6th Canadian Conf. Earthquake Engineering / Toronto / 1991 / 6ème Conf. Canadienne Sismique

Ambient vibration testing and analysis of the Bosporus Suspension Bridge

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ABSTRACT

The paper presents the results of the ambient vibration survey of the Bosporus Suspension Bridge in İstanbul. In each of the experiment series several measurements of the ambient vibration of the bridge deck were obtained at different locations and orientations and at different traffic conditions. Between 0.07 and 1.0 Hz. most of the most of vibration of the bridge can be assessed from the experimental data. The substantial amount of the vibration energy on the bridge deck is contained between 2 and 3 Hz. The results of these experiments have been analysed in terms of the modal shapes, frequencies and damping ratios. These experimentally obtained mode shapes were compared with the theoretical ones obtained on the basis of two- and three-dimensional finite element analysis. Good correlation of experimental results with the theoretical ones are obtained.

INTRODUCTION

Bosporus Suspension Bridge, commissioned in 1973, joins the European and Asian Continents in İstanbul. Figure 1 shows the general structural sections and elevations of the bridge. Based on the project design sheets of Freeman, Fox and Partners, the design engineers of the bridge, the overall structural and physical parameters of the bridge are as follows: The main span is 1074 m long. The bridge deck is of hollow steel box girder type construction, has a total width of 33.4m and carries six lanes of traffic. The deck is supported by four steel towers of 165 m height. The axial distribution of the dead load mass is 14970 kg/m (deck: 11000, cables: 3850 and suspenders: 120 kg/m). Area moment of inertia of the deck about the two principal axis are 1.3 and 63.6 m^4. Torsional constant of the deck is 3.4 m^4. Nominal radius of the cables is 0.28 m.

Vibration characteristics and the dynamic properties of the suspension bridges are important design parameters controlling their wind and the earthquake safety. The determination of the dynamic parameters of the existing structures are, thus, very important studies that assist in the calibration of

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the relevant analytical techniques (Bleich, et al.,1950). One of the best methods utilized to assess the dynamic characteristics of such massive structures is the measurement of the structural response to the ambient excitations, such as: wind and traffic noise. The structural vibrations caused by such excitations are termed the "Ambient Vibrations". Such measurements and experiments have been carried out on several suspension bridges (Abdel-Ghaffar and Housner, 1978). The ambient vibrations of the Bosporus Bridge has also been the subject of similar investigations conducted by Petrovski et al. (1974) and Tezcan et al.(1975), and Brownjohn et al.(1988).

EXPERIMENTAL SET-UP AND DATA ANALYSIS

The ambient vibrations of the Bosporus Bridge have been measured by a joint team of Boğaziçi and Middle East Technical Universities in two campaigns: in March, 1987 and November, 1988. In the measurements, depending on the amplitude of the signal, a four-channel data acquisition system consisting of either accelerometers or seismometers were employed. Figure 2 portrays the instrumental set-up.

The following equipment were used:

Analog-to-Digital Interface Board: A Metrabyte DAS-16 interface board installed in a PC to digitize analog data.

Tape Recorder: Hewlett-Packard Model 3964 A instrumentation tape recorder used to record 4 channel analog data.

Fourier Analyzer: Hewlett-Packard Model 3582 Spectrum Analyzer used to provide Fourier amplitude and phase transform, auto and cross correlation and transfer function of two channel analog data.

Acceleration Transducers: Four Shinkoh UA Series strain-gage type acceleration transducers with a range of ±1g and a flat frequency response up to 200 Hz.

Dynamic Strain Amplifier: Shinkoh DS-6002-F 6-Channel Dynamic Strain Amplifier used for the conditioning of accelerometer signals.

Seismometers: Four Kinemetrics SS-1 Ranger Seismometers with 1 Hz natural frequency.

Signal Conditioner: Kinemetrics CS-1 Signal Conditioner utilized to filtering and amplification of seismometer signals.

Analog Recorder: San-Ei Sokki Model 5M21 6 Channel Portable Direct Recording Oscillograph used to obtain direct record of the wave forms.

Measurements were taken along and across the main span and both inside and outside of the deck. Different set-ups were used to detect the vertical, lateral and torsinal vibrations. In each case, a reference station was established and simultaneous successive measurements were taken at the moving station. For the detection of torsional vibrations the vertically oriented transducers are placed at the outer edges of the deck and the difference of their signals were used. Measurements were also taken under light and heavy traffic conditions to assess the difference. The vibrations were recorded at each experiment for a duration of about 10 minutes to allow for satisfactory resolution and averaging in spectral analysis. A typical power spectrum of the acceleration obtained at the mid-span in lateral direction is provided in Figure 3. The high energy vibrations at 2.5 Hz is indicative of local vibrations of the deck.

A preliminary processing of data was carried out in-situ through the Fourier analyzer. The final processing was done in the office through playback of the recorded data via an analog-to-digital converter into a PC. For the identification of the modal vibration frequencies and shapes, frequency domain analysis involving Fourier amplitude and phase spectra, cross spectra and coherence functions were used. The half-power bandwidth method was used to estimate the modal damping ratios. The estimations vary upto ±50% from one measurement to another.

EXPERIMENTAL RESULTS

The results of these experiments have been analyses in terms of the peak frequencies. It was possible to associate some of these frequencies with the modal vibrations. In Table 1 a general assessment of the experimental modal frequencies of vibration and the identified mode shapes are provided. The first four of the experimentally obtained mode shapes are compared in Figure 4 with the theoretical mode shapes obtained on the basis of three dimensional finite element analysis. The experimental damping values are also indicated on thiese figures.

TWO DIMENSIONAL FINITE ELEMENT ANALYSIS

A finite element solution of the continuum approach developed by Abdel-Ghaffar (1978) for the lateral vibration of suspension bridges is utilized to obtain the theoretical mode shapes for the lateral vibration of Bosporus Bridge. The approach is based on the derivation of the equations of motion through the use of the Hamilton's principle under the assumptions that: (1) vibration amplitudes are sufficiently small to remain in linear ranges, (2) coupling between lateral and torsional modes are ignored and (3) the cable ends are immovable. Mathematical model of a suspension bridge should depend on the construction details and on the support conditions. In three span-two hinged bridges, the interaction between the main and side spans may not be significant. The analytically derived energy expressions are then used to express the stiffness and consistent mass matrices for the finite element application. As many equations are obtained as the number of active degrees of freedom used to express the mathematical model. The normalized interpolation functions with respect to the horizontal axis are used to obtain the displacement vector in terms of the nodal displacements. For the Bosporus Bridge a subdivision of elements is used resulting in 23 degrees-of-freedom.

The first five lateral modes of vibration of the Bosporus Suspension Bridge, computed on the basis of this simplified finite element analysis scheme are plotted in Figure 5. Even though the bridge is divided into only eight elements, the theoretical results are in good agreement with the experimental values. It is observed that in the first symmetric and anti-symmetric modes, the cable and the deck motion are in phase, whereas, in the fourth mode the two systems are in out of phase motion. The third, sixth, seventh and the eight modes can be considered as cable modes since the cable movements are dominant. In these modes the cable displacements are about 10 times that of the deck.

TABLE 1

EXPERIMENTAL AND ANALYTICAL MODAL PARAMETERS

MODE SHAPE	EXPERIMENTAL		ANALYTICAL FREQUENCY	
	FREQUENCY	DAMPING	2-D.O.F.	3-D.O.F.
First Lateral Symmetric	0.072Hz	7%	0.077Hz	0.072Hz
First Vertical Asymmetric	0.150Hz	4%	-	0.141Hz
First Lateral Asymmetric	0.215Hz	4%	0.192Hz	0.223Hz
Second Vertical Symmetric	0.230Hz	4%	-	0.233Hz
First Torsional Symmetric	0.320Hz	-	-	0.325Hz
Second Vertical Asymmetric	0.330Hz	-	-	0.340Hz
Third Vertical Symmetric	0.370Hz	-	-	0.367Hz
Second Lateral Symmetric	0.380Hz	-	0.412Hz	0.387Hz

THREE-DIMENSIONAL FINITE ELEMENT ANALYSIS

The modal vibration frequencies and the shapes of the Bosporus Suspension Bridge is determined on the basis of SAP-90 finite element analysis program (Wilson and Habibullah, 1989). The bridge deck is modeled using equivalent shell elements. The effects of axial forces on the stiffness of the cables are considered through the use of equivalent frame elements. The model used is intended to be a preliminary one and does not explicitly include the towers and side spans. However, the boundary conditions are chosen to simulate the effect of the deck and cable supports at the towers. Figure 6 provides the isometric views of, respectively, the first lateral symmetric, first vertical asymmetric, first lateral asymmetric, second vertical symmetric, first torsional symmetric and second vertical asymmetric mode shapes. Results are also listed in Table 1. The experimental and the 3-D finite element analytical values of the modal vibration frequencies are given under each inset shape.

CONCLUSIONS

The study presented involves the experimental assessment and the theoretical verification of the modal shapes and the frequencies of the Bosporus Suspension Bridge. Following is a summary of the findings and conclusions:

1. As it has also been shown by previous investigators, the ambient vibration survey techniques can be satisfactorily utilized to obtain the vibration mode shapes and the frequencies of the suspension bridges.
2. A relatively large number of modes may be necessary to obtain a reasonable representation of the response.
3. Between 0.07 and 1.0 Hz. most of the vibration of the bridge can be assessed from the experimental data. However more refined techniques and denser instrumentation may be required for the reliable differentiation of the closely spaced modes.
4. The local spurious vibrations of the bridge deck contaminate the ambient vibration of the total bridge structure and makes it impossible to recover any modal data in the frequency ranges higher than about 1.5 Hz.

5. It was not always possible to determine reliable damping values by the use of the half-power method, due to closely spaced peaks.

6. Theoretical analysis of the free vibration of suspension bridges indicate that in certain modes the displacemnts of the deck are important (Deck Modes), whereas in others the displacements of the cables (Cable Modes). The deck modes can be classified as symmetric or asymmetric and lateral or vertical or torsional.

7. Theoretical 2D and 3D finite element analysis have produced results that correlate surprisingly well with the experimental data considering the assumptions made regarding the boundary conditions, equivalent shell element modeling the deck and the equivalent frame element modeling the cables.

8. The substantial amount of the vibration energy on the bridge deck is contained between 2 and 3 Hz. These vibrations associate with vertical accelerations peaks up to 0.3g. There may be reasons to believe that these high energy vibrations constitute one of the causes of the low-cycle fatique effects observed on the welds in the deck. Future investigations should concentrate on the source, characteristics and the remedies regarding these high amplitude local vibrations of the deck.

ACKNOWLEDGEMENT

This research has been supported by the Research Funds of Boğaziçi and Middle East Technical Universities. The permission and assistance of the Turkish General Directorate of Highways are gratefully acknowledged.

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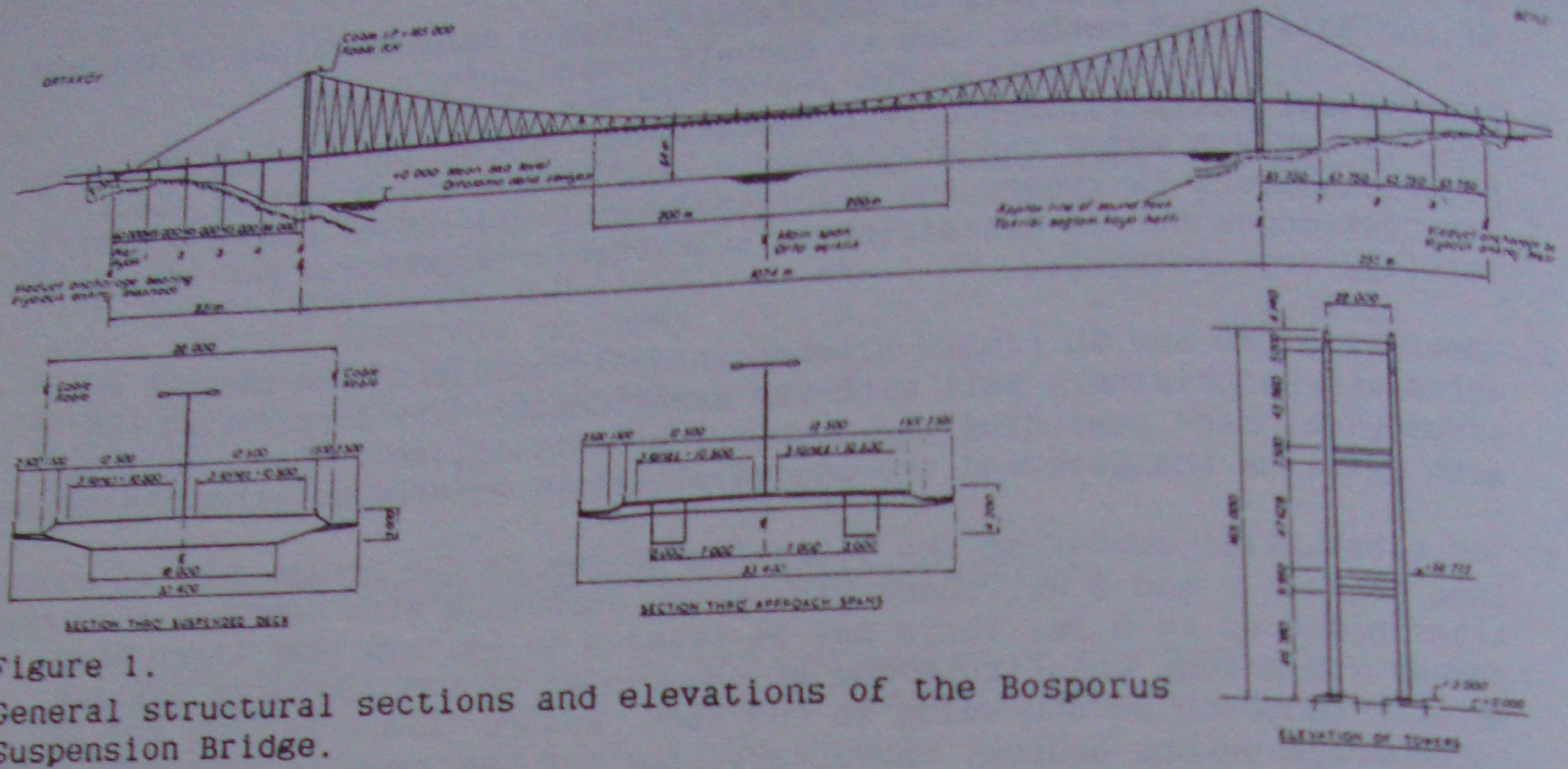

Figure 1.
General structural sections and elevations of the Bosporus Suspension Bridge.

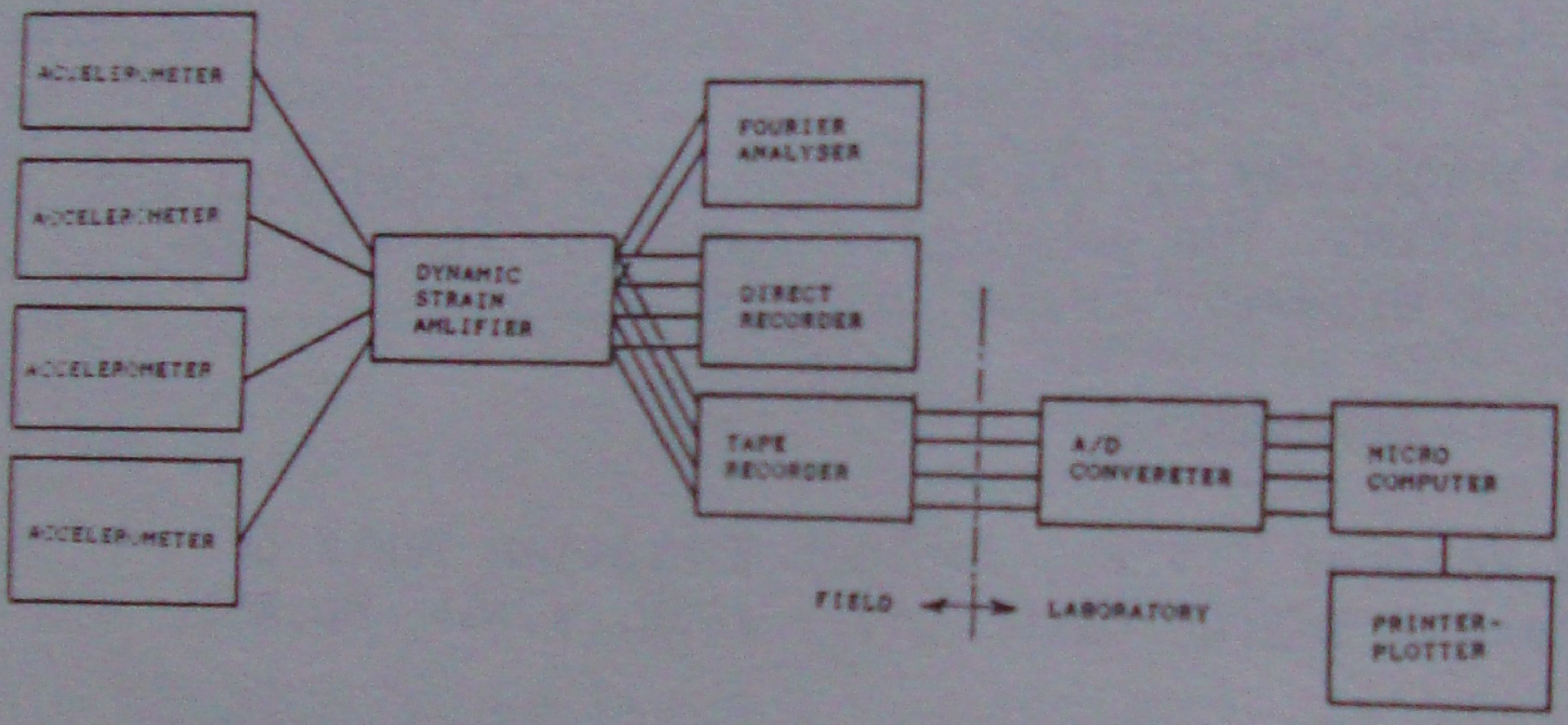

Figure 2.
Instrumental set-up using accelerometers

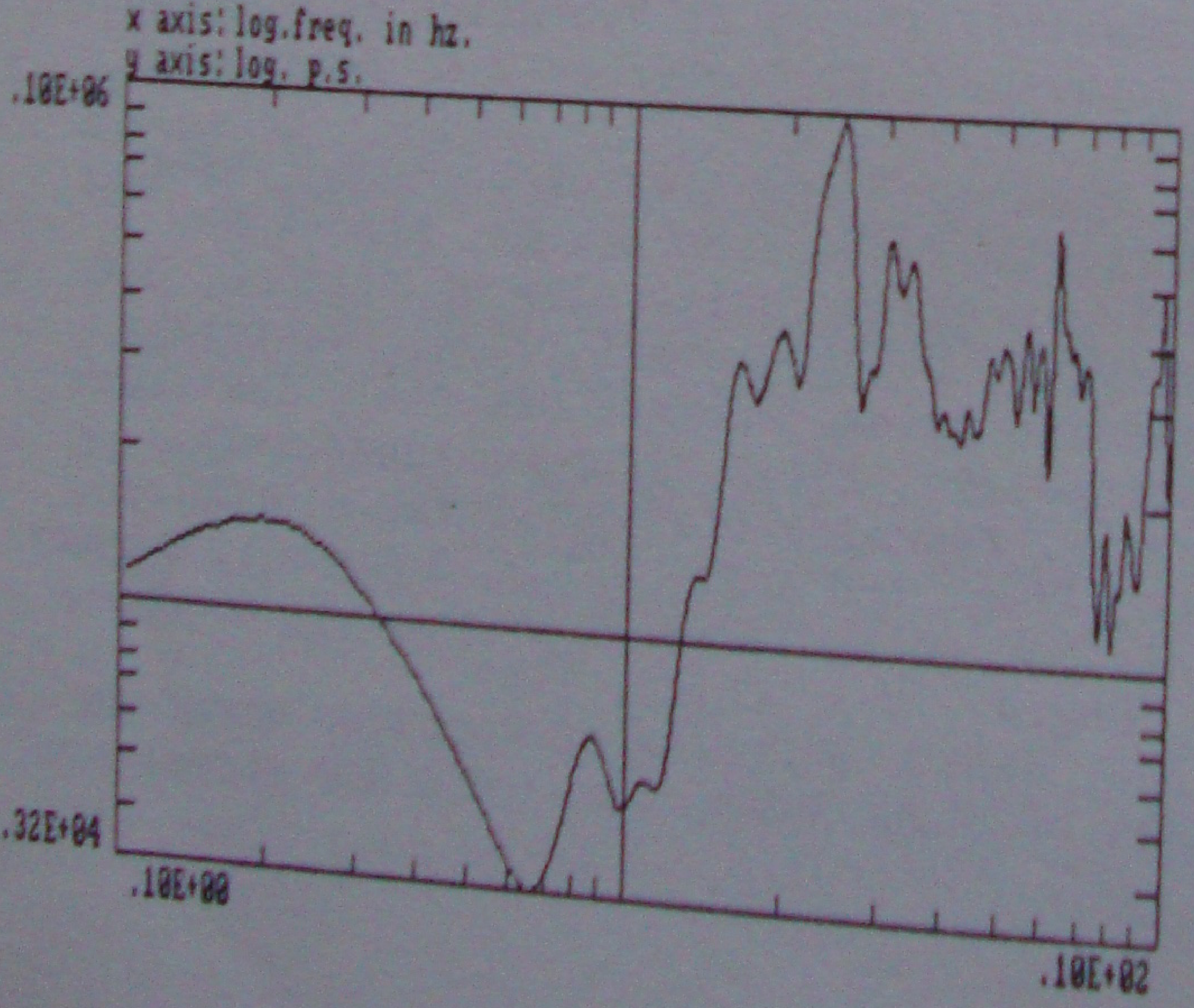

Figure 3.
A typical power spectrum of the acceleration obtained at the mid-span in lateral direction. Note the high energy peaks at 2.5Hz.

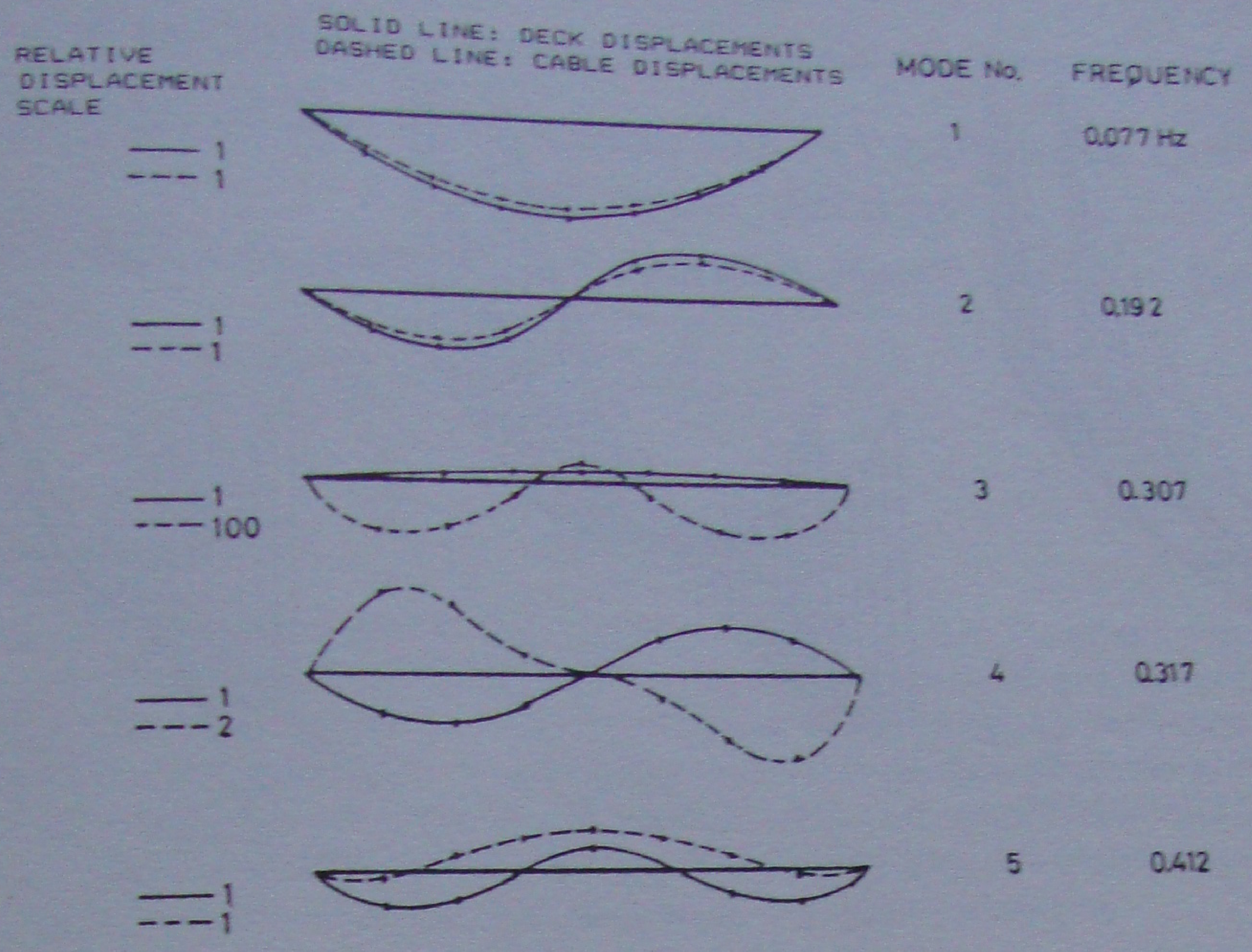

Figure 5. The first five lateral modes of vibration of the Bosporus Suspension Bridge, computed on the basis of 2 D.O.F. finite element analysis.

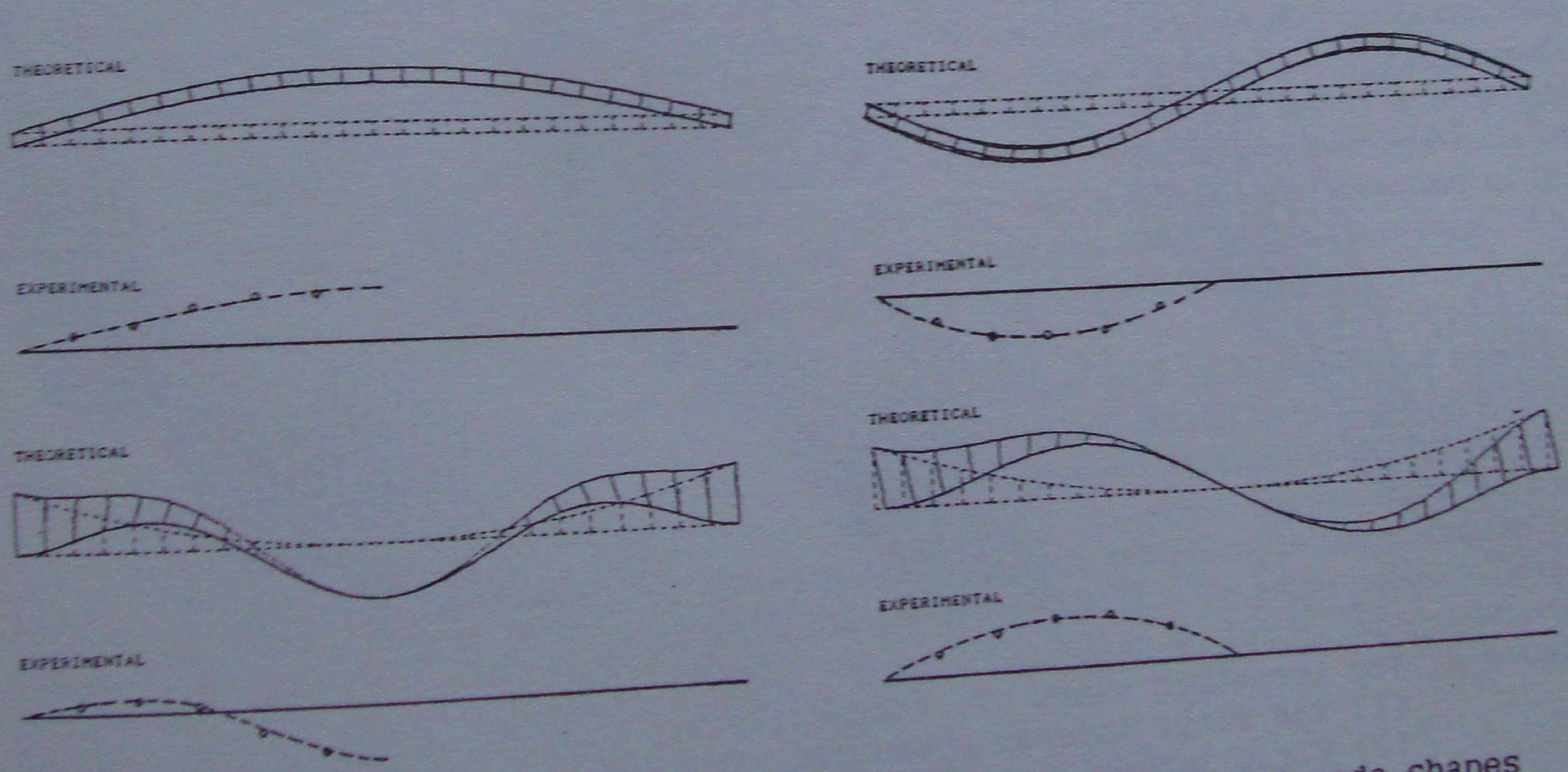

Figure 4. Comparison of the first four experimentally obtained mode shapes with the theoretical ones obtained on the basis of three dimensional finite element analysis. The experimental damping values are respectively 7%, 4%, 4% and 4% at each mode. (Also see Table 1)

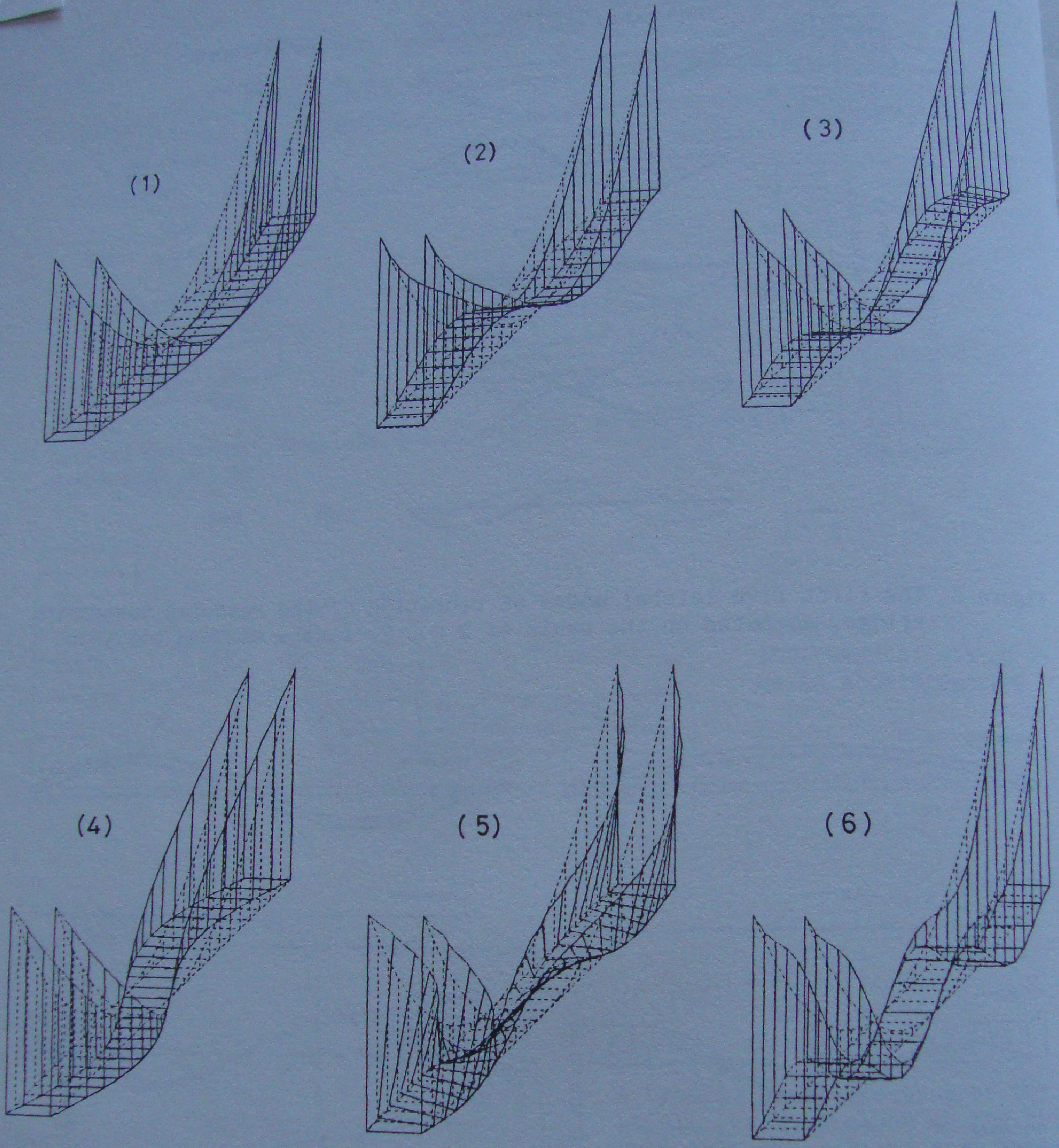

Figure 6. The isometric views of, respectively:
(1) The first lateral symmetric, (2) First vertical asymmetric, (3) First lateral asymmetric, (4) Second vertical symmetric, (5) First torsional symmetric and (6) Second vertical asymmetric mode shapes. (Please refer to Table 1 for the experimental and the 3-D.O.F. finite element analytical values of the modal vibration frequencies.)