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MEASUREMENTS OF GROUND MOTION AND MAGNET VIBRATIONS AT THE APS

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Abstract

This article presents results of ground motion and magnet vibrations measurements at the Advanced Photon Source. The experiments were done over a wide frequency range (0.05-100 Hz) with the use of SM-3KV-type seismic probes from the Budker Institute of Nuclear Physics (Russia). Spectral power densities of vertical and horizontal motions of the APS hall floor and quadrupoles on regular supports were obtained. Also investigated were magnet vibrations induced by designed cooling water flow and spectral characteristics of spatial correlation of the quadrupole vibrations at different sectors of the ring. The influence of personnel activity in the hall and traffic under the ring on the slow motion of storage ring elements were observed. Amplitudes of vibrations at the APS are compared with results of seismic measurements at some other accelerators.

1 Introduction

The Advanced Photon Source (APS) is a synchrotron radiation facility under construction at Argonne National Laboratory. It is based on a 1.1-kilometer-circumference 7-GeV positron storage ring [1]. To obtain high brilliance X-ray radiation of the positron beam from dipole magnets and insertion devices at each of 40 sectors of the ring, the transverse beam sizes and angle divergencies should be rather small all around the circumference. Special kinds of magnetic focusing lattices and design values of horizontal and vertical beam emittances $\epsilon_H = 10 \quad nm$ and $\epsilon_V = 1 \quad nm$ allow us to get the following rms beam parameters: $\sigma_H \approx 300 \quad \mu m$, $\sigma'_H \approx 25 \quad \mu rad$ and $\sigma_V \approx 100 \quad \mu m$, $\sigma'_V \approx 10 \quad \mu rad$. These tiny dimensions result in the beam position being highly sensitive to vibrations of magnetic elements that produce jitter of the positron beam closed orbit and corresponding instability of synchrotron radiation beam angle and position. The issue arises from the fact that closed orbit distortion (COD) is a summation of all disturbances around the ring, i.e. many times larger than the amplitude of the distortion caused by a single magnet. For example, in the case when every i^{th} quadrupole with focal length equal to F_i is displaced on δ_i from its ideal position, the total COD X at the point of the ring characterized by beta function β is equal to :

$$X = \sum_i \frac{\delta_i \cdot \beta^{1/2} \beta_i^{1/2}}{2F_i \sin(\pi\nu)} * \cos(\Delta\phi_i - \pi\nu), \tag{1}$$

where β_i is the beta function at the point of the i^{th} quad, $\Delta\phi_i$ is the betatron phase advance from the quad to the point of observation, and ν is tune of the storage ring.

In the realistic case of uncorrelated displacement of different quads (see results of measurements below) the summation over the APS lattice gives factors of COD magnification in comparison with amplitude of vibration of about 50 for horizontal and about 40 for vertical distortions [1]. If one assumes that 10% jitter of the effective beam emittance is not dangerous for the purposes of the X-ray users then maximum allowable amplitudes of quad horizontal and vertical vibrations are $\delta_H \approx 0.34\mu m$ and $\delta_V \approx 0.12\mu m$, respectively [1, 2].

Corresponding criteria for the single quadrupole vibration amplitude give maximum values of $\Delta_H \approx 2.2\mu m$ and $\Delta_V \approx 1.3\mu m$ – i.e., much weaker than restrictions mentioned above.

We'd like to attract attention to another source of beam jitter. The tilt of the APS dipole (across the beam orbit) $\delta\theta$ produces a vertical kick acting on the beam equal to:

$$\Delta\theta_{beam} = \delta\theta \cdot \theta_0 \tag{2}$$

where θ_0 is the bending angle of the positrons' orbit by the main field of the dipole (about 80 mrad for the APS). It's easy to calculate that angular vibration $\delta\theta \approx (\delta_V/F)/\theta_0 \approx 0.25\mu rad$ will also cause 10% effective emittance increase. If one takes a dipole-to-floor distance of about 1.2 m, then such angular amplitude corresponds to a maximum allowable horizontal (across the beam orbit) dipole vibration of about $1.2 * 0.25 = 0.3\mu m$ – even a little smaller than for quads.

If the amplitudes of vibrations are above these conditions, some feedback system of beam position steering is necessary to keep X-ray beam positions over all the ring. The frequency band of the system should be larger than the band of concerned vibrations. Therefore it's very important to have the following information about a magnet's vibrations: (1) its spectral characteristics (power spectral densities) and (2) the spectral characteristics of spatial correlation of the vibrations (spectrum of correlation).

These characteristics are taken from statistical analysis of noise; generally speaking, ground motion and vibration are considered noise. Just to remind the reader, we will define these characteristics. The power spectral density (PSD) $S(f)$ which we calculated has the following relation to the rms value of signal $X_{rms}(f_1, f_2)$ in the frequency band from f_1 to f_2:

$$\delta X_{rms}(f_1, f_2) = \sqrt{\int_{f_1}^{f_2} S(f) df}. \tag{3}$$

The spectrum of correlation $K(f)$ of the two signals $X(t)$ and $Y(t)$ (mutual correlation spectrum) is defined as:

$$K(f) = \frac{\langle X(f)Y^*(f)\rangle}{\sqrt{\langle X(f)X^*(f)\rangle\langle Y(f)Y^*(f)\rangle}} \tag{4}$$

where the brackets $< .... >$ mean averaging over different measurements (usually 63 in this work), and $X(f), Y(f)$ are Fourier transformations of $X(t), Y(t)$. *Coherence* of the two signals is equal to modulus of complex function $K(f)$. By definition the value of the coherence does not exceed 1.0. During our experiments we took these signals from two similar seismic probes distanced from each other. If the value of the coherence is close to zero in some frequency band, it means absence of any correlation between the vibrations; if two signals are well-correlated, the value of the coherence is close to 1.0. As we mentioned above, COD in the APS is rather sensitive to spatially uncorrelated motion of magnets.

2 Description of the Experiment

Measurements were taken in the experiment hall of the APS building. Quadrupole vibrations were measured mainly at Sector 39 where the magnets were installed on regular girders and connected with pipes for cooling water. Some measurements were done at the Sector 19 floor just above the tunnel under the APS building, where we investigated the effect of traffic under the ring. At the time of experiments (19-26 of May 1994) there were no installed girders and magnets.

The main probes for slow ground motion were the SM-3KV type velocity meters which allowed us to obtain data in the 0.05-200 Hz frequency band. Two SM-3KV probes were carried from the Budker Institute of Nuclear Physics (Novosibirsk, Russia). These had been previously tested in vibrational studies for the linear collider VLEPP, in the UNK tunnel (Protvino, Russia), for the Novosibirsk B-Factory VEPP-5 and electron storage ring VEPP-3, and for the Superconducting Super Collider (Dallas, TX).

A commercial velocity meter SM-3KV was modified to extend the frequency band to 0.05-200 Hz. The proper pendulum period of the probe is 2 s. A special electrical feedback system (EFS) modifies the raw signal from the coil of the pendulum, which vibrates in the magnetic field system; thus, the output signal is proportional to the velocity of vibrations without resonance, emphasizing the proper period. At frequencies above 200 Hz the feedback system gain is small and it doesn't improve probe characteristics. The probe allows measurements of vertical as well as horizontal vibrations after some simple mechanical transformations. Probes were calibrated in the working frequency range. This was done through the special calibrated coil installed in the probes and by using a special vibrating table in Novosibirsk INP. The difference in the sensitivities of the two probes is less than 10%. Calibration results are presented in Fig. 1. The signal-to-noise ratio for the SM-3KV probe with the smallest observed ground vibration signals is less than 2 above 1000 Hz and below 0.05 Hz. Under usual and noisy conditions this ratio becomes many times larger.

Table 1 summarizes the main characteristics of the SM-3KV probes.

Electrical signals from the probes were digitized and processed by a CAMAC-based experimental set-up named ASSA (also from Novosibirsk INP), which includes [3]:

Table 1: Parameters of SM-3KV Type Probe

Frequency band without EFS, Hz	1-40
Frequency band with EFS, Hz	0.05-200
Sensitivity, mV s/μm	83
Free pendulum period, s	2.0
Pendulum inertial moment, $kG \cdot m^2$	$8.5 \cdot 10^{-3}$
Effective pendulum length, m	$3.4 \cdot 10^{-2}$
Coil sensitivity, V s/m	135
Sizes, cm	$17.0 \times 14.5 \times 23.0$
Mass, kG	8.0

- CAMAC crate
- CAMAC crate controller
- Two 10-bit, 4-channel CAMAC ADC
- CAMAC differential amplifiers (this allows us to change the total gain from 0.1 to 10^2 and low-pass frequency filters from 0.5 Hz to 2000 Hz)
- Two 256-K, 24-bit word CAMAC memories
- CAMAC timer
- CAMAC interface (IBM PC)
- IBM 486 personal computer.

The ASSA set-up is fully autonomous and needs only a 110-V outlet.

Signals from both probes were digitized simultaneously by ADCs with a sampling frequency (changeable by timer from 0.1 Hz to 32 kHz) and then were sent to memory for storage. The maximum memory available for one channel is 64-K 24-bit words. It corresponds to 17.8 h of permanent measurement time with a sampling rate of 1 Hz or about 1 min with 1 kHz. For long measurements we used low-pass filters at 2 Hz or 20 Hz; for fast analyses a 2000-Hz filter was applied.

The software allows us to analyze data in both the time and frequency domains, to transform raw signal data into vibration amplitudes (i.e., transform Volts to micrometers), to change all variable parameters of the hardware (sampling frequency, gains, filters), to calculate power spectral densities of all signals and spectra of correlation between all pairs of channels, and to present results graphically and produce hard copy on a printer.

For calculations of spectra we used the optimized 512-point Raider-Brenner algorithm based on a 16-point Winograd algorithm for discrete Fourier transformation. On an IBM PC/486, the algorithm works twice as fast as the usual Fast Fourier Transformation (FFT) technique of Cooley and Tukey. This algorithm is very useful because we can average over a greater number of spectra (usually 63) in order to reduce statistical errors.

3 Results of Measurements

Let us consider vertical motion of the APS quadrupole magnet AQ-1 installed on a regular girder in Sector 39. Fig. 2 presents the 80-sec record of the quad displacement since 11:20am 20 of May 1994. This figure shows two remarkable features: during the first 40 seconds of observation the motion looks like irregular oscillations with an amplitude of about $0.1\mu m$. This motion with periods of 5-14 sec is due to micro seismic waves produced by ocean waves at the closest coastal line and is often called "7-second hum." Due to their small attenuation such waves (few dozen kilometers wavelength) are clearly seen even in central parts of continents. In the PSD of the ground motion it will correspond to a wide "microseismic" peak at 0.07-0.2 Hz (see below).

The last 40 seconds of Fig. 2 illustrate the motion of the quadrupole while a man was passing beside. One can see that it caused 2.6 micron down displacement of the quad (together with the floor). This is twice above the allowable level for the APS. Of course, during the machine operation there will be no staff inside the hall, but any relocation of equipment heavier than 80 kG may cause the same static effect.

Another point of trouble is traffic under the ring, in a tunnel under Sector 19. The measurement of floor motion was done when a compact car drove in, stopped for a few seconds, and drove out of the tunnel. This resulted in 1.5 micron displacement as shown in Fig. 3.

Vibrations with higher frequencies (say, more than 1 Hz) are mostly due to technical noises; the strongest one is pressure fluctuations in flow of cooling water. Usually rms vertical amplitude of the quadrupole vibrations (frequency band 2-50 Hz) during our measurements was about 0.015-0.02 micron without water flow and as large as 0.06-0.09 micron with 200 g/sec cooling water flow. This is under the allowable levels for the APS mentioned in the Introduction and in rather well coincidence with previous measurements with S-500 vibroprobes by *Teledyne Geotech* [4]. Figure 4 shows power spectral densities of the quadrupole vibration with cooling water on and cooling water off.

To compare spectral properties of different signals *an amplitude ratio* $R(f)$ is often used which is equal to the square root of the corresponding PSDs ratio:

$$R(f) = \sqrt{\frac{PSD_1(f)}{PSD_2(f)}}. \tag{5}$$

Figure 5 shows the amplitude ratio for PSDs from Fig. 4 (PSD_1 - water on, PSD_2 - water off). One can see that the biggest effect the water flow gives – a factor of about 40 – is at a frequency of about 32 Hz. In the absence of water flow, mechanical properties of the girder give 8-10 times amplification of vibrations at frequencies about 46 Hz and 67 Hz as shown in Fig. 6 (PSD_1 - spectrum of the quadrupole vibration, PSD_2 - spectrum of the floor vibration).

Horizontal vibrations of the AQ-1 quadrupole have rms values in the band 2-50 Hz of about 0.02-0.04 micron in the absence of water flow; this is practically the same as for vertical motion. But the situation was cardinally changed when the 200-g/sec water flow was switched on. In Fig. 7 one can see a 4-second record of the quad vibrations. The maximum double amplitude of observed 10-Hz oscillations is up to 3 micron. The

10-Hz frequency is determined by the resonance of the girder support structure that is mechanically driven by coil and pipe vibrations due to the water flow.

Figure 8 presents PSDs of horizontal quad vibrations with cooling water on (solid line), and how the spectrum changed after a wooden stick was installed between the quad and the wall of the hall (it improved rigidity and decreased the rms amplitude four times from 0.84 micron to 0.22 micron, see dashed line). The PSD of horizontal movement of the floor is marked by stars. One could conclude that something similar to an additional wooden support may be used to obtain horizontal vibrations below the acceptable level (0.25-0.34 micron). Alternatively, other measures to damp the dangerous 10-Hz resonance should be applied.

Inasmuch as correlation properties of quad vibrations are important for estimation of positron beam orbit jitter, the corresponding experiments were carried out. The results of measurements of vertical motion coherence are shown in Fig. 9. The dashed line shows that in the case when two SM-3KV type probes are close to each other (0 meters distance) both of them produce the same signal and coherence is very close to 1.0 in the frequency band 0.08-70 Hz as it should be in the case when probes' internal noises are much less than a useful signal. The marked line corresponds to coherence of motions of two AQ-1 quadrupole magnets in different sectors of the APS ring (namely Sector 39 and Sector 37, distance about 60 meters). One can surely say that quad motions are practically uncorrelated at frequencies above 1-2 Hz because the degree of coherence is less than 0.5. Below 1 Hz and down to 0.07 Hz the coherence is close to 1.0 because at these frequencies the microseismic waves (correlated over large distances, at least over 20 km wavelength) are the main contribution to motion of the ground and quadrupoles. Frequencies below 0.05 Hz are, in fact, out of range of SM-3KV type probes, and in the next section we will discuss uncorrelated slow ground motion on the basis of other investigations.

4 Discussion and Conclusions

It is interesting to compare the spectra of vertical vibrations of the APS floor (this work), at KEK [5], in the SSC tunnel [6], and in the hall of the VEPP-3 storage ring (Novosibirsk) [7] (see Fig. 10). All data were obtained under "quiet" conditions (night or weekend). One can mention that all the spectra look rather similar, contain "microseismic" peak at 0.07-0.2 Hz, and demonstrate the same "falling" character. A valuable difference occurs at frequencies 1-100 Hz where technical noise plays a major role. One can see that the APS spectrum is closer to the VEPP-3 spectrum (that storage ring was under operation during measurements) than to data from KEK and SSC sites which were far away from additional sources of vibrations.

Slow ground motion, which is not considered in this experiment, may be separated into two parts: first, ground motion that is generated by local sources such as winds, temperature gradients, ground water, etc. It cannot be treated adequately as waves propagated in the ground. Amplitudes of such movements may sometimes cause significant influence on the accelerator's operation, but nevertheless, this ground motion is regular – it doesn't take place in the absence of the origin (wind, temperature fluctuations, etc.).

The second kind of low frequency motion has principally inevitable character and leads to diffusive wandering of ground. There is experimental law that states that diffusion of *relative* positions of two points of the ground takes place in accordance with the ATL formula [8]:

$$dX^2 = A \cdot T \cdot L, \quad A \approx 10^{-4} \mu m^2/(s \cdot m), \tag{6}$$

where T is time of observation, L is distance between the points, and dX is the rms value of the displacement.

Due to the small value of the coefficient A in Eq.(6), this diffusion often exists as a background for large regular processes but was properly measured in long term observations in geophysics laboratories and in accelerator tunnels (see [9]). The rms value of the close orbit distortion ΔX during time period T in a storage ring with circumference C may be roughly estimated as [9]:

$$\Delta X \approx 2\sqrt{ATC}. \tag{7}$$

Taking the APS parameter $C = 1100$ m, one may estimate that after two years, rms COD (without correction) will be about 0.5 cm. This value is not acceptable for the dynamical aperture of the ring.

Finally, let's summarize some results of the work:

- measurements of ground motion and magnet vibrations were done in the frequency band 0.05-100 Hz;
- correlation measurements have shown that motion of magnets may be treated as uncorrelated in the high frequency part of the spectrum (above 1-2 Hz);
- rms values of uncorrelated vertical and horizontal magnet vibrations under quiet conditions are about 0.015-0.04 micron, i.e., below allowable level for the APS;
- cooling water flow rate of about 200 g/sec doesn't cause dangerous vertical vibrations of quadrupoles;
- 10 Hz mechanical resonance of the system "quadrupole-girder" driven by the water flow fluctuations leads to quadrupole vibration amplitudes some three times above acceptable limits and additional damping support is needed;
- relocation of heavy masses inside the APS experiment hall or traffic in and under the ring may cause unacceptably large single quadrupole magnet vertical displacements.

5 Acknowledgments

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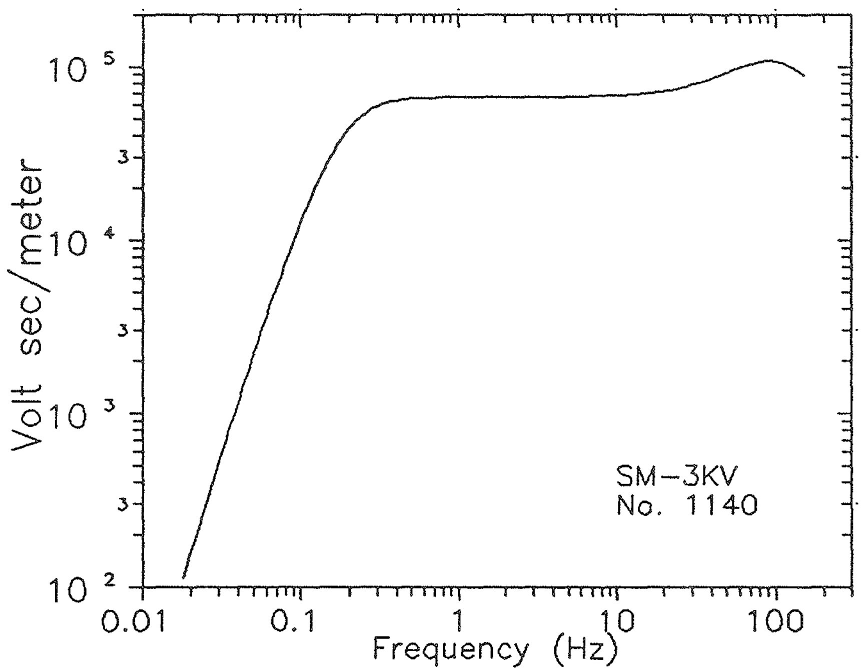

Figure 1: Calibration data for SM-3KV type seismometer.

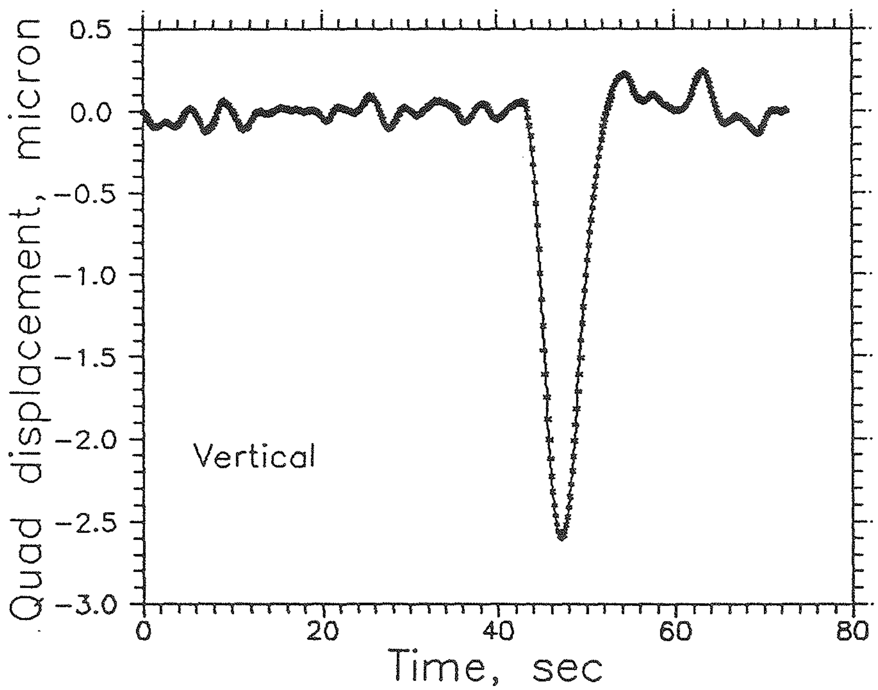

Figure 2: Low frequency vertical motion of the APS quad and effect of a man passing closely.

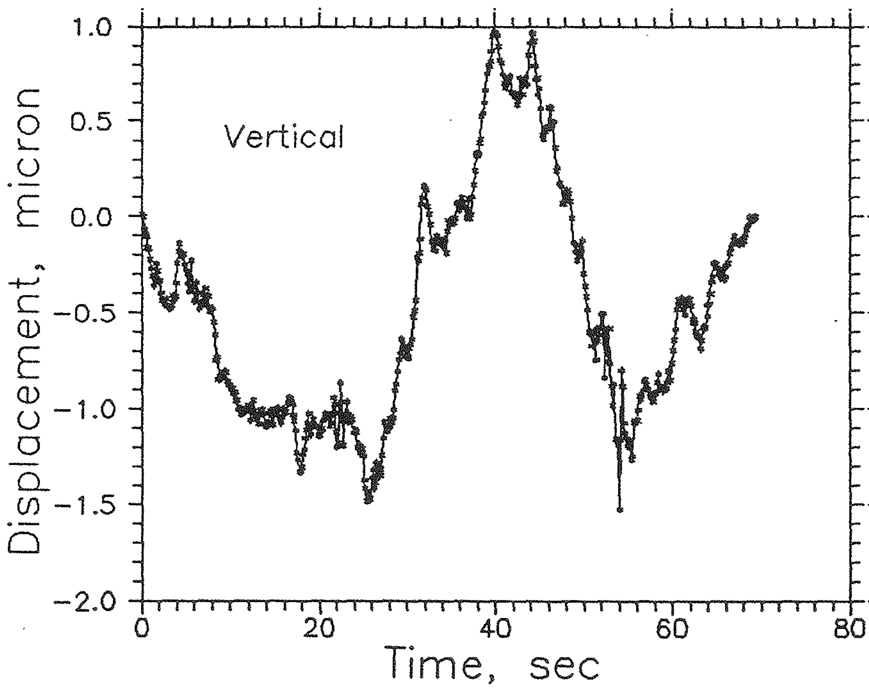

Figure 3: Vertical motion of the APS experiment hall floor just above the tunnel while a compact car is passing trough the tunnel.

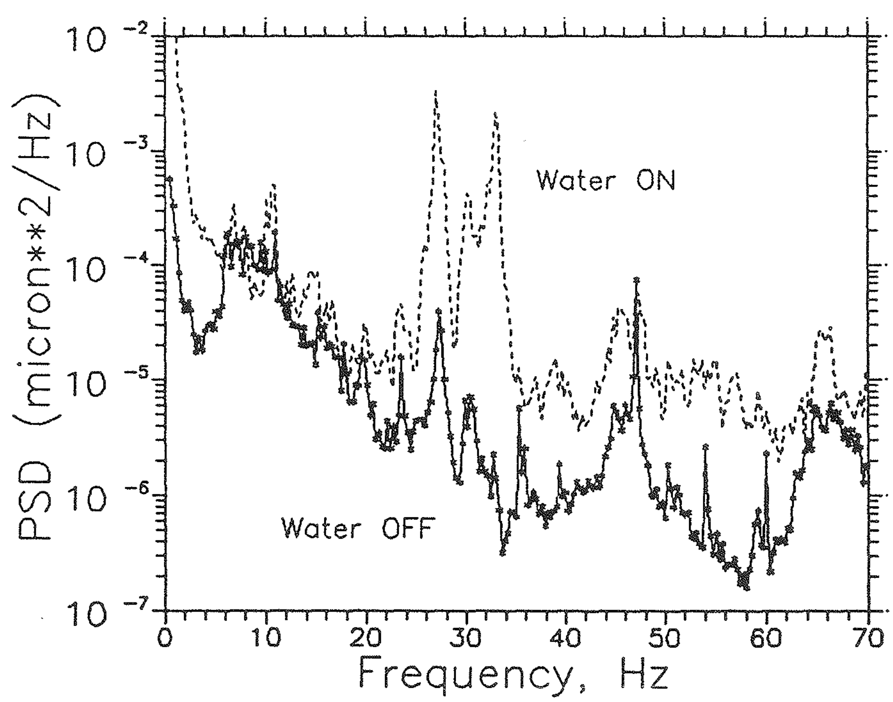

Figure 4: PSD of vertical vibration of the APS quad with cooling water on and off.

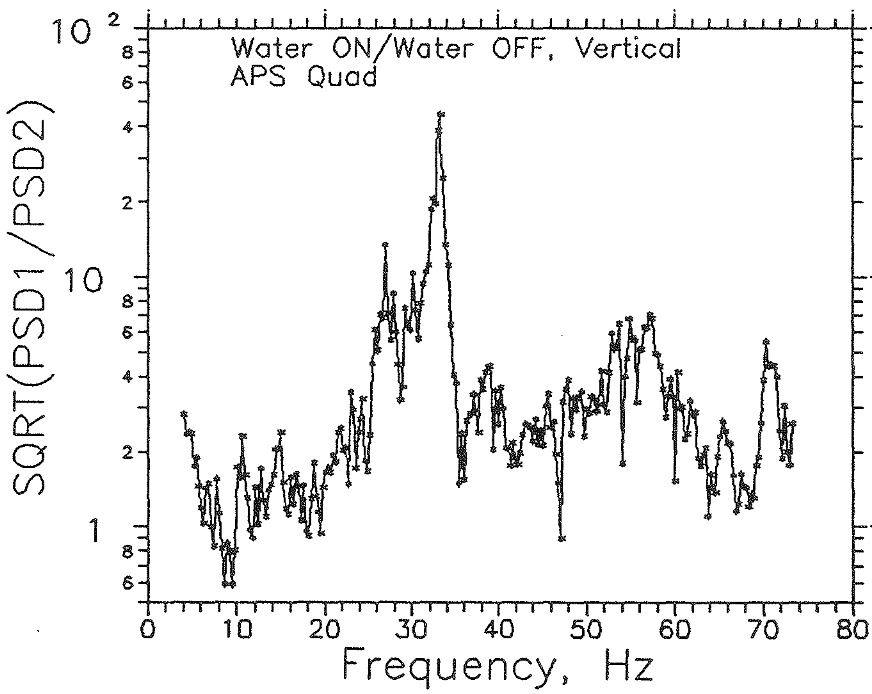

Figure 5: Spectral amplitude ratio: effect of cooling water flow 200 g/sec on vertical vibration of the APS quadrupole.

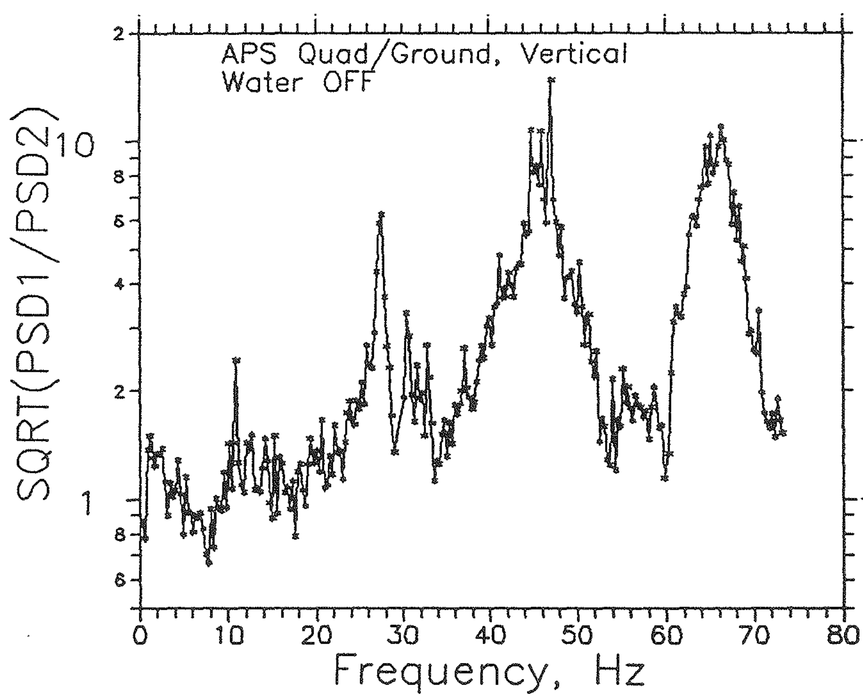

Figure 6: Spectral amplitude ratio of vertical vibration of the APS quad and the floor of the experiment hall.

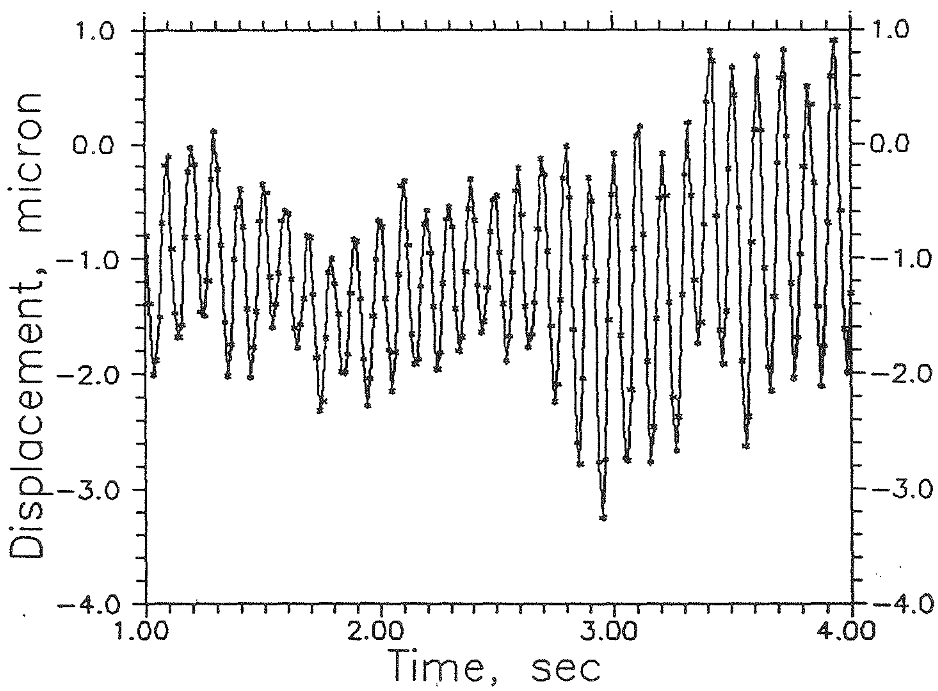

Figure 7: Horizontal vibration of the APS quad with cooling water flow rate 200 g/sec.

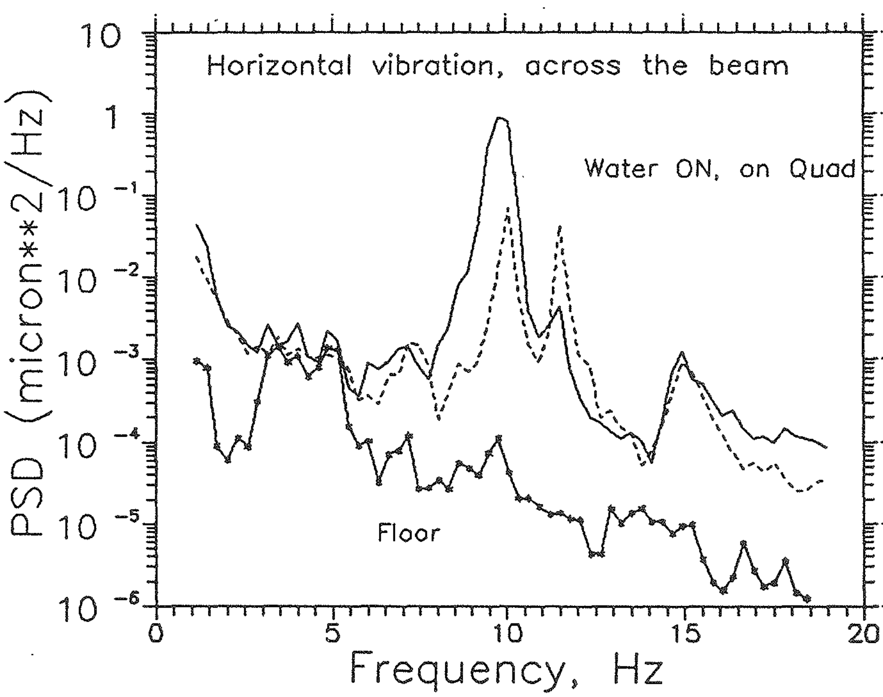

Figure 8: PSD of horizontal vibration of the APS floor (marked line), the APS quad with cooling water on (solid line), and the same quad with an additional wooden support installed (dashed line).

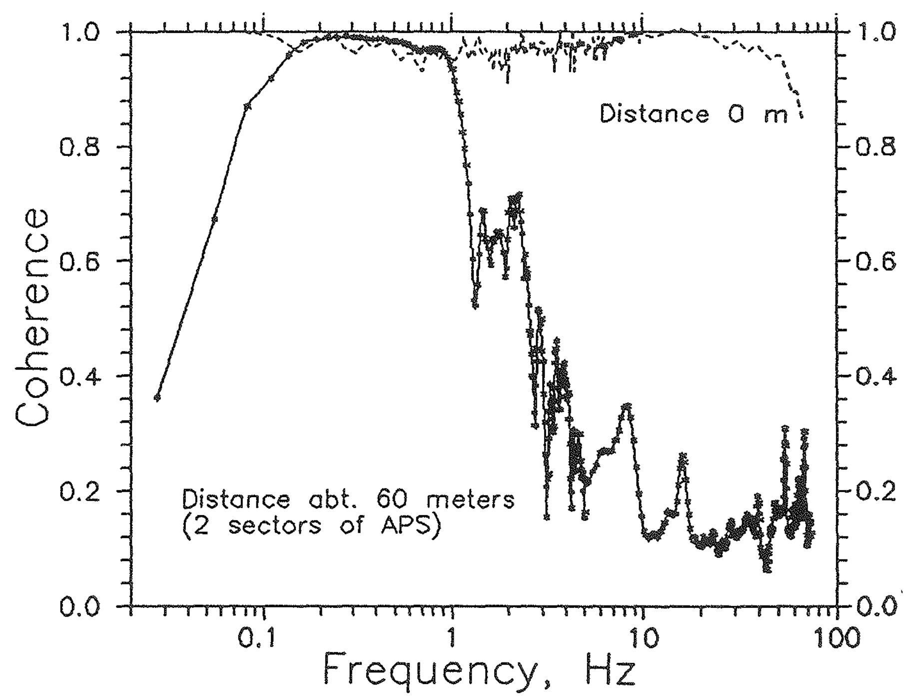

Figure 9: Coherence spectra of vertical motions of two APS quadrupoles distanced by two APS sectors (about 60 meters).

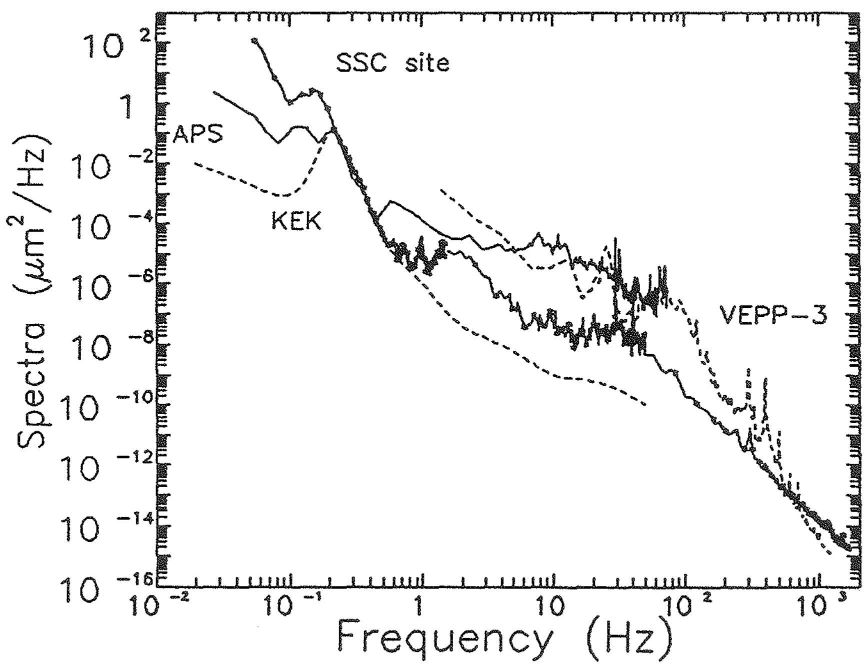

Figure 10: Power spectral densities at the APS and other accelerator tunnels: SSC, VEPP-3, KEK.