.

Reinforced concrete	Welding	Bolt (rivet)
5 %	1 %	2 %

3.2. IR magnets

Since the beam sizes of the colliding beams are smallest at the IP (~2 μm vertical and ~100 μm horizontal), the effect of the motion of the IR magnets on the beam is more critical to the beam operation than that of the non-IR magnets. The same sensors were used to study the motion of some of the IR magnets, the supporting table and so on as indicated in Figure 4. The PSD curves of these components are plotted in Figure 5. There is a large peak around 8 Hz in the x direction in all spectra. The supporting table shows a vertical peak at this frequency as well. The origin of this vibration is not known at this point. The same fitting method was applied to investigate this 8-Hz peak. However, the formula in Eq. (1) did not represent the peak as well as in the non-IR magnet case. This is probably because the structures of the spectrum are much more complicated than those of the non-IR magnets. The complication comes from the fact that the IR magnets are mounted on a supporting table, which is attached to a movable stage.

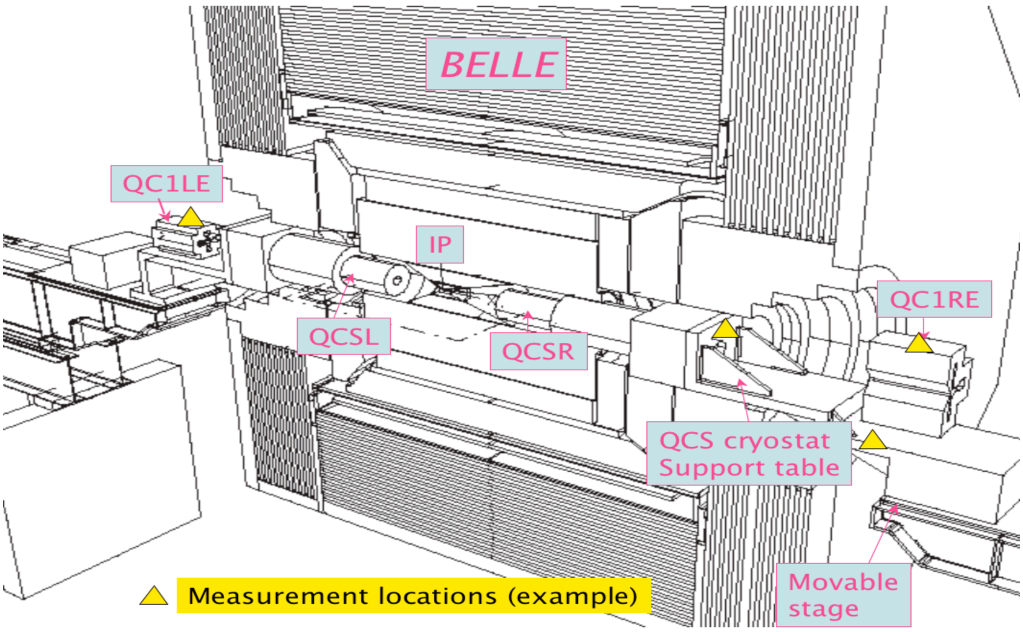

Fig. 4 Layout of the IR. Measurement locations are indicated by solid triangles.

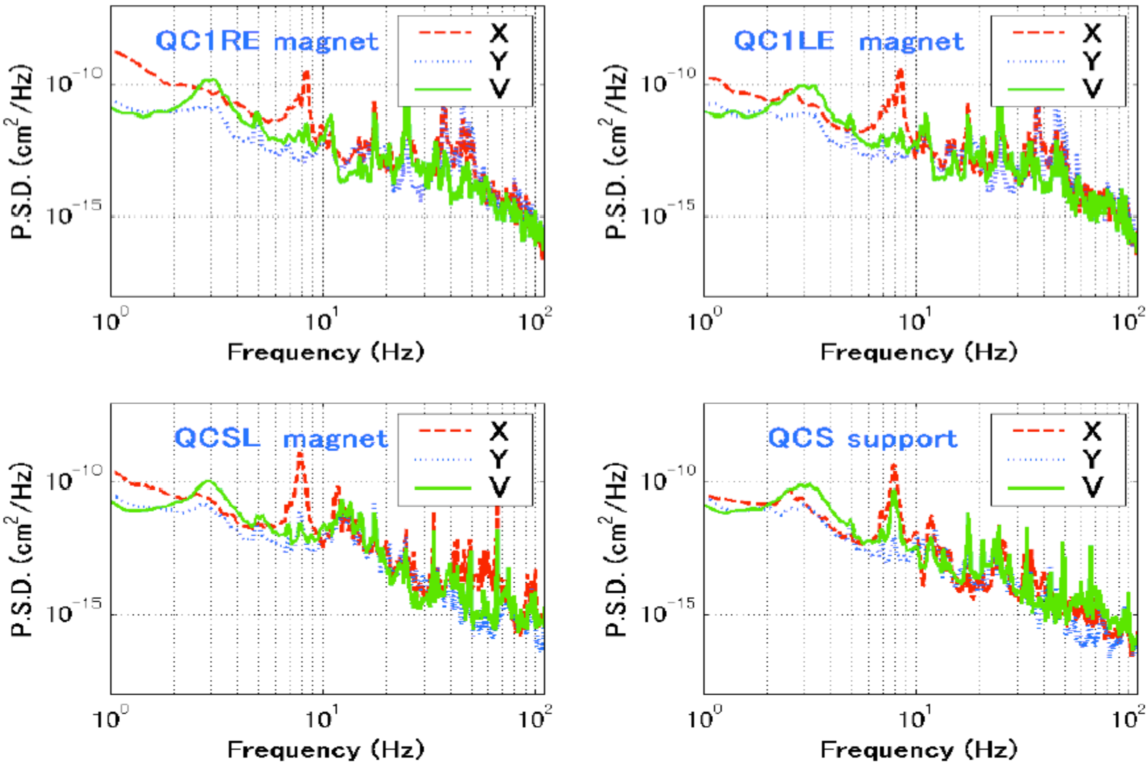

Fig.5 PSD plots of the IR magnets and the QCS supporting table.

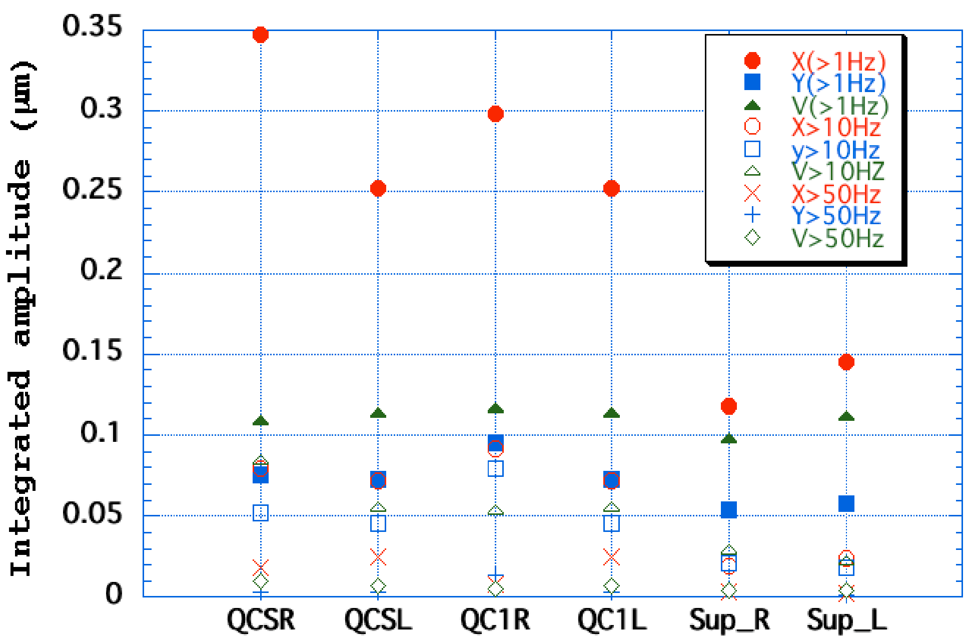

Fig. 6 The integrated amplitude of the IR magnet for different frequency ranges.

The integrated amplitudes are calculated for different frequency ranges and plotted in Figure 6. The amplitude is largest in the x direction in all cases. The vibration is on the order of several tens of nanometers. Compared with the horizontal and vertical sizes of the colliding beams at the IP, the vibration amplitudes of the IR magnets are small.

3.3. Effect of the air conditioning on the floor motion

A clear on/off effect due to the air conditioning (AC) in the BELLE electronics hut (see Figure 1) was observed in the floor motion near the IP. The floor motion was always recorded when taking data on the IR magnet. When the AC was turned off for regular maintenance work, we observed a change in the floor motion. Figure 7 compares the output signals from the sensors when the AC was on and off. The amplitude of the vibration was reduced in all three directions when the AC was turned off. The RMSs of the vibration were calculated and plotted for the x, y and v directions in Figure 8. Since there are multiple measurements of the floor motion, statistical error bars are also shown. The on/off effect is clearly seen on the right side floor of the IP. The effect on the left side floor is not as clear. The vibration amplitude of the right side floor seems slightly larger than that of the left side floor even when the AC is off. Figure 9 shows the integrated amplitudes for various frequency ranges for the AC on/off cases of the right-side floor motion. The on/off effects are not clear for low-frequency ($f<10$ Hz) vibrations but become prominent at higher frequencies. The vibration amplitude is almost twice as large for $f>100$ Hz vibrations in all three directions. However, the vibration amplitude decreases rapidly with an increase in frequency, and therefore the AC on/off effect on the KEKB beam operation is not serious.

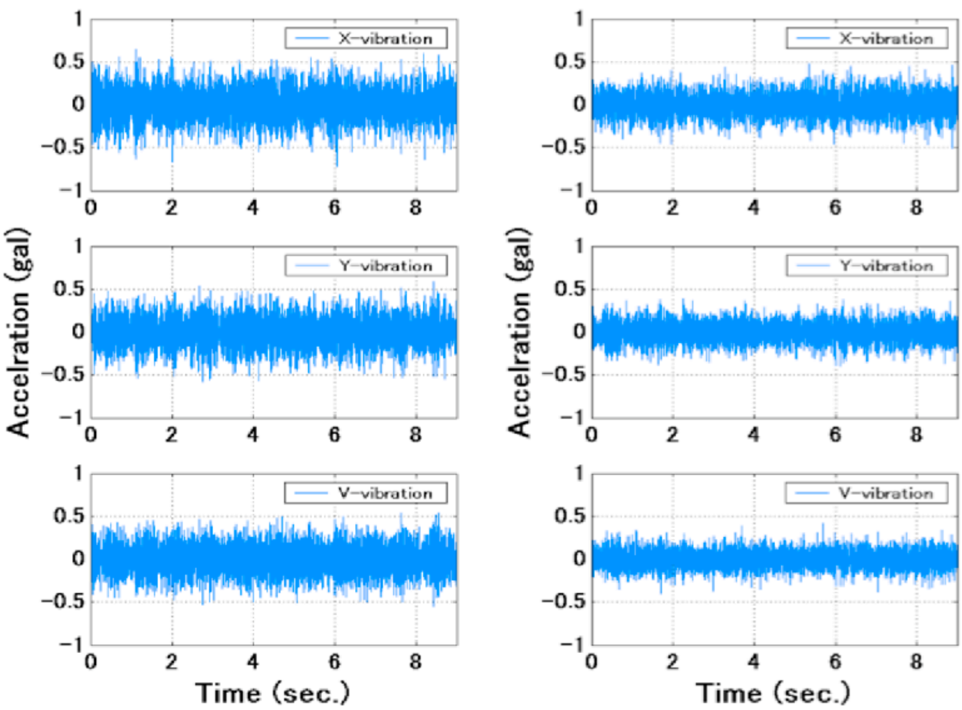

Fig. 7 Floor motion (Left: AC on/Right: AC off)

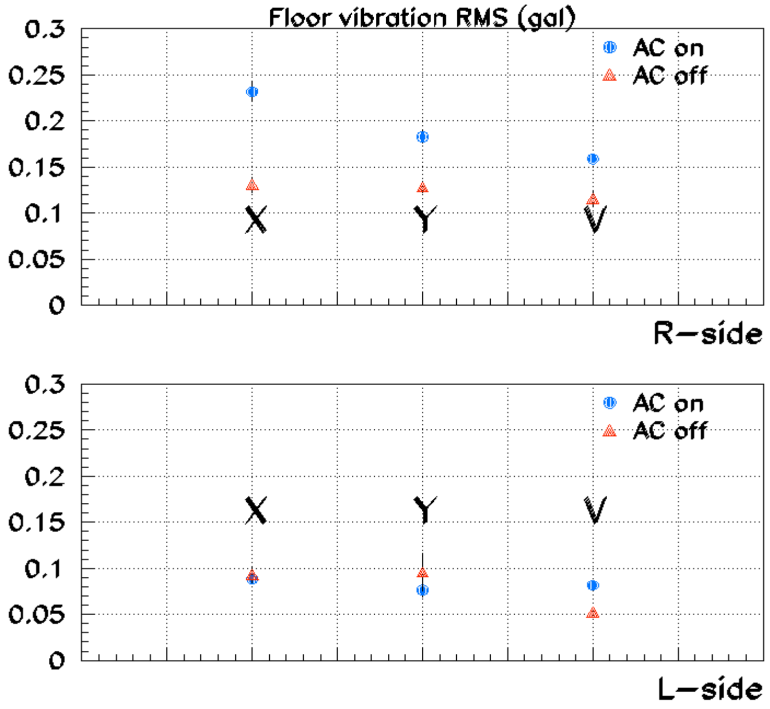

Fig. 8 RMS of the floor vibration.

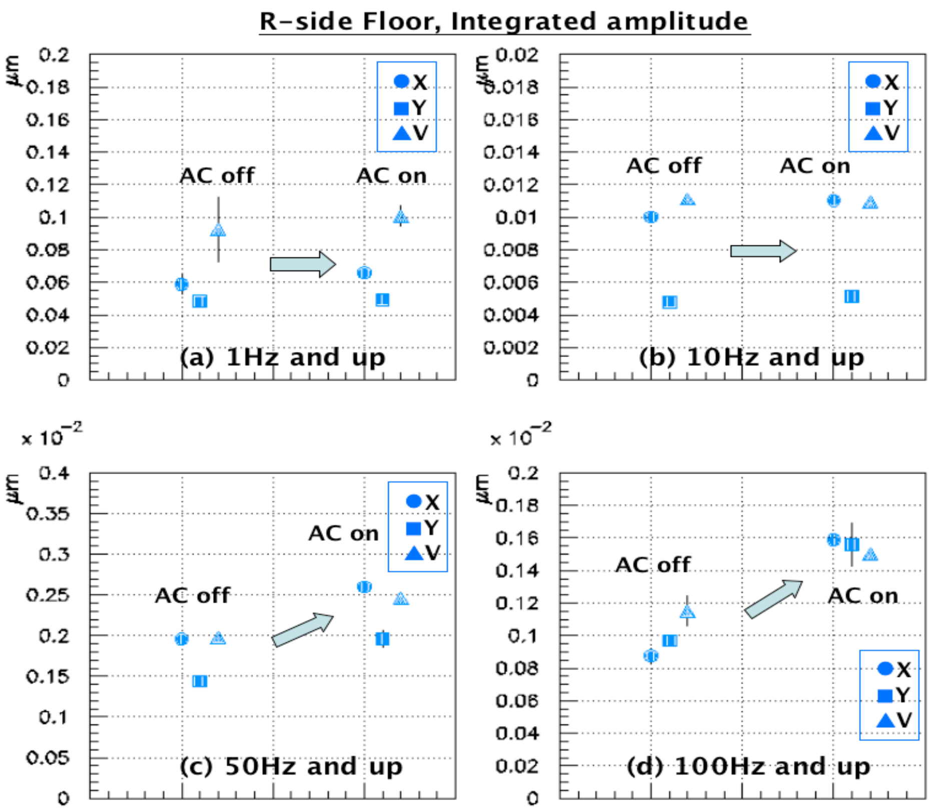

Fig. 9 Comparison of the integrated amplitude for various frequency ranges.

4. SUMMARY

The vibrations of the magnets and the floor in the KEKB tunnel were measured using acceleration sensors. The PSD curves of the non-IR magnet systems have much simpler structures than those of the IR-magnet systems. There is a clear 13-Hz peak in the horizontal vibration, which corresponds to the 1^{st}-order natural frequency of the non-IR magnet system. The IR magnet systems show more complicated spectra due to the multi-structured supporting system. The IR magnets have the largest vibration amplitude in the x direction with an integrated amplitude of a few tens of nanometers. Although the vibration amplitude is much smaller than the size of the colliding beams, the effects on the beam operation needs to be evaluated. Simultaneous measurements of beam oscillations by beam position monitors and mechanical vibrations by acceleration sensors are planned. A clear on/off effect due to the air conditioning in the BELLE electronics hut was seen in the floor motion near the IP. The effect is clearer on the right side floor of the IP and in the frequency region above 50 Hz. The integrated amplitude of the floor vibration in the high frequency region is on the order of a nanometer. This is not considered to be a serious problem for KEKB operation where the beam sizes at the IP are ~2 μm vertically and ~100 μm horizontally.

References

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[5] "Technical Guidelines for Seismic Design of Nuclear Power Plants", JEAG(Japan Electric Association Guide) 4601-1987