# Ambient Vibration Effects on the Colosseum

## Effets des vibrations environnantes sur le Colisée

## Wirkungen von Umgebungsschwingungen auf das Kolosseum

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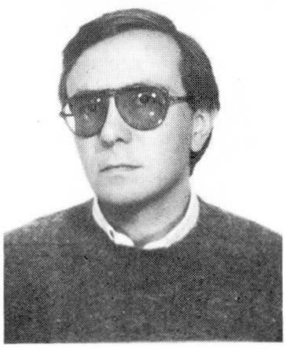

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## SUMMARY

This paper describes some results obtained from ambient vibration tests on the Colosseum. Three structural resonances are investigated for the tallest portion of the monument. A troublesome question related to the basement characteristics is addressed for future research. The amplitude of the vibrations was found not to influence the structural state of the monument.

## RÉSUMÉ

L'article décrit les résultats d'essais sur les effets des vibrations environnantes sur le Colisée. Trois cas de résonances ont été étudiés pour la partie supérieure du monument. Une question troublante concerne la caractéristique de la fondation, laquelle mérite une recherche ultérieure. Il est montré que l'amplitude des vibrations n'a aucune influence sur l'état structural du monument.

## ZUSAMMENFASSUNG

Der Bericht beschreibt die Ergebnisse von Untersuchungen zum Einfluss der Umgebungsschwingungen auf das Kolosseum. Es wurden drei Resonanzfälle für die höchsten Tragwerksteile des Bauwerks identifiziert. Die ungelöste Frage hinsichtlich der Unterbaueigenschaften wird Gegenstand weitergehender Forschung bilden. Es gilt als erwiesen, dass das Ausmass der Schwingungen keinen Einfluss auf den Erhaltungszustand des Monuments ausübt.

## 1. INTRODUCTION

The present paper is part of a research project organized by ENEA (the italian agency for new tecnologies, energy and environment), solicited by the Archeological Commission of Rome, to investigate the seismic hazard to historical monuments in Rome and to take necessary steps for their preservation.
As a matter of fact the several world-famous historical monuments in Italy have suffered to various degrees during past earthquakes. Although Rome is not classified in the zoning map as seismic region, strong earthquakes have been historically felt in the city: the latest of these has been the Avezzano earthquake of January 13, 1915, whose magnitude was 6.8. Documents describing this earthquake provide detailed informations about damage to residential buildings but not to historical monuments [2].
The symbol of the monumental heritage in the Capital of Italy is, without doubt, the Colosseum. To date Colosseum is not very healthy due to many reasons. Among these are, according to many authors, the vibrations induced by the very caotic traffic of Rome.
The structure has been monitored to study the effects of the traffic induced vibrations, as well as the vibrations from the near underground, and to have a first glance at its dynamic characteristics.
The investigation has regarded the tallest wall of the structure (Figure 1).

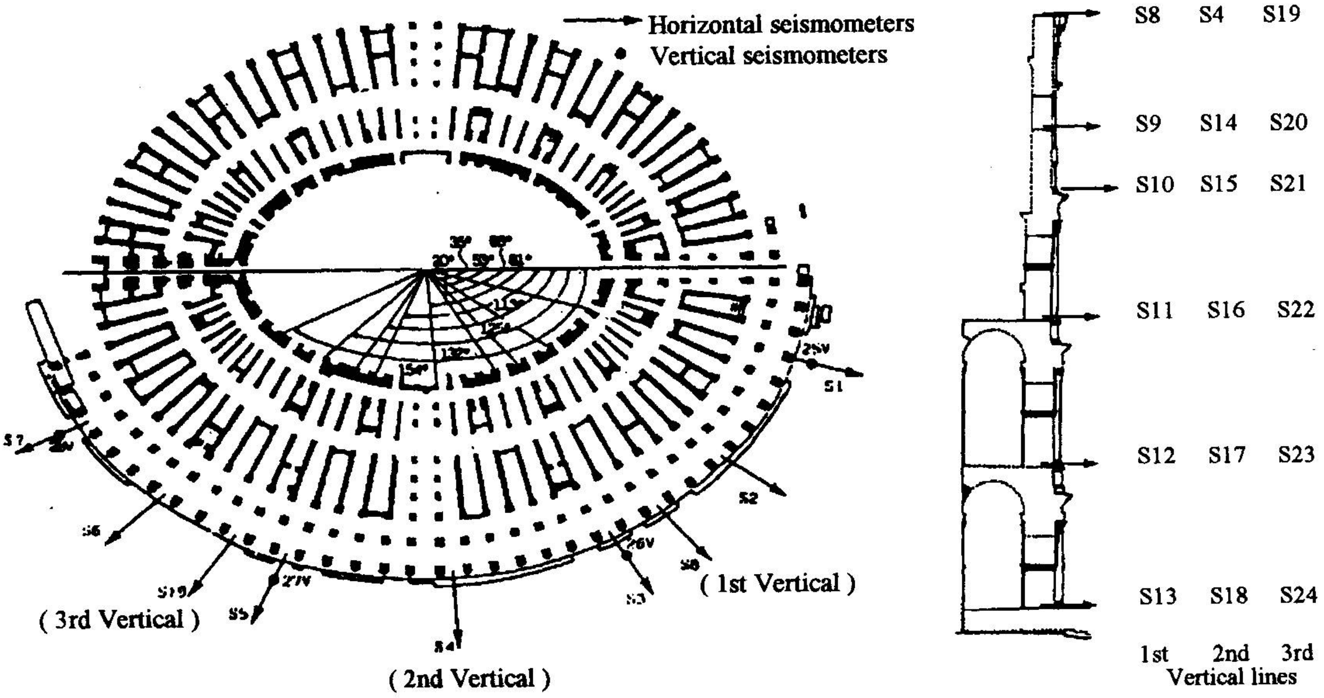


Fig. 1 Plan view and sections of the seismometer locations

The instrumentation has been done by using 13 seismometers deployed in four different configurations.
Data processing consisted of spectral analysis: FFT, power spectral density, cross spectral density, phase and coherence functions.
This analysis resulted in the characterization of the structural resonances and the associated modal shapes. These have not been related to the structure modal shapes due to its complexity.
A statistic analysis have been carried out to determine the effective value of the velocity, which has been compared to the maximum values suggested by the german code (DIN 4150).

## 2. EXPERIMENTAL ANALYSIS

The measurements have been done by ISMES in May 1985 using 13 seismometers (Teledyne Geotech S13800). The signals have been recorded on magnetic tape by a TEAC SR-50 14 traces analog recorder. The analog signals have been later digitized with a sampling rate of 0.005 sec.
In figure 1 is depicted the layout of the seismometers locations. The locations S1 to S7 are fixed in horizontal radial directions at the top of the wall. Three different vertical lines of measurements have been considered and instrumented with the other six seismometers at separated times. A fourth layout regarded the measurement of the vertical vibrations: four vertical seismometers have been located on the basement (Locations 25V to 28V).
Four registrations, at different hours of the day and in two different days, have been carried out. For each configuration 30 minutes of recording have been performed at hours of very intense traffic.
ISMES analized the whole 30 minutes record in order to extract the 5 minutes interval characterized by the highest energy content. The analysis herein described regards these 5 minutes intervals.

## 3. SPECTRAL ANALYSIS

As we have already said, four series of measurements have been carried out. The spectral analysis interested all the series of measurements.
A frequency domain analysis has been carried out calculating the power spectral density for each record of each series of measurements and the cross spectral density with phase and coherence functions between a reference record and each of the other ones.
For the analysis the IMSL routine CSSWD have been used with the following parameters [10]:

W (window) = Bartlett-Priestley

M (window parameter) = 5000

The time series have been analyzed for time intervals of 100 seconds, out of the 300 total, in order to discriminate any difference due to the transit of the train in the nearby underground. The records obtained during the transit of the train at the locations S13 and S8 are illustrated in figure 2.

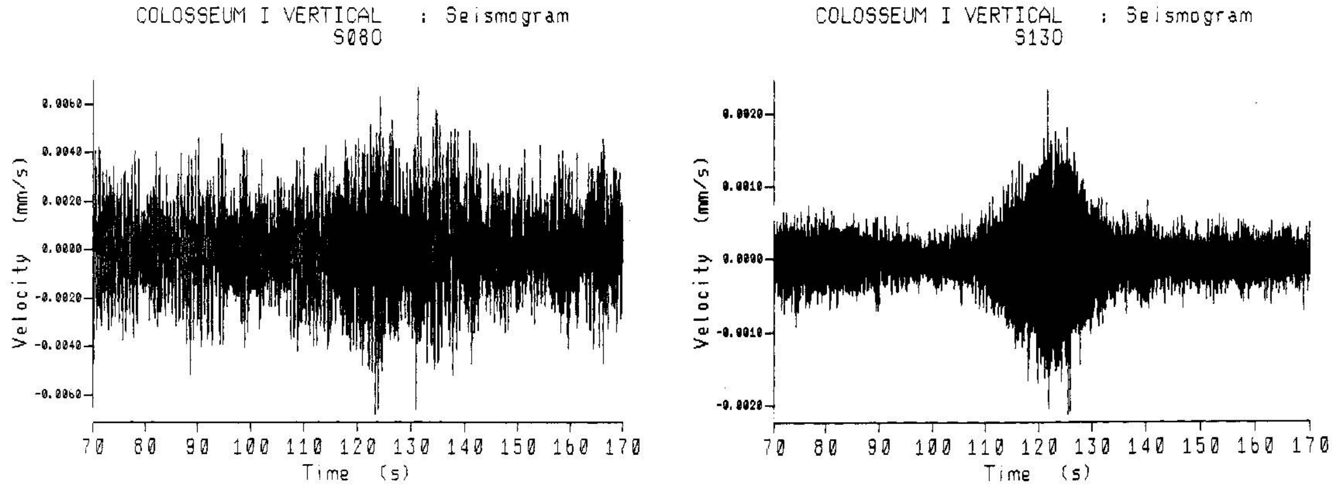


Fig. 2 Seismograms at locations S13 and S8 obtained during the transit of the train of the underground

The transit of the train is apparent only at the S13 location at the basement, moreover there is amplification over the whole time range going from the basement to the top of the wall. The frequency domain analysis proves that there is no significant difference in the behaviour, with and without the transit of the train.
The cross spectral analysis individuates the frequencies that can be considered structural resonances. The corresponding peak amplitudes of the power spectral density give an idea of the associated modal shapes.
The analysis shows several relevant frequencies for each vertical, but only the following:

$$f_1 = 1.46 \text{ Hz} \qquad f_2 = 1.70 \text{ Hz} \qquad f_3 = 2.75 \text{ Hz}$$

are common to all the verticals and present significative coherence and phase relationships so that they are recognized as structural resonances.
In Table 1 phase and coherence of the cross spectra relative to the first vertical line at the above mentioned three frequencies are listed.

| 1st vertical | Freq. | 1.46 | 1.70 | 2.75 |
|---|---|---|---|---|
| S13-S12 | Phase<br>Coherence | 0.00<br>1.00 | 0.00<br>1.00 | 0.00<br>0.90 |
| S13-S11 | Phase<br>Coherence | 0.00<br>0.98 | 0.00<br>1.00 | 0.00<br>0.97 |
| S13-S10 | Phase<br>Coherence | 0.00<br>0.98 | 0.00<br>0.98 | 0.00<br>0.92 |
| S13-S9 | Phase<br>Coherence | 0.00<br>0.98 | 0.00<br>0.98 | $\pi$<br>0,90 |
| S13-S8 | Phase<br>Coherence | 0.00<br>0.98 | 0.00<br>0.98 | $\pi$<br>0.80 |

Table 1 Cross spectral phases and coherences relative to the structural resonances

In figure 3 are illustrated the corresponding modal shapes. Obviously the change in the stiffness at the sensor locations S11, as at sensors S16 and S22 for the second and third verticals respectively, is found in the modal shapes.
The power spectral densities for to records in locations S13 and S8 and the relative cross spectrum are reported in figures 4, 5 and 6 to illustrate the complexity of the response of the structure.

The analysis of the records obtained at the top of the wall shows the following results:
a) the cross spectral analysis identifies the same two frequencies, $f_1$=1.46 Hz and $f_2$=1.70 Hz, as the vertical lines;
b) the coherence functions are very good for all the locations relatively to the frequency $f_2$ and quite poor for the first one at the locations S5, S6, S7 with respect to S1. This result is probably due to the small amplitude of the signals of these measurements as from the power spectral densities. It also could be related to the results from the vertical sensors discussed later.

The seismograms in figure 7 are relative to the vertical sensors 25V, which is closer to the underground, and 26V. As you can see the effects of the train transit fade rapidly. The power spectral densities of the records at 25V to 28V show a very sharp peak at the frequency $f_1$, the same of the horizontal seismometers. The cross spectral analysis confirms that this is a structural resonance. Figures 8, 9 and 10 show the power spectral densities and the cross spectrum of the records at 25V and 26V.

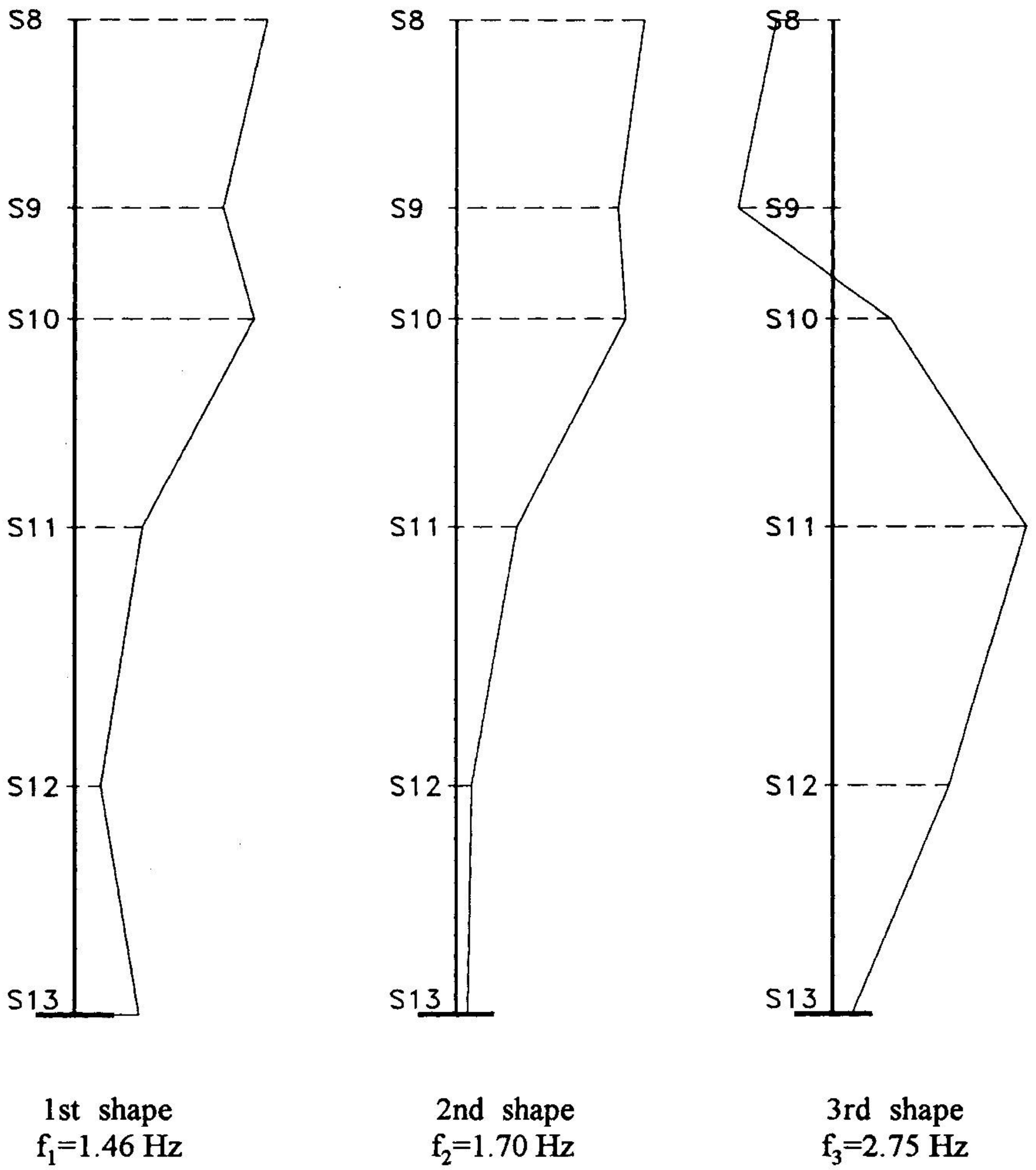


Fig. 3 Modal shapes of the first vertical associated to the structural resonances

Although the number of sensors is limited, it is apparent that the basement of the structure has not a pure rocking movement as from spectral analysis. A lack of structural continuity of the top portion of the basement could, in part, explain this behaviour. The heterogeneity of the soil underlying the monument could play an important role [6, 7, 8 and 9]. In any case further investigations are necessary.

## 4. OTHER RESULTS

The original signals have been analyzed in order to calculate the velocity effective values and the peak values over successive time intervals lasting 1.28 sec.

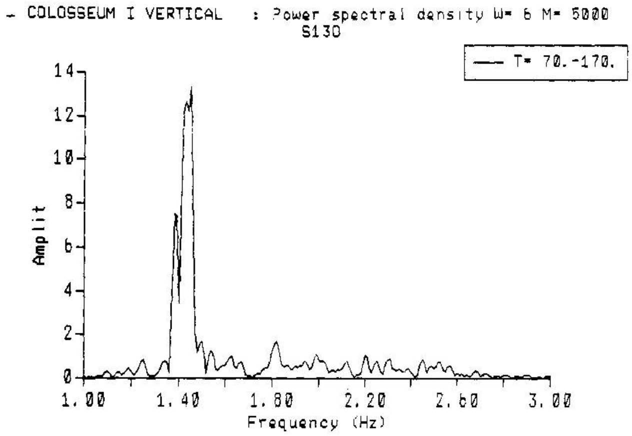


Fig. 4 Power spectral density - S13

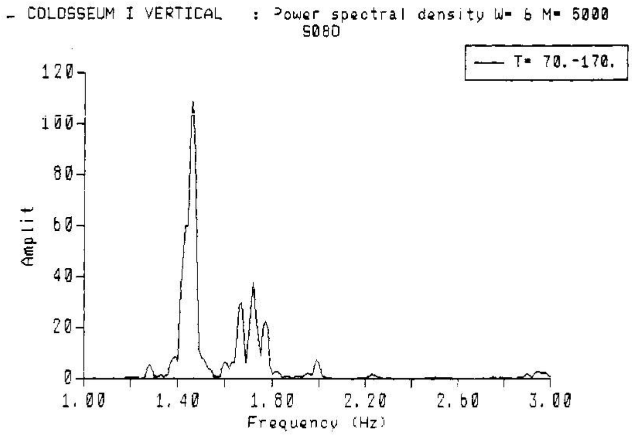


Fig. 5 Power spectral density - S8

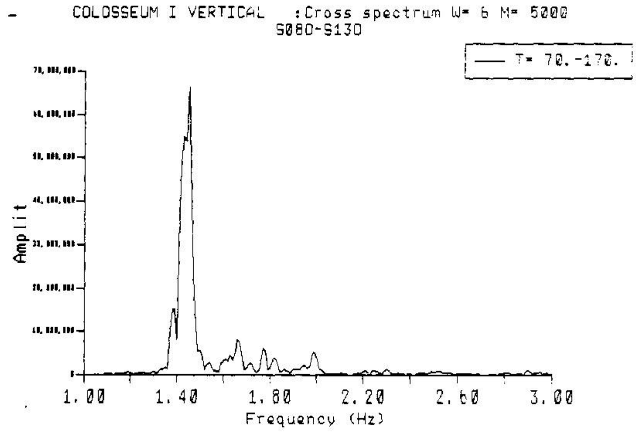


Fig. 6 Cross spectrum S13-S8

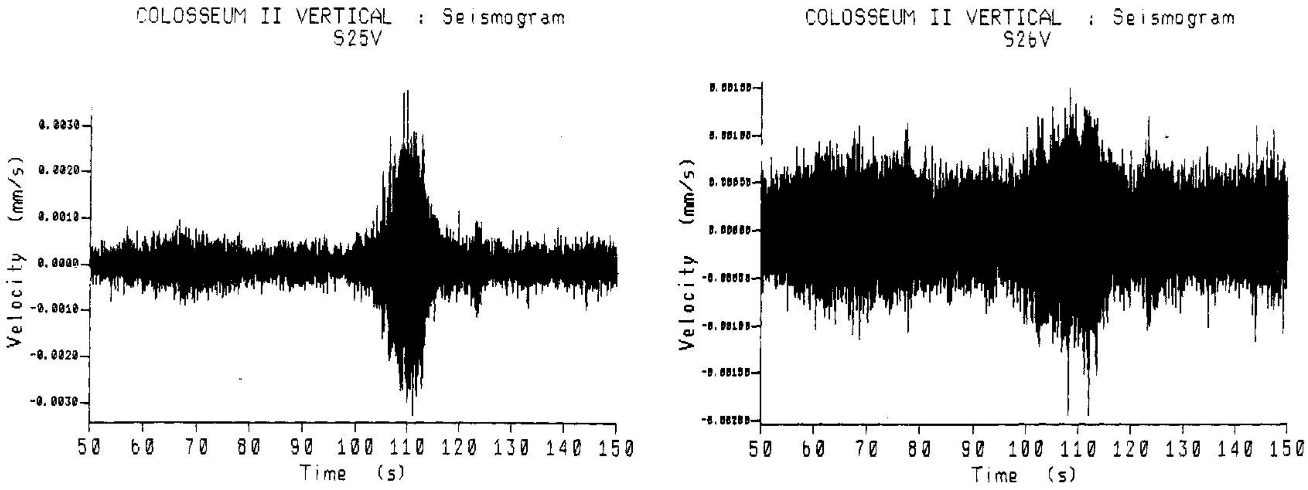


Fig. 7 Seismograms at locations 25V and 26V obtained during the transit of the train of the underground

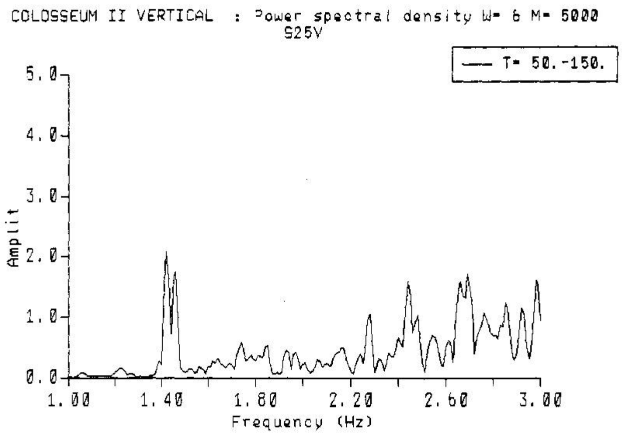


Fig. 8 Power spectral density - 25V

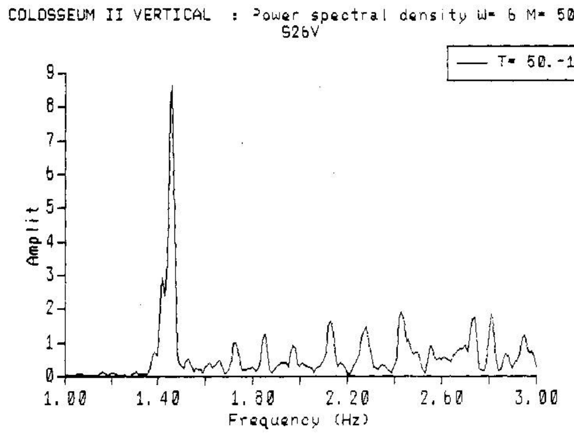


Fig. 9 Power spectral density - 26V

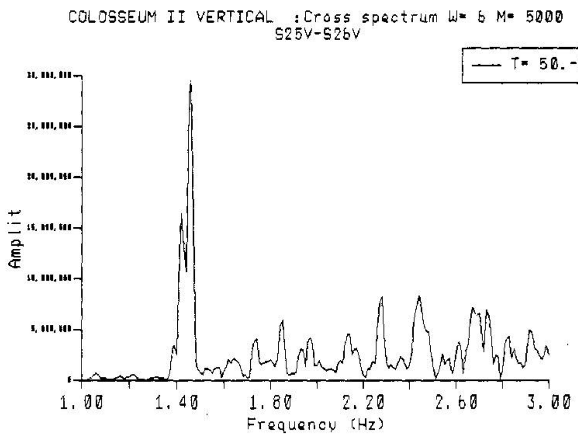


Fig. 10 Cross spectrum 25V-26V

The velocity effective values have been calculated according to the well-known formula:

$$\underline{x} = \sqrt{\frac{\int_{t_1}^{t_n} x^2 dt}{t_n - t_1}}$$

where:

$\underline{x}$ = effective value
x = recorded value
$t_n$ - $t_1$ = time interval.

The velocity effective values are always < 0.12 mm/sec and the peak values < 0.32 mm/sec.
The comparison with the maximum value at the basement of historical and archeological monuments suggested by the german code DIN 4150 (2-3 mm/sec) pointed out the limited effects of the traffic induced vibrations on the Colosseum. This result, in conjunction with the statements referring to the seismograms at locations S13 and S8, allow us to state that the traffic induced

vibrations could have contributed, over the tenths of years, to the bad health status of the monument, but they do not represent an immediate hazard to it.
It is reasonable that many of the illnesses of the monument are to be found in the weathering of the exposed surfaces as well as in the pollution and aced rains. Nonetheless more detailed monitoring of the structure and geotechnical investigations are advisable in order to define the restoration design.

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