Seismic Vibration Studies for Future Linear Colliders

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Abstract

Results of seismic vibration measurements made in the LEP tunnel are presented. The LEP site is shown to be one of the quietest accelerator sites in the world with rms amplitudes for frequencies >10 Hz not exceeding 0.1nm. The results show that spatial correlation disappears at high frequencies (10-100 Hz) for distances of more than a few tens of meters. At low frequencies the amplitudes are greater, at about 0.1 Hz the amplitude of vibration is almost 1 micron but the correlation at this frequency is very good up to a distance of 3km. Good correlation over long distances will certainly simplify the linear collider alignment problem but requires the tunnel to be built on a site which has a continuous and solid rock structure. It has been shown that essential systems such as water cooling and ventilation plants can significantly increase the level of vibrations.

1. INTRODUCTION

To be able to transport low emittance beams to the interaction point of any future high energy e^+e^- linear collider and to make head-on collisions with vertical beam sizes of a few nanometres requires a thorough understanding of the characteristics of seismic vibrations. A collaboration between CERN and INP (Protvino) to measure seismic vibration levels on the CERN site began in 1992. The first series of measurements were made in the TT2A tunnel (an old beam transfer tunnel) and have been reported earlier [1]. This paper gives the results of a second series of measurements which were made in the arc between points 4 and 5 of the LEP tunnel during a shutdown and are more representative of the conditions that will exist in the tunnel of a future linear collider. Points 4 and 5 are the deepest points of the LEP tunnel (about 120 m and 80 m underground respectively) - this is where the tunnel goes under the Jura mountains. This part of the tunnel was bored out of the "molasse" rock and from test borings made many years ago is known to be compact, homogeneous, hard and dry. It is situated about 7 km to the North of the CERN main site and 11 km to the North-West of the centre of Geneva. The main emphasis in this work has been placed on the spatial correlation of vibrations over long distances.

2. EQUIPMENT AND METHOD

All results were obtained with the Russian-made SM-3KV single-axis seismic probes which are described in detail in [1]. The probes are essentially pendula carrying small coils. The voltages induced in these coils are proportional to the speed with which they oscillate in a known magnetic field. These probes measure vibrations in the 0.1-100 Hz band. The data acquisition system consists of CAMAC modules specially built for this application by INP, an IBM PC AT computer and special INP software (for details see [1]). For the spatial correlation measurements two identical data acquisition systems placed up to 3km apart were used . A timer connected to both systems via two 1.5km long cables was used to synchronise the start, stop and timing of data taking (few ms accuracy). Data treatment methods are described in [1]. For completeness the main expressions and relationships are given again in the Appendix.

3. RESULTS OF MEASUREMENTS

Power spectra of seismic vibrations were measured in the LEP tunnel for quiet conditions. "Quiet " means during the night at the weekend with all accelerator systems and devices turned off. The results for vertical vibrations are compared in Fig.1 with results obtained in the TT2A and UNK tunnels.

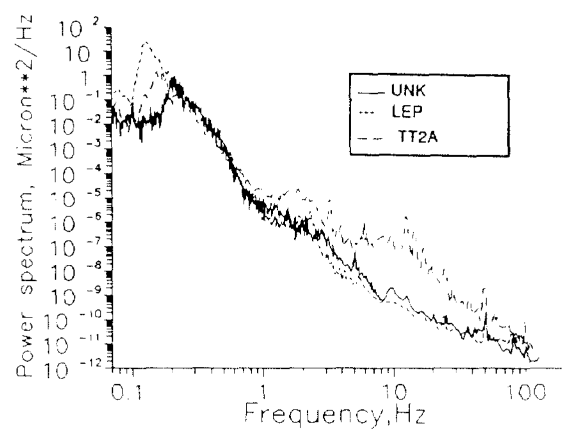

Fig.1 Power spectrum of vertical seismic vibrations

The figure shows that whereas in the 0.3-100 Hz band the spectra of vertical vibrations in the LEP and UNK tunnels are approximately the same, in the 2-10 Hz band the LEP tunnel is quieter - this is because LEP is deeper underground (the measurements in the UNK tunnel were made at about 25m). In the frequency band where the so called "cultural" noise usually manifests itself, i.e. at f > 1Hz, the vibration level in the TT2A tunnel which is on the main CERN site is much higher than LEP and UNK.The peak in the 0.07- 0.2 Hz band (the "micro-seismic peak") is attributed to the action of the waves of nearby oceans on the land. The amplitude of the peak depends on the distance from the ocean and on the prevailing weather above the ocean. From the integrated spectrum shown in Fig.2 we see that the rms amplitude of vibrations with frequencies >10 Hz does not exceed 0.1 nm for both the LEP and UNK tunnels.

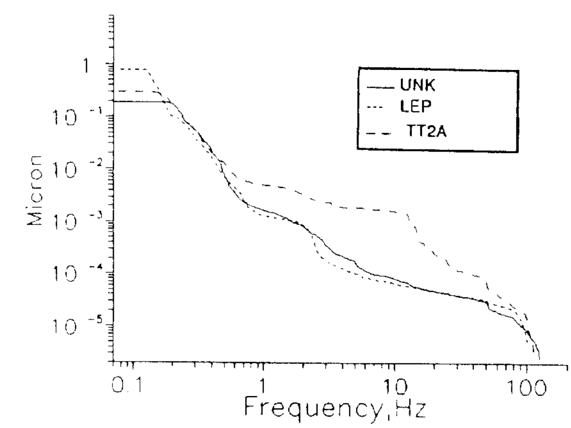

Fig.2 Integrated spectrum of vertical vibrations

Good correlation over long distances will certainly simplify the linear collider alignment problem. Correlation spectra for distances between probes of 0 to 3000 m are shown in Fig.3. The solid and dashed lines correspond to night time and day time measurements respectively.

The correlation spectra of the probes placed together confirm that in the 0.07-70 Hz band the signal-noise ratio is large enough. At high frequencies however (70-100 Hz), LEP being so quiet, the noise of the electronics becomes comparable with the very low level seismic signal and makes accurate correlation measurements difficult. At some frequencies the night-time correlation is better than the day-time correlation, this is because there is an increased level of external electromagnetic noise during the day.

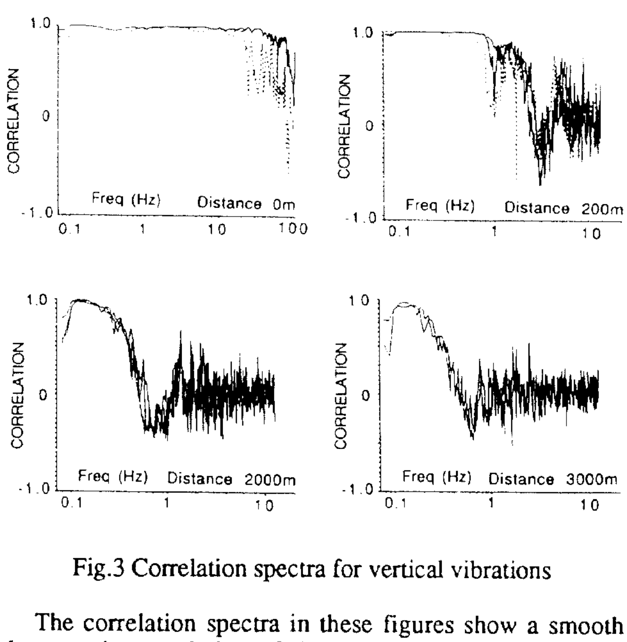

Fig.3 Correlation spectra for vertical vibrations

The correlation spectra in these figures show a smooth decrease in correlation of the high frequency part of the spectrum as the distance between probes increases. Even at a distance of 3000m the micro-seismic signal is still well correlated. This indicates that at least in this region of the LEP tunnel there are no serious breaks in the Earth's surface structure.

Although the LEP tunnel is basically a very quiet place auxiliary systems which are required to run during operation of the accelerator will create additional noise. Fig.4 shows the effect of turning on a water cooling station situated in an annex of the tunnel about 200 m from one of the probes and 800 m from the other. At some frequencies the level of vertical vibrations increased by a factor of three or four.

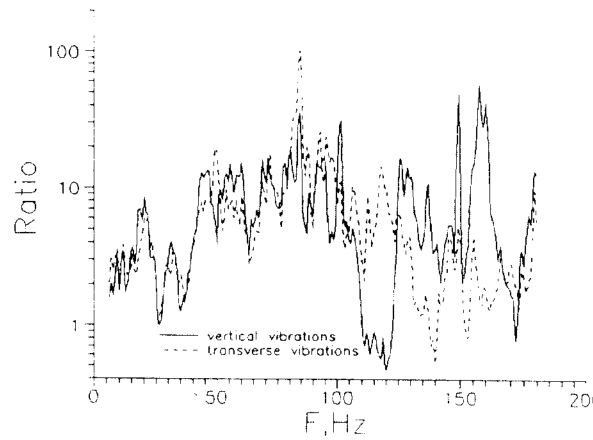

Fig.4 Ratio of vibrations for water cooling station on and off

The influence of the ventilation system (measured near point 4) is shown in Fig.5. The data in these two figures covers a frequency band which is outside the normal working region of the probes but since only the ratio of two spectra from the same probe is used the data obtained is probably correct (especially if the probes are not moved or touched).

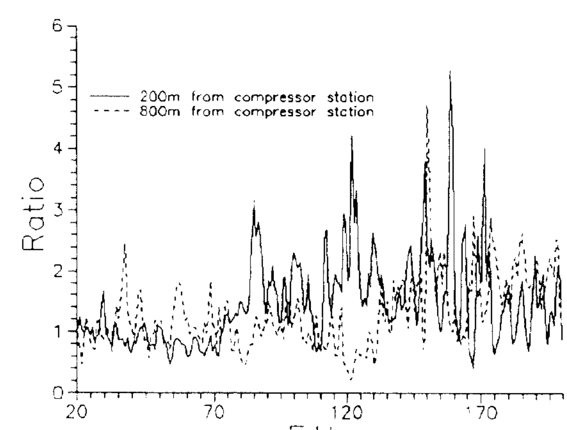

Fig.5 Ratio of vibrations for ventilation system on and off

The ventilation system has a strong influence on the vibration level - at some frequencies the level is increased by a factor of one hundred. For a linear collider such systems would have to be designed and situated more carefully to reduce vibrations to acceptable levels.

4. CONCLUSIONS

Measurements made in the LEP tunnel show the level of seismic vibrations in "quiet" conditions to be very low - the root mean square amplitude of vibrations with frequencies greater than 10 Hz for example does not exceed 0.1nm. It has been shown however that essential systems such as water cooling plant and ventilation systems can significantly increase the level of vibrations. A careful design and location of such systems is clearly necessary for any future linear collider.

This study has shown that the correlation disappears at high frequencies (10-100 Hz) for distances between probes of more than a few tens of meters. The vibration level at these frequencies is however small. At low frequencies the amplitudes are greater, at about 0.1 Hz for example the amplitude of vibration is almost 1 micron but the correlation at this frequency is very good up to 3km.

Good correlation over long distances will certainly simplify the linear collider alignment problem but can only be achieved if the tunnel is built on a site which has a continuous and solid rock structure.

5. REFERENCES

[1] V.Balakin, V.Juravlev, A.Sery, A.Sleptsov, Y.Valiaev, W.Coosemans, G.Ramseier, I.Wilson, V.Lawson-Chroco. "Measurements of Seismic Vibrations in the CERN TT2A Tunnel for the Linear Collider Studies". CERN SL/93-30, CLIC-Note 191.

6. APPENDIX

Power spectral density is defined as follows:

$$P(f) = 2 \lim_{T \to \infty} \frac{1}{T} \left| q(f) \right|^2$$

where

$$q(f) = \int_{-\frac{T}{2}}^{\frac{T}{2}} x(t)\, e^{-i\omega t}\, dt$$

Since the power spectrum of a real signal is a symmetric function we limit ourselves to positive frequencies in our definition of power spectrum density and therefore multiply by a factor 2.

The measured variable x(t) in this work is velocity and P(f) as defined above is the velocity power spectral density (PSD_v) and has units of $(\mu m/s)^2/Hz$. The dispersion or variance σ^2 (the most important characteristic of a random signal) can be obtained from the power spectrum by integrating over the frequency range

$$\sigma^2 = \frac{1}{T} \int_{-\frac{T}{2}}^{+\frac{T}{2}} | x(t) |^2\, dt = \int_0^{\infty} P(f)\, df \quad \text{for } \langle x \rangle = 0$$

Inspection of the power spectrum readily indicates which frequencies make the major contributions to the overall amplitudes.

The associated "displacement" power spectral density PSD_d has units of $\mu m^2/Hz$ and is defined as PSD_v / ω^2 where ω is the local circular frequency. A presentation of results in the form of a PSD_d is particularly useful since the total rms displacement Z_{rms} is given by

$$Z_{rms} = \sqrt{\int_0^{+\infty} PSD_d(f) df}$$

and the contributions of the various frequencies to the total rms displacement can be determined by integrating the spectrum from $-\infty$ or f_{max} to the frequency of interest.

$$I(f) = \sqrt{\int_f^{f_{max}} PSD_d(f) df}$$

If the power spectrum is defined in [micron^2/Hz] then the integrated spectrum has the dimension [micron].

In practise however the time of measurement T is limited. So in order to find the power spectrum with some precision many measurements are averaged.

$$P(f) = 2\left\langle \frac{1}{T} | q(f) |^2 \right\rangle$$

The autocorrelation function (non-normalised) of a random process :

$$a(\tau) = 2 \lim_{T \to \infty} \frac{1}{T} \int_{-\frac{T}{2}}^{+\frac{T}{2}} x^*(t)\, x(t+\tau)\, dt$$

is connected to the power spectrum via the Fourier transformations:

$$P(f) = \int_{-\infty}^{+\infty} a(\tau)\, e^{-i\omega\tau} d\tau$$

$$a(\tau) = \int_{-\infty}^{+\infty} P(f)\, e^{i\omega\tau} df$$

The normalised cross-correlation function in the frequency domain is given as follows

$$N_{12}(f) = \frac{\langle p_{12} \rangle}{\sqrt{\langle p_1 \rangle \langle p_2 \rangle}}$$

where $p_{12}(f)$ is the mutual power spectrum

$$p_{12}(f) = \lim_{T \to \infty} \left\langle \frac{1}{T} q_1(f)\, q_2^*(f) \right\rangle$$

where ' and < > means complex conjugation and averaging on different measurements respectively. The real part of $N_{12}(f)$ we called "correlation", and the modulus of $N_{12}(f)$ "coherence".