AMBIENT VIBRATION TESTING OF BRIDGE STRUCTURES

A DISSERTATION

submitted in partial fulfilment of the
requirements for the award of the degree
of
MASTER OF ENGINEERING
in
EARTHQUAKE ENGINEERING
(With Specialization in Structural Dynamics)

By

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in this dissertation entitled, "**AMBIENT VIBRATION TESTING OF BRIDGE STRUCTURES**" in partial fulfillment of the requirements for the award of the degree of MASTER OF ENGINEERING in EARTHQUAKE ENGINEERING with specialization in STRUCTURAL DYNAMICS, submitted in the department of Earthquake Engineering, University of Roorkee, Roorkee, is an authentic record of my own work carried out for a period of about six months from August 1995 to January 1996 under the guidance of Dr. S.K. Thakkar, Professor and Head, and Mr. R.N. Dubey, Lecturer, Department of Earthquake Engineering, University of Roorkee, Roorkee, India.

The matter embodied in this dissertation has not been submitted by me for award of any other degree or diploma.

Date: 30.1.96

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This is to certify that the above statement made by the candidate is correct to the best of our knowledge.

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ABSTRACT

The ambient vibration testing of the structures is a direct and practical method of determining the dynamic characteristics of structure such as natural frequencies, mode shapes and damping. In this testing, structure is excited by natural microtremors, wind, traffic load and machine or man made blast.

The cable stayed bridges have proven to be economical for medium to long spans. Cable stayed bridges posses low weight and reduced ability to absorb energy by sliding friction. So the inertia force generated in the structure is very low as compared to external loads. As the cable stayed bridge has complicated structural systems because of different stiffness structural members, it is important to carry out elaborate dynamic analysis, and compare with experimental data.

This thesis presents the results of ambient vibration testing of two cable stayed bridges (i) across Ganga canal at Roorkee, and (ii) across Ganga canal at Hardwar. The vibration produced were picked up by seismometers and recorded in solid state recorder. The experimentally measured time periods were compared with the values obtained from mathematical models for the two bridges. A reasonably close agreement in the fundamental time period between theoretical and experimental values have been observed for both the bridges.

CONTENTS

CHAPTER

1. INTRODUCTION

2. REVIEW OF LITERATURES

3. DESCRIPTION OF VIBRATION MEASURING EQUIPMENT

4 VIBRATION SURVEY SOFTWARE

5. ANALYTICAL TECHNIQUE FOR CALCULATING MODE SHAPES

6. EXPERIMENTAL ANALYSIS OF BRIDGES

7. ANALYTICAL INVESTIGATION OF BRIDGES

8. SUMMARY AND CONCLUSIONS

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

The term "Ambient Vibration" covers any kind of uncontrollable input such as wind, waves, moving vehicles, and so on. The advantage of relying on this type of input is that the test procedure is considerably simplified, as the only equipment required during the test is for the data acquisition.

Now a days, the ambient vibration measurement survey is the most applicable method to determine the dynamic properties of a structure at any stage of construction or occupancy. The main goal of dynamic analysis or testing is to determine the natural frequency, mode shapes and damping of structure. Knowledge of these properties is to understand and interpret structural response during wind excitation or microtremores or earthquake and compare observations with theoretical results. The above properties are used to improve the existing earthquake resistant design practices. The technique can be used to verify mathematical models and to investigate changes in resonant frequency before and after earthquake.

In ambient vibration survey (AVS), prototype structures are excited by natural microtremores, wind, traffic load, and machine or man made blast. Typical surveys have include suspension bridges, rotating machinery supports, earth dams, urban areas, floors, nuclear power facilities, offshore platform, high rise buildings.

1.2 PURPOSE OF AMBIENT VIBRATION SURVEY

The codes of practice often provide some empirical formula for determining time period of tall building. The seismic coefficients are worked out using response spectrum from these time periods. It is possible to arrive at the more reasonable expression of time periods from the results of ambient vibration testing. There are possibilities of obtaining following information from ambient vibration testing:

i) Data base on dynamic characteristics of different type of structures.
ii) Experimental verification of theoretical mathematical models.
iii) Study of soil structure interaction effect on dynamic characteristics.

A typical test setup of such a test of cantilever structure is shown in fig. 1. The analysis of data is carried out by vibration survey software to determine dynamic characteristics.

1.3 OBJECTIVES OF AMBIENT VIBRATION SURVEY

The following are the objectives of carrying out ambient vibration testing of two bridges:

i) To carry out the AVS testing of the cable stayed bridges across Ganga canal at Hardwar and at Roorkee.
ii) To analyze the data obtained experimentally.
iii) To carry out analytical studies using mathematical models for determining dynamic characteristics of the cable stayed bridges.
iv) To compare the experimental and analytical results.

1.4 SCOPE OF THE INVESTIGATION

The ambient vibration survey was done for two bridges at Hardwar and at Roorkee. Both bridges were tested for mild traffic excitation and recorded by Kinemetrics Solid State recorder(SSR-1) through Ranger seismometres (SS-1). The time period of the bridges were experimentally determined and compared with the theoretical result which was obtained by modelling of the bridges and analyzing by space frame program.

1.5 COMPOSITION OF THESIS

Chapter 1: Introduce Ambient Vibration Survey (AVS), objectives and scope of testing.

Chapter 2: In this chapter the past AVS testing on different bridges are discussed.

Chapter 3: Describes the brief description and feature of AVS measuring equipment

Chapter 4: Describes the software which is used for the analysis of recorded data.

Chapter 5: Describes the analytical technique for analyzing the data.

Chapter 6: Describes the steps followed for the AVS testing of two bridges.

Chapter 7: Describes the steps followed for analytical investigation of the two bridges under consideration.

Chapter 8: Describes the summery and conclusion drawn after the testing of bridges.

CHAPTER - 2

REVIEW OF PAST WORK

In past, all over the world, ambient vibration testing had being done on various types of structures. Department of earthquake engineering, itself conducted few tests so for, includes three storyed building of department of earthquake engineering, communication tower of electronics and computer science department, water storage tank near Sarojini bhawan, water storage tower near G.P.hostel. Some of the other famous ambient vibration testing work all over the world are, Maxicali general hospital, a nine storyed building and a large no. of suspension bridges. In all those testing a reasonably close agreement in natural frequency between theoretical and experimentally measured values have been observed.

2.1 AMBIENT VIBRATION MEASUREMENTS OF THE GOLDEN GATE BRIDGE [1]

The Golden Gate bridge lies across the entrance to the Francisco Bay and joins the Northern and Southern peninsulas. The bridge was opened to traffic in 1937. The bridge consists of a mainspan of 1,280 m. and two sidespans of 343 m. each. The spans are suspended from the main cable, which is supported by the two towers. Both towers are 210 m. high from the pier to base of the saddle casting, and rise 227 m. above the water. An elevation is presented in Fig. 2. Figure 3 shows a typical span cross-section.

2.1.1 Ambient Vibration Instrumentation

SENSORS: Typically seismometers have been used in ambient vibration measurements because of their high sensitivity and ease of use. However, most seismometers have flat response down to only one or two hertz, limiting their usefulness at low frequencies. Large, flexible structures often have modal frequencies below one hertz. Also, long cables can attenuate the seismometer outputs and increase the noise level, as the voltage output is very low.

Servo accelerometers were chosen for use in this project, as modal frequencies well below one hertz and several thousand foot cables were expected. Bridge response was measured using Kinemetrics Modal FBA-1 and FBA-11 force-balance accelerometers. Their dynamic range is 100 dB, allowing vibration as low as 10^{-5}g to be measured. Cable lengths of thousands of feet will not affect the output of these sensors. Up to 12 accelerometers were used to measure simultaneously motion at various locations. Wind speed was measured with bridge response using an anemometer system.

CABLING: The cable system was designed such that the reference accelerometers (which remained in the same place throughout the span measurements) were connected by short cables to a junction box. This junction box was connected by a 1,000ft. cable to the central recording station.

2.1.2 Measurements

MAINSPAN AND SIDESPAN MEASUREMENTS: 12 channels of accelerometers were used to measure vertical, longitudinal (along span), and transverse (across span) motion. At each 18 stations shown in fig 2, six accelerometers were installed. The position and sensitive direction of these six accelerometers are shown in fig 3. Six accelerometers were fixed at reference station 8. The other six "moving station" accelerometers were in tern mounted at locations A through F at each of the other stations.

TOWER MEASUREMENTS: The motion of the San Francisco (south) tower of the Golden Gate Bridge was measured using 9 channels of accelerometers. Station 5 was the reference station.

2.1.3 Conclusion

Many problems were encountered in the design of the instrumentation and in the data acquisition during the field portion of the ambient vibrations measurements of Golden Gate Bridge. These includes sensor choice , sensor mounting, cable design, and protection from environment. Extensive, high quality data were acquired during the field measurements.

2.2 AMBIENT VIBRATION MEASUREMENTS OF THE HUMBER BRIDGE[3]

Figure 4 is the schematic representation of the complete Humber Bridge, and Fig. 5 provides details of the box girders, showing the typical accelerometer locations at E,W,B,and T. Except for the end boxes of each span and one box at the center of the main span, the 124 box girders are 18.1 m long, 22 m wide and 4.5 m deep. The footpath/cycle traces are 3 m wide panels cantilevered out from the edges of the boxes. The boxes are welded together and stiffened torsionally.

2.2.1 Natural Frequencies and Mode Shapes

Finite element models of three basic kinds were produced. First one in the vertical plane which had three nodal degree of freedom, vertical(z), longitudinal(y) translations and rotation about the x-axis. Second, a model in the horizontal plane which had lateral(x) and longitudinal displacements with rotation about the z-axis as nodal degrees of freedom. Into this model rotation about y was introduced into the tower only, as an variable for some calculations, but it had no significant effect on the modal characteristics. Neither of these two models is able to produce torsional modes, and for this purpose a third, fully three-dimensional, model was produced, which had six nodal variables. For the two-dimensional models, all parts of bridge were represented by beam elements, for which both an elastic stiffness matrix and a geometric stiffness matrix were obtained. For the three dimensional model cables, hangers and towers continue to be represented by beam elements, but deck is replaced by plate elements. A lumped mass matrix was used in all calculations.

2.2.2 Test Planning and Program

The instrumentation used, consisted of three force balance servo-accelerometers. A four channel FM tape recorder was used to record the signals from the three accelerometers, and a Signal Processor was used for on-site spectral analysis. The aim was to calculate the values of frequency, damping and spectral amplitude, the type of mode, i.e. torsional, lateral or vertical

All the signals were replaced into the the signal processor. To determine resonant frequencies and amplitudes, each signal was analyzed separately using the auto power facility. The term "auto power" is used because it is a function available on the signal processor: the auto power spectra are single sided and each spectral value is an acceleration amplitude, determined directly from the square root of the modulus power spectrum.

2.2.3 Comparison of Measured and Predicted Modal Properties

Vertical Modes: For most the modes, agreement is within the variation of measured values. Also good agreement is found with the three-dimensional model.

Lateral Modes: Because of the low signal for the lateral acceleration, the auto power spectra are clear, hence the modal characteristics for the lateral modes are with some exceptions, poorly defined. In many of the spectra there is a peak at about 0.004 Hz which has no clear mode shape and conclusion must be that this is a characteristics of the excitation and not of the bridge itself.

2.2.4 Conclusions

The two dimensional mathematical model of the complete bridge is able to predict accurately the natural frequencies and mode shapes of the in-plane span modes. The estimated frequency values are reliable.

2.3 AMBIENT VIBRATION MEASUREMENT OF BOSPORUS BRIDGE [4]

Bosporus bridge, across the Bosporus river is in Istambul, Turkey, having a main span of 1074 m. It has steel towers, wide shallow box girders side spans of roughly equal length but which are supported on the columns rather than being carried by the cable and single hinged hangers throughout the center span. Bridge is saturated by more than 140 000 vehicles per day. Figure 6 shows the general arrangement.

2.3.1 Testing Procedure

Three force balance servo accelerometers were used , these have an operating range of +/- 0.25g in the frequency band of 0 - 30 Hz. Figure 7 shows two dimension finite element model and the stations which measurements were taken. The objective is to find frequency, damping spectral amplitude.

All signals were replaced to the signal conditioning which analyzed separately and also performs cross - spectral analysis. Resonant frequencies, amplitude ratios were obtained from inspection of the accelerations auto power spectra for each measurement.

2.3.2 Conclusions

i) Within the range of 0 to 1.1 Hz the measurements identified 18 vertical modes and 20 lateral modes in the main span.

ii) The experimental frequencies and mode shapes were compared to those obtained by two and three dimensional analysis. In general the compared and measured natural frequencies and mode shapes were in done agreement.

2.4 AMBIENT VIBRATION OF FAITH SULTAN MEHMET BRIDGE [5]

Faith Sultan Mehmet bridge is second Bosporus river highway bridge at Istanbul, Turkey, open for traffic in 1981. It has a box girder deck 39.4 m. wide overall and 1090 m. long steel towers rise 110 m. above GL . The deck roadway is 8 m. above foundation level at the towers where an arrangement of rocker and expansion are provided. Figure 8 shows the general arrangement .

2.4.1 Mathematical Modelling

Two dimensional model: The vertical plane model has only three degrees of freedom (DOFs) assigned to each nodal point, these being two translation degrees of freedom in the vertical and longitudinal axes and one rotational degrees of freedom about the lateral axis. Figure 9 shows arrangement of nodal points for 2-D model used for the vertical plane and lateral analysis; it has 139 nodes and 196 elements with 393 DOFs in the vertical plane model.

Three Dimensional modelling: With six degrees freedom allowed for each node in this model, it is possible to obtain not only vertical and lateral modes, but also torsional modes. The main difference between 2-D and 3-D models is in the representation of the deck, which is now represented by beam elements in 2-D model and one in 3-D it is represented by equivalent plate elements with similar bending, torsional and members properties to those of the box-girder deck. The fig 10 shows the general 3-D arrangements of nodal points for the three dimensional model, it has 280 nodes, 276 beam elements, 61 plate elements and 1586 DOFs.

2.4.2 Objectives and Instrumentation

The objective of the test were to determine modal properties of the bridge in terms of its natural frequencies, mode shapes and damping ratios in order to validate the mathematical modelling described above and to investigate the relationship between the loading and response amplitude. The acceleration were sensed by up to five servo accelerometers and amplitude by power supply/conditioner units.

2.4.3 Conclusions

i) The measured vertical frequencies and mode shapes match the predicted values for a mathematical model.

ii) The vertical modes of the deck are clearly defined while the lateral modes are weak, sparse and poorly defined.

iii) The longitudinal tower modes clearly show the effects of the cable restraint as they have maximum amplitude between the tips and the deck level relatively high natural frequency.

CHAPTER - 3

AMBIENT VIBRATION MEASURING INSTRUMENT

3.1 ACCELERATION LEVEL IN STRUCTURE

The vibration amplitudes to be picked up in structure is usually quite low. The natural time periods of masonary buildings and concrete gravity dams is of the order of 0.25 sec or low, the acceleration levels in these structures under ambient vibration is of the order of 10^{-5} g to 10^{-3} g. In flexible structures like multistoried buildings and tall structures, the natural time periods are of the order of 1.05 sec or more, the acceleration levels under ambient vibration is of the order 10^{-4}g to 10^{-2}g. The ranger seismometers with high sensitivity are suitable for measuring frequencies of stiff structures in the range of 1 Hz to 100 Hz. Force balance accelerometers are suitable for making frequency measurement of flexible structures in the range of DC to 50 Hz.

Ambient vibration measuring instrument available in the department of earthquake engineering is described below:

3.2 SOLID STATE RECORDER (SSR-1) [15]

The SSR-1 is a highly flexible digital seismographic event recorder which records into solid-state RAM. It utilizes a 16 bit A to D converter to provide 96 dB of dynamic range.

It can support up to six sensors which can be passive or active sample rates of 1000 sps for a signal channel, 500 sps for 3 channels and 200 sps for all six channels can be selected.

The low power design of the SSR-1 offers the user a selection between two 12 volts 6.5 amp hour sealed lead dioxide batteries or 27 D-size alkaline/manganese cells, or any external 12 volt supply. Accurate timing is provided using TCXO clock. The whole system is housed in a rugged aluminum case and sealed against dust and moisture. Separately housed in a polyethylene box, the batteries and fuses are accessible without opening the instrument compartment, All I/O, power and timing connections are recessed into a front panel for protection. Because of its design the SSR-1 can be normally operated without opening the housing.

3.2.1 Specification of SSR-1

RAM	4 MB
Dynamic range	96 dB with 16 bit accuracy
Sampling size	200 sps

3.3 OPERATING INSTRUCTIONS FOR RANGER SEISMOMETER (SS-1)

3.3.1 Brief Description of SS-1

The SS-1 Ranger Seismometer is a versatile, high sensitive, portable seismometer specially designed for a variety of seismic field applications under adverse environmental conditions. The ranger combines high sensitivity, field selectable mode (horizontal or vertical) and rugged water-tight construction, in a package measuring only 5.5 inches in diameter by 12 inches long and weighing only 10.9 pounds. Figure 12 shows the detail of seismometers.

The ranger is spring-mass instrument with electromagnetic transduction. Its permanent magnet assembly is the seismic mass while the coil is attached to the frame. The ranger can be used either horizontally or vertically and is well suited to field or laboratory use. The mass is supported by two circular flexures which constrain it to a single degree of freedom. A helical spring is used to suspend the mass. When the seismometer is used horizontally, the spring is controlled by positioning a hanger rod attached to the spring. The basic natural period of the mass, flexures, and suspension spring is extended by the addition of small rod-magnates installed around the mass. There period extending magnets interact with the magnetic field of the mass, effectively producing a negative restoring force. In order to achieve the desired period, the field strength and position of the period-extending magnates are carefully adjusted at the factory.

3.3.2 Specification of Ranger Seismometer(SS-1)

Positioning	Longitudinal, Transverse and Vertical direction
Natural period	1 sec.
Coil resistance	5500 ohms
Critical damping resistance	6500 ohms
Generator constant	340 volts/m/sec
Total mass travel	2 mm
Weight	1.45 kg

3.3.4 Adjustment of SS-1

The SS-1 ranger seismometer should not be installed within six inches of any steel or magnetic object. To unclamp the mass, turn the transport lock fully counter clockwise. Apply full finger torque to seat the transport lock against its gasket inside the case. This makes the seismometer weather proof in its operating mode.

The mass is brought to the center of its span of travel by means of the spring hanger rod at the top of the instrument. After unlocking the mass by turning the transport lock fully counter clockwise, make this adjustment as follows:

i) Unscrew and remove the access cover/handle.

ii) While holding the spring hanger knob with one hand, loosen the collect nut with the other hand.

iii) Move the spring hanger rod with the mass is fairly near center. Centering is determined by the coincidence of two lines which are visible through the viewing part. With the mass reasonably centered, tighten the collect nut.

iv) Fine centering of the mass is now achieved by means of the mass centering nut. Turn this nut until the two lines, as seen through the viewing port, coincide.

v) Replace the access cover/handle,being sure that its gasket is properly seated.

3.4 ADVANTAGES AND LIMITATIONS OF AMBIENT VIBRATION SURVEY

3.4.1 Advantages

There are following advantages which makes this method particularly attractive over the other methods:

i) The instrumentation is light weight and portable.

ii) This permits data to be recorded at a large number of locations with very little interference with the normal flow of activity.

iii) There is no requirement for attachment of equipment to the structure with the resulting patchwork which have to be done.

iv) The level of vibration recorded are those that, the owners have no fear of damage during the testing.

v) The instrumentation will cover a wide frequency range.

vi) This method is also economical over other methods.

3.4.2 Limitations

i) The displacement due to vibration should be small within elastic limit. When the displacement goes beyond the elastic limit it gives misleading results.

ii) The second limitation depends upon instrumentation which are used in the testing as for example the Kinemetric SSR-1 has a frequency range 1 Hz to 100 Hz.

CHAPTER 4

VIBRATION SURVEY SOFTWARE

4.1 INTRODUCTION

The Kinemetrics Seismic Workstation Software is a collection of the programs written for the IBM PC and designed to provide the user with commonly required data processing programs and to provide a software core to which custom programs are centred around a common data format (CDF) for multi-channel time series data so that programming redundancy is minimized. The block diagram of the program relationships are shown in fig 13.

4.2 INTRODUCTION TO QUICKTALK (QT) (SSR-1 COMMUNICATION PROGRAMS)[15]

QuickTalk (QT) is an integrated environment for communication with Kinemetrics SSR-1 Solid State Recorder using an IBM PC. It provides for direct communications as well as remote access over telephone lines and modems. A spreadsheet like parameter Worksheet is built into the program to ease the setup of experiments which require periodic changes in the configuration of the recorder. Quicklook, is also available from within Quicktalk to provide graphical display of received event files.

What Quicktalk really does that standard PC communications programs dont's is to mainly "insulate" the user from the simple (and often times crypic!) SSR-1 two-character commands and 187 numeric parameters. Many of these commands are accessed from the "user friendly" pop up complete with on text sensitive help in many areas.

Since QuickTalk directly access the PC's serial port, interrupt controller, and display screen memory, 100% hardware compatibility with the IBM PC is absolutely required. Also, the Bios (Basic Input Output System) ROM must be compatible. Quicktalk supports color display adapters, microchrome adapters and monitors as well as the Liquid Crystal and Plasma displays used on many Laptop computers. Communications at speeds up to 115.2 kilobaud are supported on faster computers.

4.3 INTRODUCTION TO QUICKLOOK (QL16)[15]

Quicklook (QL16) gives the field user a quick visual presentation of seismic waveform data recorded on Kinemetrics SSR-1 recorders. Maximum amplitude, event duration and predominant frequencies can all be readily determined.

It provides an immediate visual presentation of the data with no additional processing. It is also especially helpful in quick determining, which records require further analysis. Finally, QL16 can be used during periodic inspections to display functional test records to verify proper operation on the spot.

The program QL16 is provided with Kinemetrics SSR-1 digital seismic recording instruments. The program allows seismic records to be displayed graphically on the screen of an IBM PC (or 100% compatible) computer. The program is compatible with both 12 bit(SSR-1) data and 16 bit (SSR-1) data. The event can be viewed as soon as they are transferred to the PC.

QL16 automatically scales the event to fit on the screen in both X and Y axes. Once initially displayed, channels which are temporarily not wanted can be removed from the display and areas of interest can be quickly examined in greater detail by working with the cursor and zooming it.

4.4 TIME SERIES FILE PROCESSING

The first step in data processing on the seismic Workstation is to acquire raw instrument data and convert it into the Workstation common data format (CDF). This stage of processing is handled by the Instrument Interface Software as shown on the block diagram in Fig. 13.

Once the raw instrument data has been converted to a CDF file (with default file extension "D16"), the next few processing steps are to decode the serial time code (if necessary), and to edit the raw data down to a subset for processing by the Vibration Survey programs.

4.5 SPECTRAL ANALYSIS

The program for spectral analysis include FFT and QFFT. Both programs perform non-averaged fast Fourier transforms on up to four channels of data from CDF files. The programs FFT differs from QFFT only in the respect that FFT allows 4 times larger transforms to be computed compared to QFFT. However, FFT utilizes disk files for storage of the intermediate results, thus slowing down processing.

The QFFT program is described in the following sections. However the command descriptions are equally applicable to the FFT program commands.

4.6 INTRODUCTION TO QFFT [15]

The iterative spectral analysis program QFFT provides the user with the ability to view pre-recorded data graphically in the frequency domain. QFFT also provides the user with the capability for graphically zooming displays for the detailed viewing, and producing labeled hard-copy output on the optional printer or pen plotter. Detailed frequency auto-plots are scaled both horizontally and vertically. Time series plots have units of volts and seconds. Frequency amplitude plots have units of Fourier amplitude and Hertz.

4.6.1 STARTING THE ANALYSIS SESSION

QFFT is started with a command of the form:

QFFT file name

where "file name" is the name of the CDF time series data file to be processed. The program then responds with a, series of questions to determine the processing parameters which are to be used in the processing the file are shown in fig 14.

As indicated in fig 14 the first question requests to enter the number of channels to be analyzed. The acceptable range of values are shown in square brackets and the user response must be typed in integer format (no decimal point is allowed). In the example, the acceptable range is 1 through 4 channels, and the user has elected single-channel processing mode. Note that the larger the number of channels to be processed, the smaller the allowable transform size. This is due to data array space limitations of QFFT.

The second question printed by QFFT requests the transform order (size) to be entered. This is the power of two of the number of input data points which will be used in the FFT computation. Thus, a selection of 11 means that 2048 data points will be processed. Yielding an input spectrum with 1024 points from 0 Hz (DC) to the Nyquist frequency (1/2 * sampling rate). Note that the upper limit of the acceptable range which is displaced is adjusted for the number of channels which has been selected in the preceding question.

The third question requests to select the transform window desired. Refer to any digital signal processing text for an explanation of the theory and appropriate use of a window function.At this points, QFFT searches for the specified data file, reads the header information, and displays the comment, sample rate used, and the assigned channel names.

Next, QFFT requests the number of data file channel to be processed for each of the QFFT analyzer channel selected.

The final question requested by QFFT is to determine the point within the data file at which processing is to begin. This is useful for comparing transforms of data at different points within a given file, as well as for skipping past a bad section of the file. The maximum time offset which QFFT will accept is 30.0 sec. and the user input may contain a decimal point.

At this point the initial dialog is complete, and QFFT proceeds to read the input data file and to execute the operations specified. After FFT calculations are complete, the seismic Workstation screen is cleared, and the initial plot is displayed as shown in fig 20.

The initial QFFT plot consists of two "frames" in which functions are displaced. The upper frame (frame #1) is a linear-linear auto-scaled plot of the input time series for analyzer channel 1, while the lower frame (frame #2) contains an auto-scaled semi log plot of the amplitude spectrum of the data. In the case of frame #1, the horizontal axis (time) is scaled in seconds, while the amplitude is normalized to full-scale. For frame #2, the horizontal axis is frequency in Hertz. Note that the top of the plot is also labeled (form left to right) with the data file name, the comment found in the header of the file and the analyzer channel number.

CHAPTER 5

ANALYTICAL TECHNIQUE FOR CALCULATING MODE SHAPES

5.1 THEORY FOR ANALYSIS OF DATA[6]

The acceleration response of a physical structure can nearly always be characterized as a mixed random process, a composite of random process and a deterministic shaping function. The deterministic shaping function results from the response of the structure in its normal modes to the random input provided by the natural process of wind and micro tremor. The random portion results from the nature of the input, as well as extraneous noise present in the measurements.

The random process is described by explicit method. These include: the probability density function, the autocorrelation function, and the power spectrum.

One property of the spectrum of a random process is that each segment of the infinite duration time history, being different from any other segment, makes a unique contribution to the spectrum. Thus the spectrum resulting from any finite time measurement is only an approximation to the true spectrum of the complete process. This properties presents the greatest problem in the measuring the spectrum of a random process. The solution is accomplished by spectrum averaging. The average of the many independent measurements is a better statistical estimate of the true value than any single measurement. In the process of averaging, the random components of the signal are diminished and the systematic components are enhanced.

During the field program, measurements are taken at different positions of the structure in the several different orientations. These data are analyzed by determining the relation between each signal and a reference signal. The reference location is chosen so that it contains information for all the modes of the interest. Consider the generalized measurement situation shown in fig 15, with two accessible points on the structure X and Y.

X and Y are related by linear quantity H, and Y is contaminated by some uncorrected noise source N.

The recorded time-function signals x(t), y(t) are Fourier transformed into linear spectra:

$$S_x = F\{x(t)\} \qquad \ldots(1)$$

$$S_y = F\{y(t)\} \qquad \ldots(2)$$

From these linear spectra, three power spectra can be computed. These are the "input" power spectrum,

$$G_{xx} = S_x S_x^* \qquad \ldots(3)$$

and "output" power spectrum,

$$G_{yy} = S_y S_y^* \qquad \ldots(4)$$

and the cross power spectrum,

$$G_{yx} = S_y S_x^* \quad \ldots(5)$$

Where the asterisk in these equations indicate a complex conjugate. The output power spectrum can be expressed with two parts, one due to the input and one due to the uncorrelated noise source:

$$S_y = HS_x + S_n \quad \ldots(6)$$

substituting (6) into (5), the cross spectrum can be written

$$G_{yx} = HG_{xx} + G_{nx} \quad \ldots(7)$$

After signal averaging these terms become

$$\overline{G}_{yx} = H\overline{G}_{xx} + \overline{G}_{nx} \quad \ldots(8)$$

Assuming either that S_n is small or that G_{yx} has sufficiently smoothed through averaging to make G_{nx} negligible, the cross spectrum terms are given by

$$\overline{G}_{yx} = H\overline{G}_{xx} \quad \ldots(9)$$

The transfer function is given directly calculated:

$$\therefore H = \frac{\bar{G}_{yx}}{G_{xx}} \qquad \ldots(10)$$

To measure the degree to which one signal is dependent on the other instead of the another uncorrelated source, the coherence function is evaluated. The coherence function is defined by

$$\gamma^2 = \frac{|\bar{G}_{yx}|^2}{G_{xx}\,G_{yy}} \qquad \ldots(11)$$

Equation (11) can be rewritten in the conventional form:

$$\gamma^2 = \frac{|H|^2\bar{G}_{xx}}{|H|^2\bar{G}_{xx} + \bar{G}_{nn}} \qquad \ldots(12)$$

At a given frequency, γ is the fraction of power at the system output is due to the input. If G_{nn} is zero, $\gamma^2 = 1$. This indicates a perfect linear, non-noise contaminated relation between input and output. If $|H|^2\bar{G}_{xx}$ (the output term due to the input) is small compared with the noise, γ^2 will be close to zero. γ^2 is lying between 0 and 1.0 that gives a positive indication of the relationship between input and output.

Consider the structure shown in figure 15, representing the plan view of the crest of a concrete arch dam. Structural coordinates are indicated for radial vibration of the arch. The set of time series $x_1(t)$, $x_2(t)$, ...$x_i(t)$....$x_n(t)$ is transformed to the frequency domain:

$$\begin{aligned} S_1(f) &= F\{x_1(t)\} \\ S_2(f) &= F\{x_2(t)\} \\ \cdot \quad \cdot \quad &\cdot \\ \cdot \quad \cdot \quad &\cdot \\ S_i(f) &= F\{x_i(t)\} \qquad \text{...(13)} \\ \cdot \quad \cdot \quad &\cdot \\ \cdot \quad \cdot \quad &\cdot \\ S_n(t) &= F\{x_n(t)\} \end{aligned}$$

Modal frequency of the structure appear as the peaks in the amplitude spectra $|S_n(f)|$. The amplitude spectra of figure 17 , shows the three lowest modal frequencies.

The i^{th} mode shape coefficient H_{ij} at each natural frequency f_j normalized to the value at coordinate 1, is simply

$$H_{ij} = \frac{\tilde{G}_{ij}(f_j)}{G_{11}(f_j)} \qquad \text{...(14)}$$

The relative phase of the complex product $S_1(f)S_i(f)$ gives the mode shape deflection.

Damping estimates are obtained from the width of the peak corresponding to the modal frequency of the interest:

$$\xi = \frac{1}{2}\frac{BW}{f_i} \qquad ...(15)$$

Where ξ is the critical damping ratio and BW is the peak width (bandwidth) in Hz measured at 1/ 2 of the amplitude spectrum value $S(f_1)$.

It can be shown that the length of time series required to give reasonable estimate of the damping is

$$T_\alpha = \frac{2n}{\xi_1 f_1} \qquad ...(16)$$

Where T is the length of records, ξ_1 is the damping ratio in lowest mode of interest, f_1 is the corresponding frequency and n is the number of averages required for a sufficiently smooth spectrum. Experience has shown that a maximum of 32 averages are required for most civil structures.

5.2 FIELD PROCEDURE DATA ANALYSIS AND INTERPRETATION

Most ambient or shaker excited building vibration tests assume that the structure can be approximated by a damped, linear, discrete or continuous system whose properties varies with reference to a line. Two simultaneous velocity recordings are made in each run. One of the transducer (the reference instrument) is left in place while the other is shifted up and down or sideways measured. All the transducers are oriented parallel at the same location on the structure to record identical structural motion. This measurement provides a relative calibration between channels of the entire transducer amplifier, filter, recorder and analog to digital conversion system.

5.2.1 Selection of time for recording

The length of recording for each measurement is very important. Too short a period of time will result in unreliable spectra, and thus limit the usefulness of mode-shape and damping estimates. Too long of a recording increases project effort and cost. As a rule of thumb one hour of recording time is required for each second natural period corresponding to the lowest mode of interest.

CHAPTER 6

EXPERIMENTAL ANALYSIS OF BRIDGES

6.1 AMBIENT VIBRATION TESTING OF BRIDGE ACROSS GANGA CANAL AT ROORKEE[7]

6.1.1 Description of Bridge

Ambient vibration testing of Roorkee bridge was carried out on 12th of December 1995. The cable stayed pedestrain bridge at Roorkee was built in 1981 over the Ganga canal. It is without any intermediate support to keep waterway free for militry training exercises. It is a single span bridge.

Important data foe the Roorkee bridge are follows:

Span	73.60 m.
Height of towers above base	10.90 m.
Clear roadway width	1.67 m.
Center to center distance between girders	2.084 m.
No. of cables connecting girder to tower top (In one plane)	8
No. of cables used for back stay (In one plane for one tower)	5
Material used for tower and girder	Mild steel
Diameter of cables	35 mm

6.1.2 Instrumentation For Testing of Bridge

Two Kinematrics 1- sec seismometers SS-1 and one Kinemetrics SSR -1 portable digital event recorder were used in the testing. The seismometers were placed at mid span of the bridge. One seismometer was placed along longitudinal direction, one transverse and one along vertical direction.

6.1.3 Description of Test

The bridge was tested for mild traffic which were recorded by Kinemetrics SSR-1 recorder in digital form. The digital data was then transferred to hard disk of PC Note book using software utility **QUICKTALK (QT)**, which is already discussed in section 4.2. Six events were recorded and amongst them event no 4 was analyzed. Using option **QL16.exe** the plot shown in fig 19 was obtained, for channel no.1, which is the complete graphical representation of digital data recorded earlier in three channels of event number 4 (File name rbr00004.ssr).

For getting natural frequency, option **fd.exe** was used. Two points were selected on frequency plot of channel no.2 (as channel no 1 is time channel) is shown in fig 21, by marking the plot through entering character 'T'at two different points. After entering the no. of cycles between the above two selected points, the value of natural frequency is displaced on the screen plot by typing the character 'F' on the plot. The value of natural frequency was obtained as 2.952 Hz.

The plot of **QFFT** from samples of the recorded data of event no 4 are shown in fig 20. Steps have already been described in section 4.6.

6.2 AMBIENT VIBRATION TESTING OF BRIDGE ACROSS GANGA CANAL AT HARDWAR [8]

6.2.1 Description of the Bridge

The cable stayed bridge at Hardwar was built over new supply channel on the state highway. Important data for Hardwar bridge are follows:

Span = 2 * 65m.	130 m
Roadway	7.5 m.
Footpath at either side	1.5 m.
Bed level of channel(R.L.)	287.35 m.
Full supply level (R.L.)	290.25 m.
Width of canal at bed level	116.0 m.
Material used for deck,tower, well cap and well	M30 concr.
Diameter of high tensile steel series for cables	7 mm.
Live load	IRC loads

6.2.2 Instrumentation For Testing Of Bridge

Three Kinemetrics 1-sec (natural period) seismometers SS-1 and Kinemetrics SSR-1 portable digital event recorder were used in the testing. The seismometers were placed at the center of the span along the three directions i.e. longitudinal transverse and vertical directions. The seismometers were placed on footpath which is 1.5 m. wide.

6.2.3 Description of the test

Description of the test had already been discussed in the section 6.1.3. The QL16.exe plot of first channel of the three seismometers for the event no. 1 (file name HB000001.SSR) is shown in the fig 26 . The frequency plot for the channel no. 1 of the event no. 1 is shown in fig. 28. The value of natural frequency which has being obtained is 2.316 sec. The results of the test are tabulated in table.

6.3 RESULTS OF THE TESTING

The experimentally measured values of the fundamental time periods of the two bridges are tabulated below -

Table : Experimental Time Periods for Bridge

BRIDGE	TIME PERIOD(sec)
Roorkee	0.338 sec
Hardwar	0.451 sec

The first three mode shapes for longitudinal direction are shown in fig nos, 29, 30, 31.

7.4 MATRIX METHOD OF ANALYSIS [9]

7.4.1 General

The analysis of structures, static or dynamic requires the solution of algebraic equations, or calculations of the eigen values of the system. In either case the problem can be handled in a systematic manner in compact matrix notation. The structure is idealized into a skeletal structure which retains the properties of the original structure. The stiffness matrix of the structure as a whole is assembled from the stiffness matrix of the individual members. The resulting equation can be solved for time periods and modal amplitudes in dynamic analysis.

7.4.2 Assumptions

The assumptions involved are essentially such as to facilitate mathematical modelling of a real system in such a manner that the behavior of the prototype structure can be simulated.. The assumptions involved in linear elastic analysis are:

i) The structural material is homogeneous and isotropic.

ii) All special members are replaced by line member oriented along the centroidal axis of the original member.

iii) The line members, however, retain all properties of the original member i.e. length, inclination, area and moment of inertia.

iv) The member intersections are infinitesimal in size.

v) Members having a common junction are assumed to be concentric.

vi) The structural material has a well defined linear relationship between applied and resultant displacement.

7.4.3 Member Stiffness Matrix

The stiffness matrix method of analysis is one in which compatibility of displacements is assumed and the equilibrium equations at the nodes are formulated in terms of the nodal displacement components. the method proceeds from part to whole i.e. member stiffness matrices are generated and contribute to the assembly of the overall stiffness matrix of the structure.

The stiffness matrix of a rigid frame arbitrarily oriented in a 2-D space having three degrees of freedom at each node namely translation along x,y axis and rotation about z axis. Member stiffness matrix thus generated are then contributed to the assembly of the overall stiffness matrix of the structure.

7.4.4 Transformation Matrix

In order to establish the equilibrium equations it is essential that force components at nodes of the members meeting at a node, be in the same directions. This transformation of force components from local coordinates system to the global coordinate system is achieved by means of a transformation matrix. The stiffness matrix of a member is originally derived i local coordinate system and then modified so as to represent the stiffness in global coordinate system by using equation:

$$\left[K_G\right] = \left[R\right] \left[K_L\right] \left[R^T\right]$$

K_G = stiffness in global coordinates

K_L = Stiffness in local coordinate system

R = Transformation matrix

7.4.5 Free Vibration Characteristics

The global stiffness matrix $\left[K\right]$ is obtained as explained in earlier section. The generalized mass matrix is assumed to be diagonal and the the diagonal elements at each node correspond to the two translation and one rotational degrees of freedom.

The equation of motion for free vibration can be expressed in the form

$$[K]\{\phi\} = p^2 [M] \{\phi\}$$

where p is undamped natural frequency and ϕ is the mode shape factor. Above equation can be expressed in the following form i.e.

$$A X = \lambda X$$

which represents the eigen value problem whose solution leads to evaluation of natural frequencies and corresponding mode shapes. The form adopted are

$$[M^{-1}] [K] \{\phi\} = p^2 \{\phi\} \text{ or}$$

$$[K^{-1}] [M] \{\phi\} = (1/p^2) \{\phi\}$$

equation is generally preferred for the sequential determination of eigen pairs.

7.5 COMPARISON OF RESULTS

The experimental and theoretical fundamental time period of the two bridges are shown in the table below:

Table : Theoretical and Experimental Time Period For First Mode

Bridge	Theoretical	Experimental
Roorkee	0.310 sec.	0.338 sec.
Hardwar	0.470 sec.	0.451 sec.

The theoretical time periods of the bridge at Roorkee is slightly less than the experimentally found value. Where as that of Hardwar bridge it is slightly more than the experimental values. These difference may be due to approximation taken for mathematical modelling.

The obtained first three time periods for Roorkee bridge and Hardwar bridge are tabulated below :

Table : First Three Time Periods Of The Bridges as Calculated Theoretically (sec)

Bridge	First	Second	Third
Roorkee	0.310	0.112	0.056
Hardwar	0.470	0.398	0.236

CHAPTER 8

SUMMARY AND CONCLUSION

8.1 SUMMARY

The cable stayed bridge has complicated vibrational systems due to different structural properties, it is important to carry out elaborate dynamic analysis. In this study ambient vibration testing of two cable stayed bridges were done. The objective of this study is to determine fundamental time periods for both the bridges.

In order to carry out dynamic analysis a lumped mass model of the bridges are made. For Hardwar bridge soil springs are also taken into account for the flexibility of the foundation and surrounding soil.

The time period of the bridges are determined from the measured response under mild traffic excitation. The vibration were picked up by Ranger seismometers (SS-1) and by Solid State Recorder (SSR-1). The recorded data was then analyzed by using seismic workstation software (SWS).

8.2 CONCLUSIONS

Following conclusions can be drawn from the study:

i) Time Period for longitudinal vibration shows reasonably close agreement between experimental and theoretical value for both the bridges.

ii) Most of the time vertical vibration exceeds the max. limit, during the testing of Roorkee Bridge. This is the major limitation of the instrument itself.

iii) It is not possible to get the time period for vertical and transverse direction from the vibration record as record does not shows dominance of single frequency.

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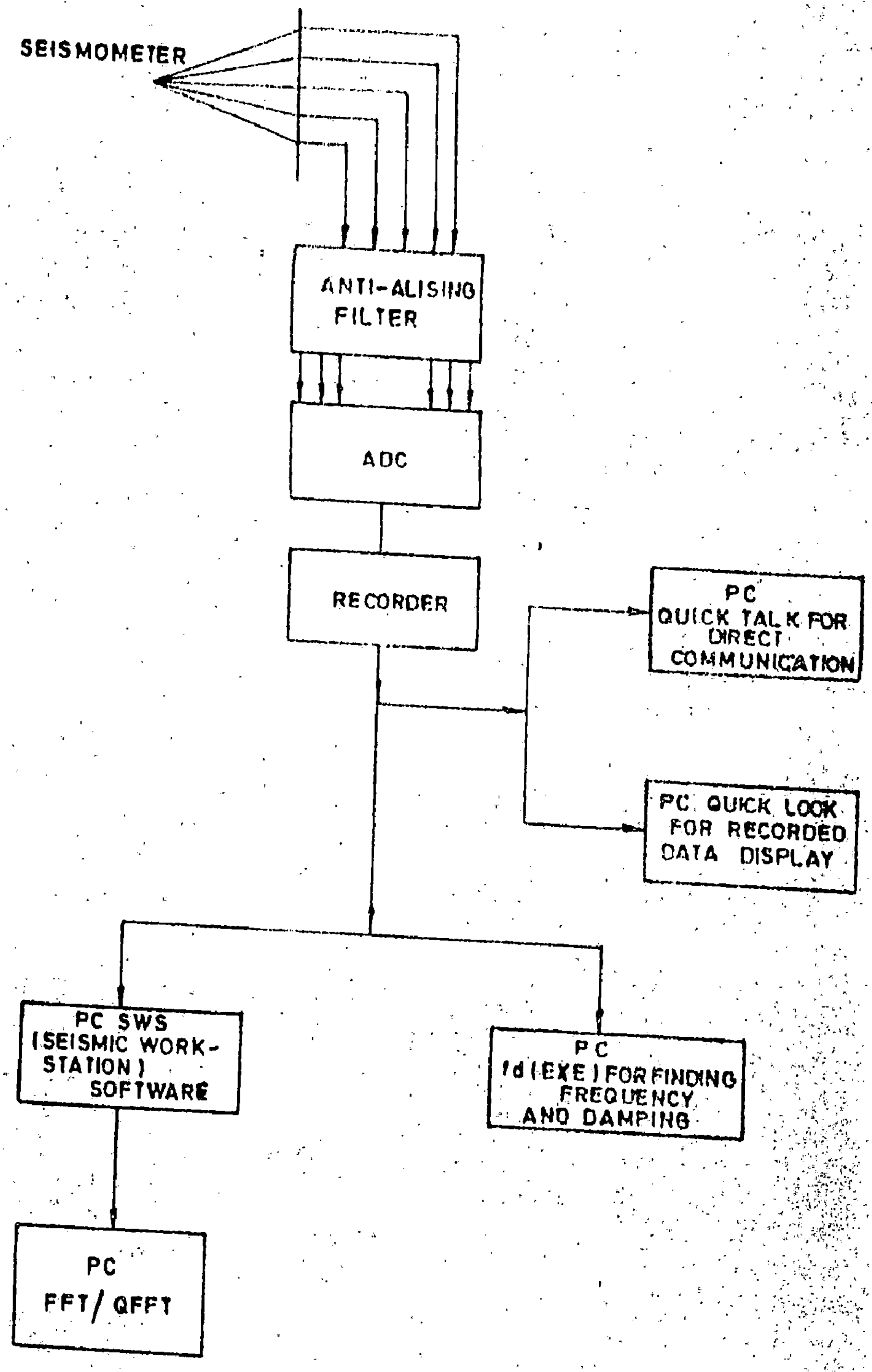


Fig. 1 Ambient Vibration Test Set-up

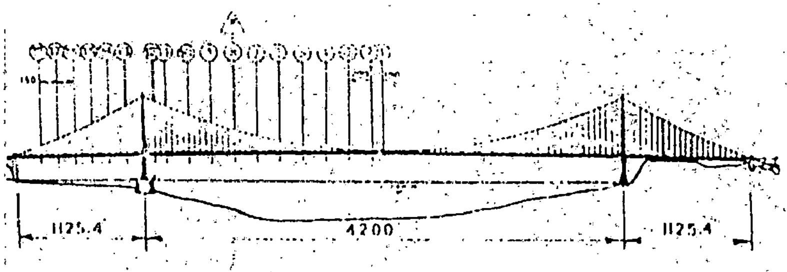


FIG. 2.—Measurement Stations Along Suspended Structure

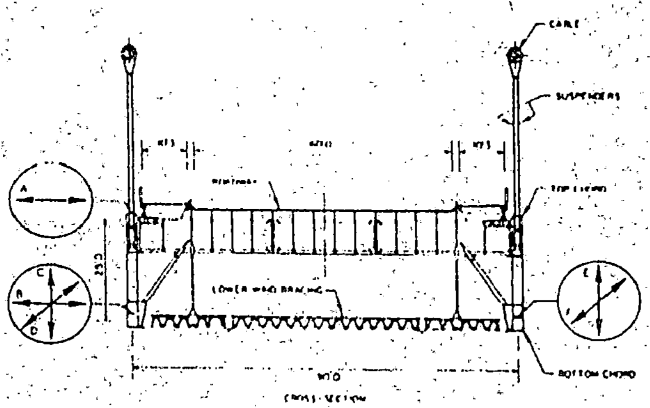


FIG. 3.—Positions and Orientation of Six Accelerometers at Typical Cross Section of Suspended Structure

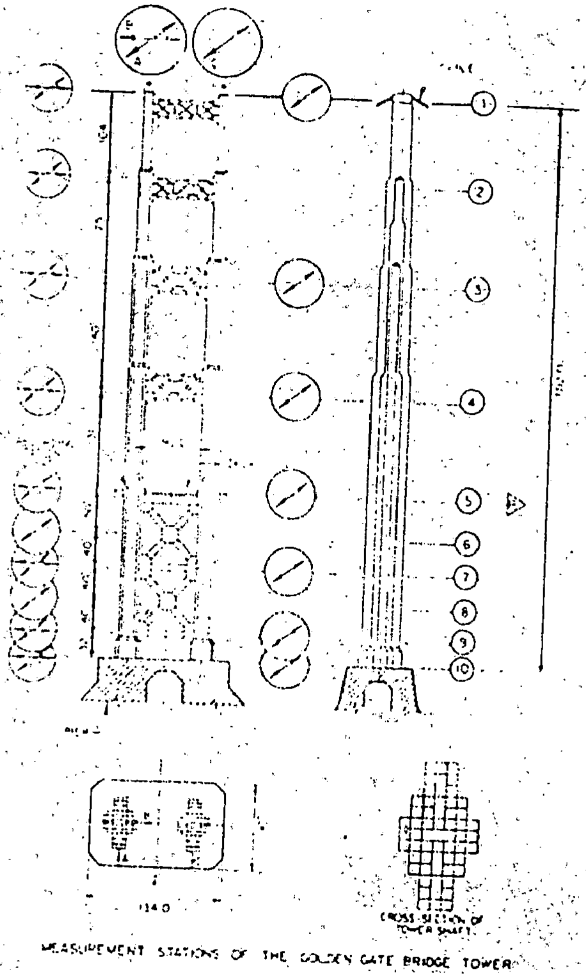


FIG. 4.—Measurement Stations of Golden Gate Bridge Tower

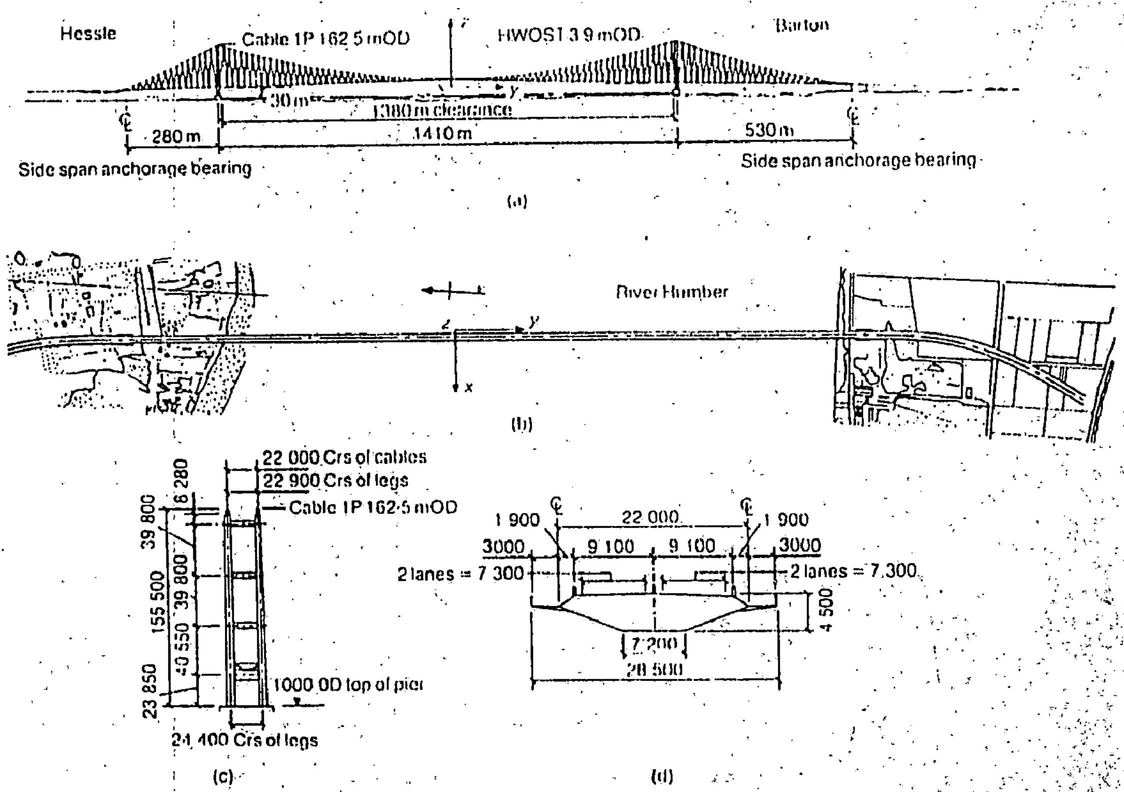


Fig. 5 *Humber Bridge general arrangement: (a) elevation; (b) plan; (c) elevation of towers; (d) section through deck*

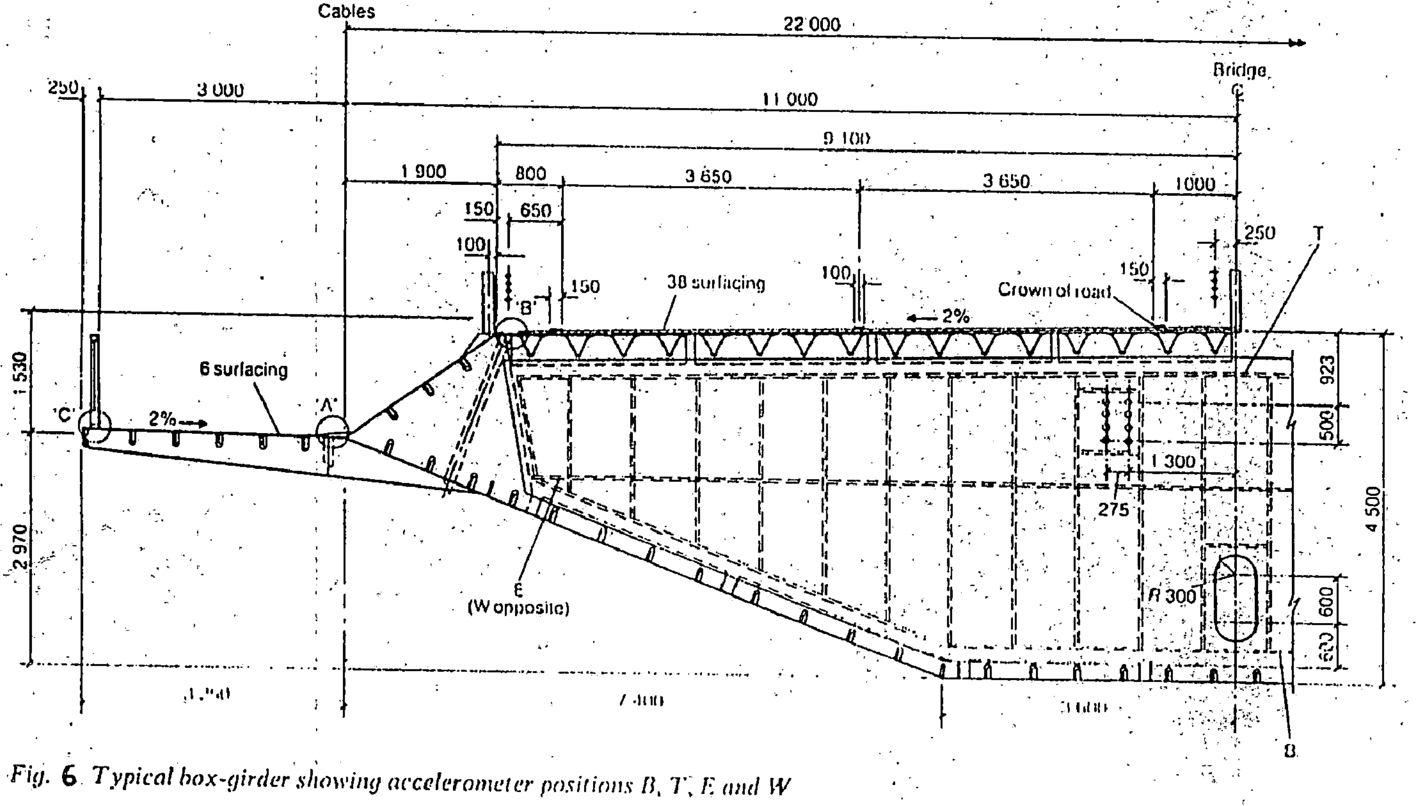


Fig. 6 *Typical box-girder showing accelerometer positions B, T, E and W*

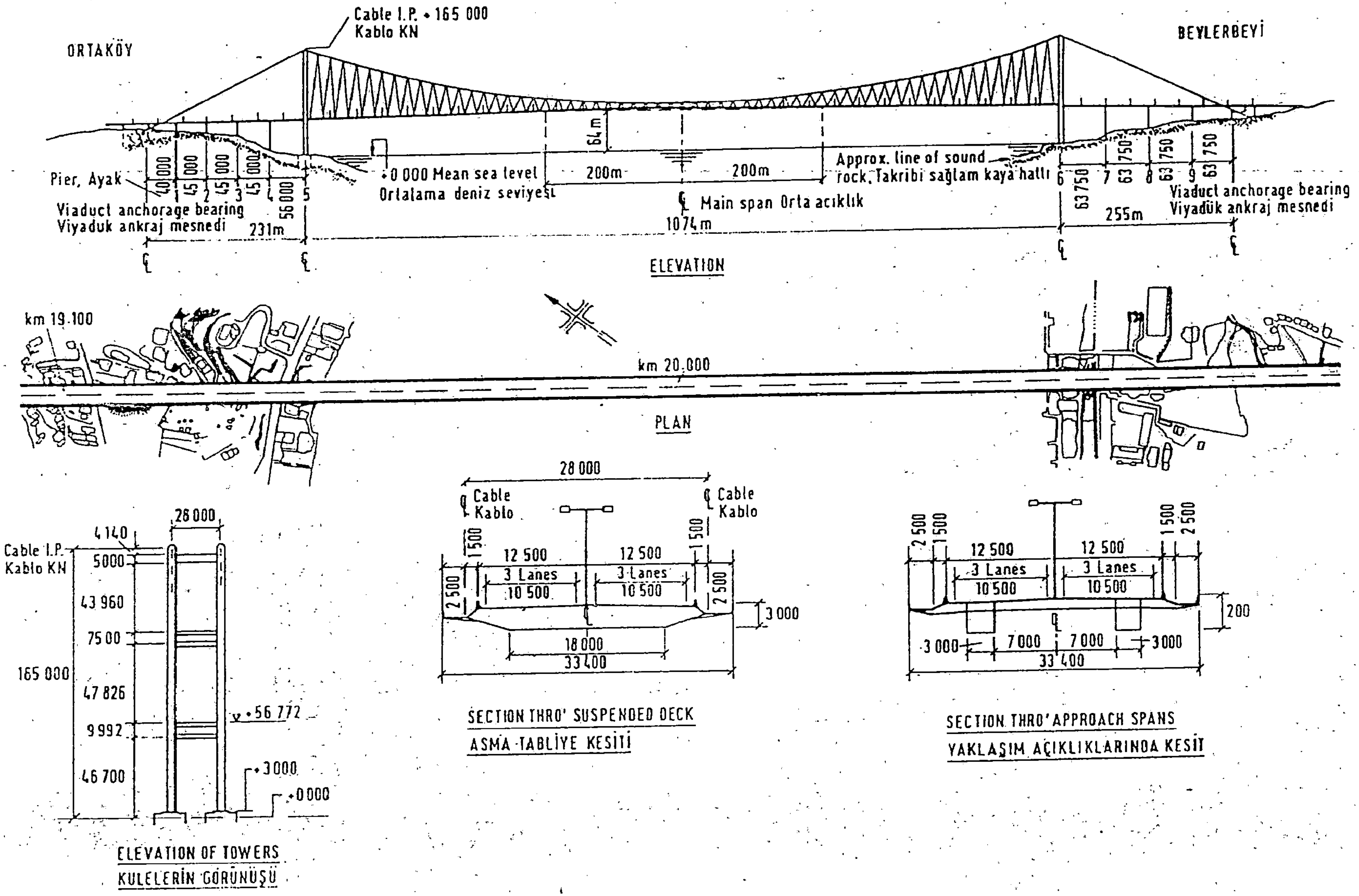


Figure 7 Bosporus Bridge: general arrangement

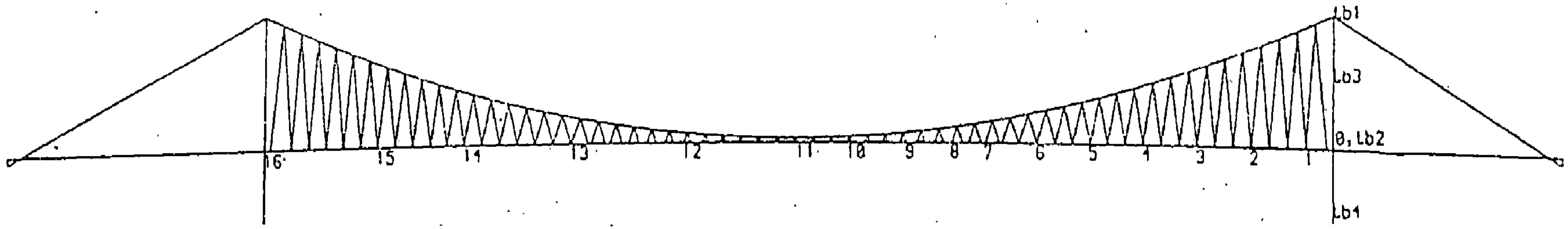


Figure 8: Two-dimensional finite element mesh and measurement stations

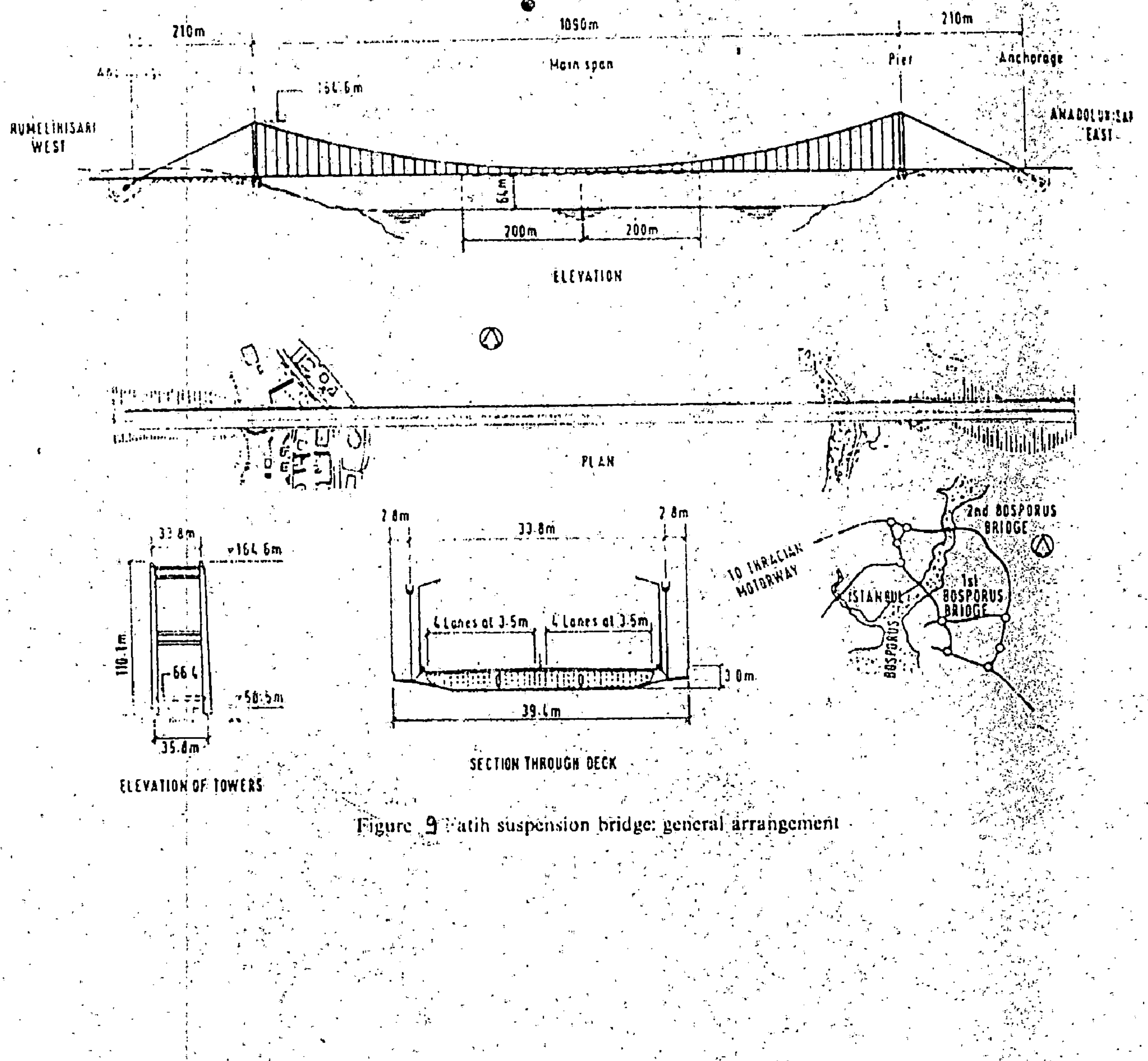


Figure 9 Fatih suspension bridge: general arrangement

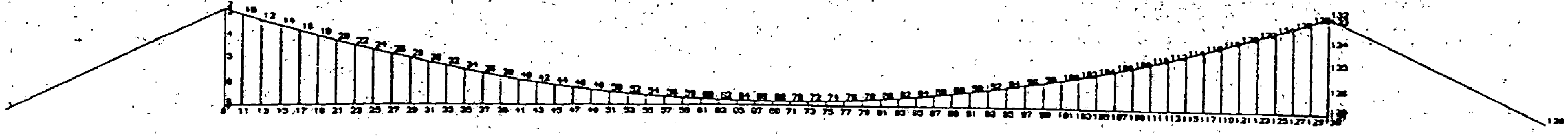


Figure 10 The two-dimensional mathematical model of Fatih Bridge: nodal points

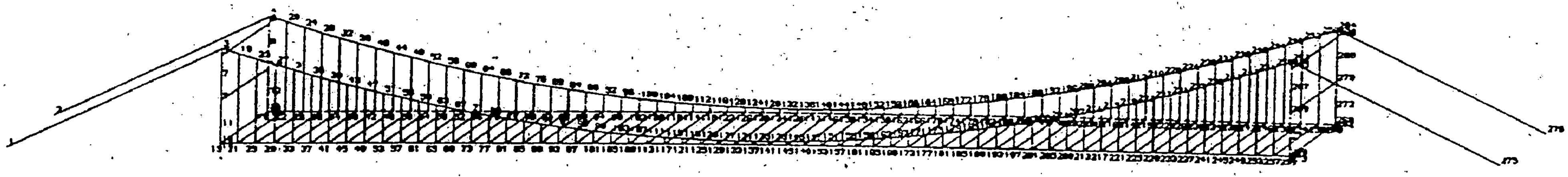


Figure 11 The three-dimensional mathematical model of Fatih Bridge: nodal points

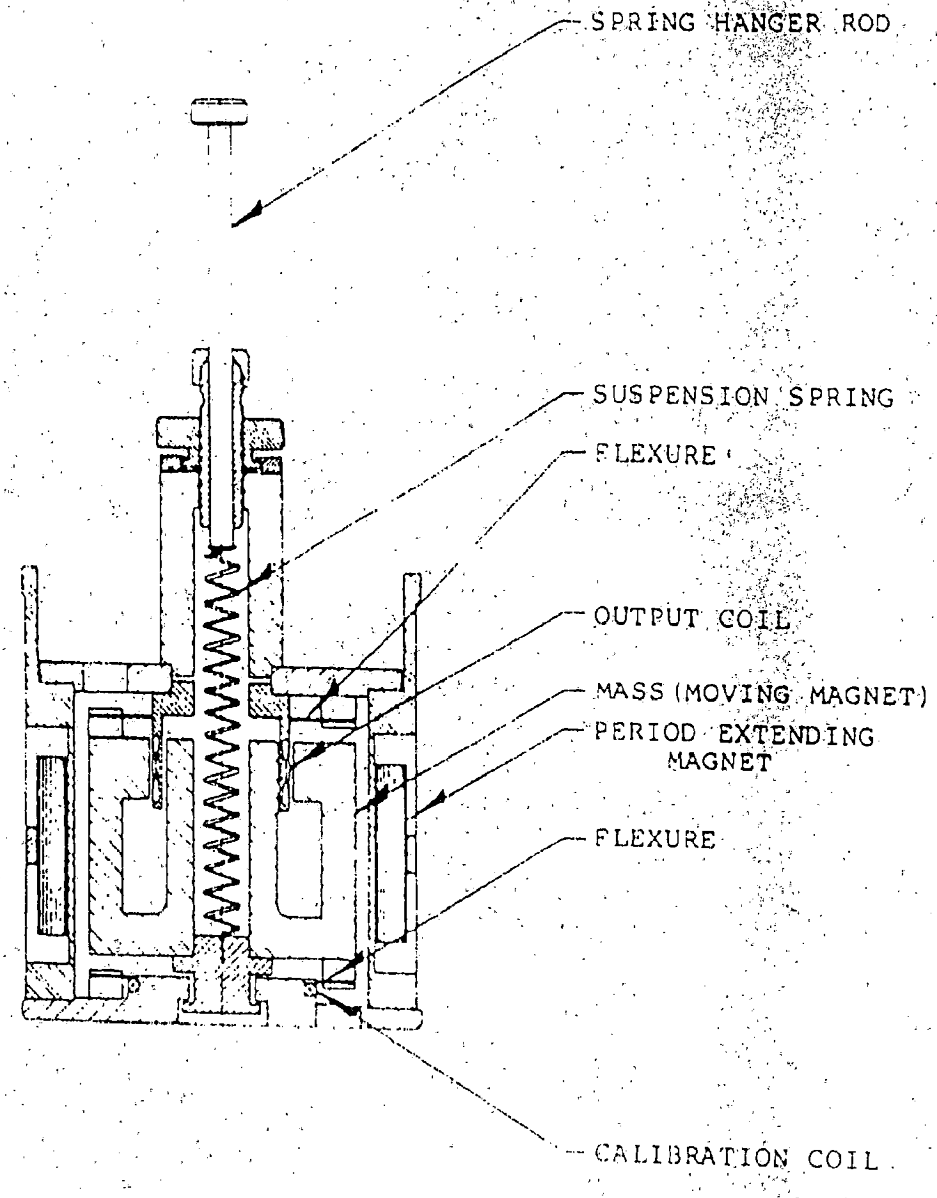


FIG. 12 GENERAL CONSTRUCTION OF RANGER SEISMOMETER

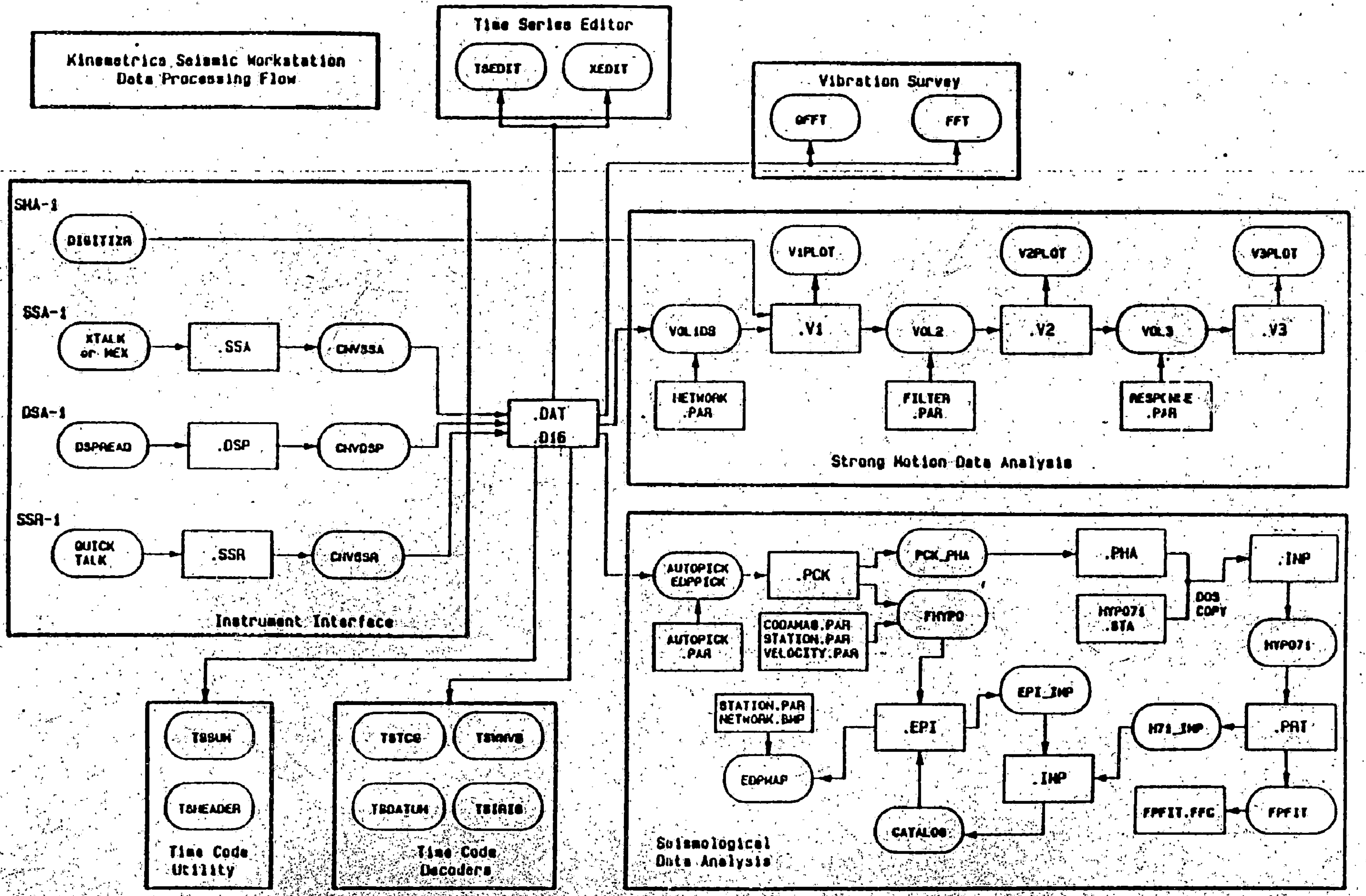
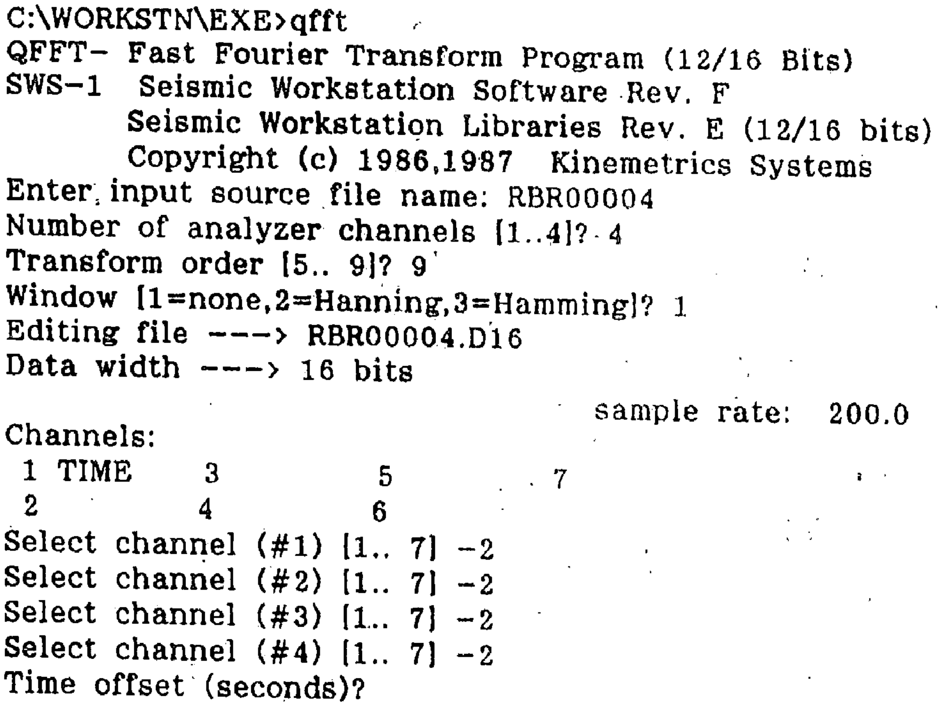
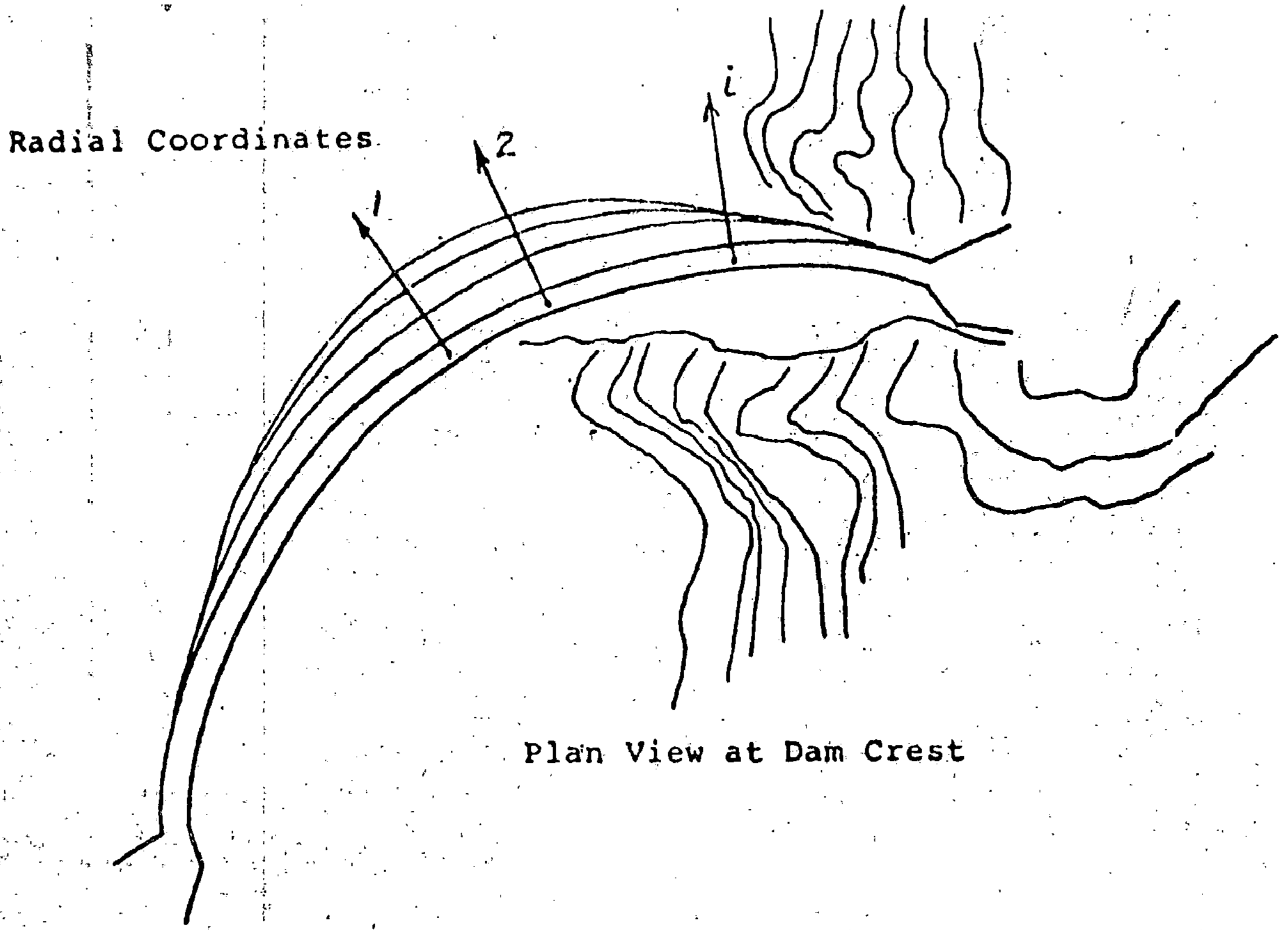


Fig 13 Block Diagram of SWS

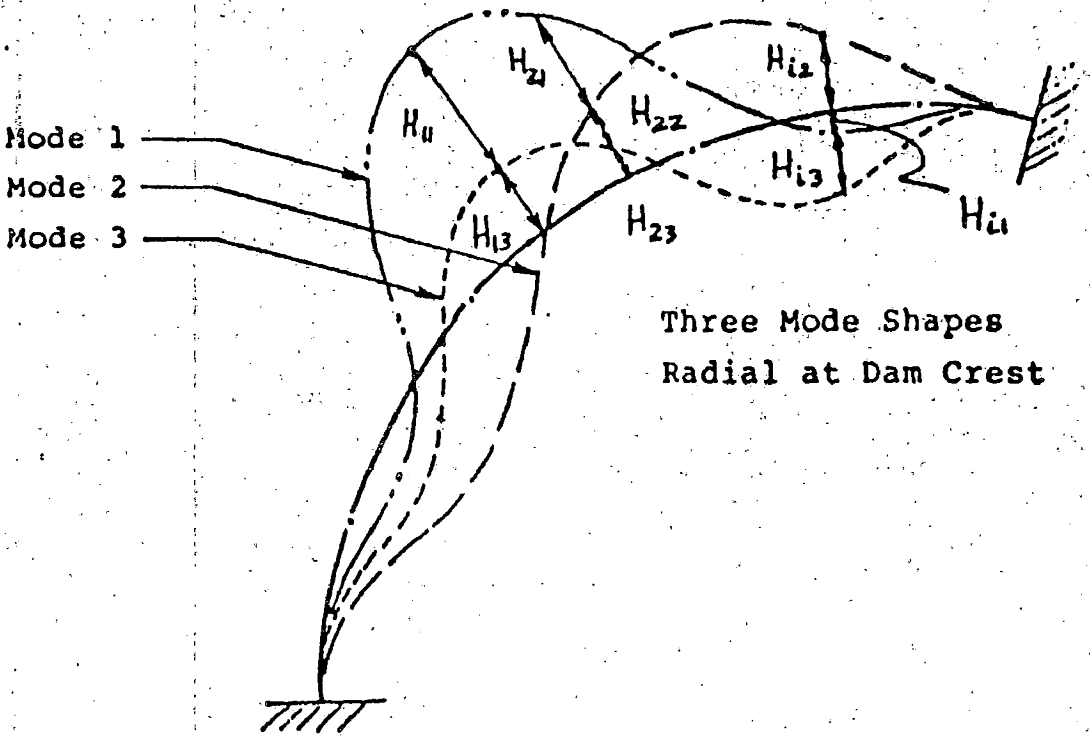


```
C:\WORKSTN\EXE>qfft
QFFT- Fast Fourier Transform Program (12/16 Bits)
SWS-1  Seismic Workstation Software Rev. F
       Seismic Workstation Libraries Rev. E (12/16 bits)
       Copyright (c) 1986,1987  Kinematrics Systems
Enter input source file name: RBR00004
Number of analyzer channels [1..4]? 4
Transform order [5.. 9]? 9
Window [1=none,2=Hanning,3=Hamming]? 1
Editing file ---> RBR00004.D16
Data width ---> 16 bits
                                      sample rate:  200.0
Channels:
 1 TIME    3          5          7
 2         4          6
Select channel (#1) [1.. 7] -2
Select channel (#2) [1.. 7] -2
Select channel (#3) [1.. 7] -2
Select channel (#4) [1.. 7] -2
Time offset (seconds)?
```

Fig 14 QFFT Initial Diaglog



Plan View at Dam Crest



Three Mode Shapes Radial at Dam Crest

Figure 15 EXAMPLE STRUCTURE

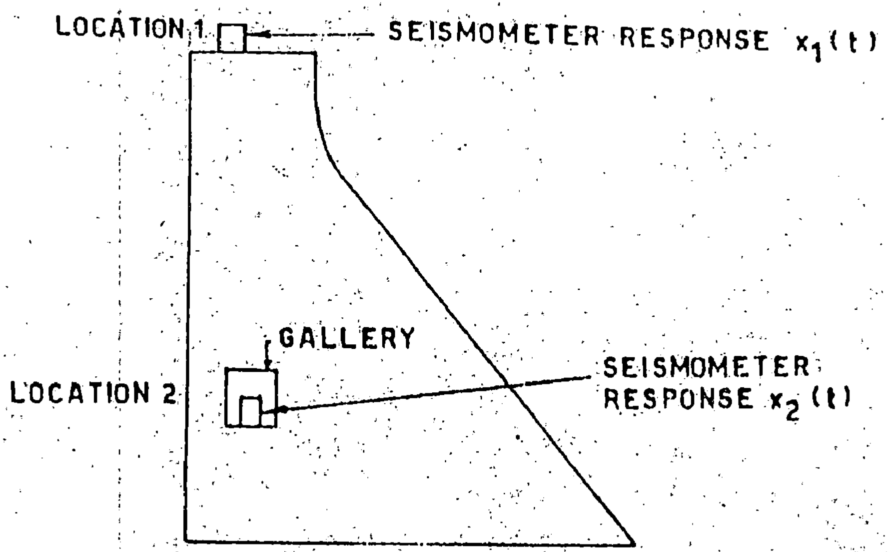


Fig. 16 Position of seismometers in gravity dam

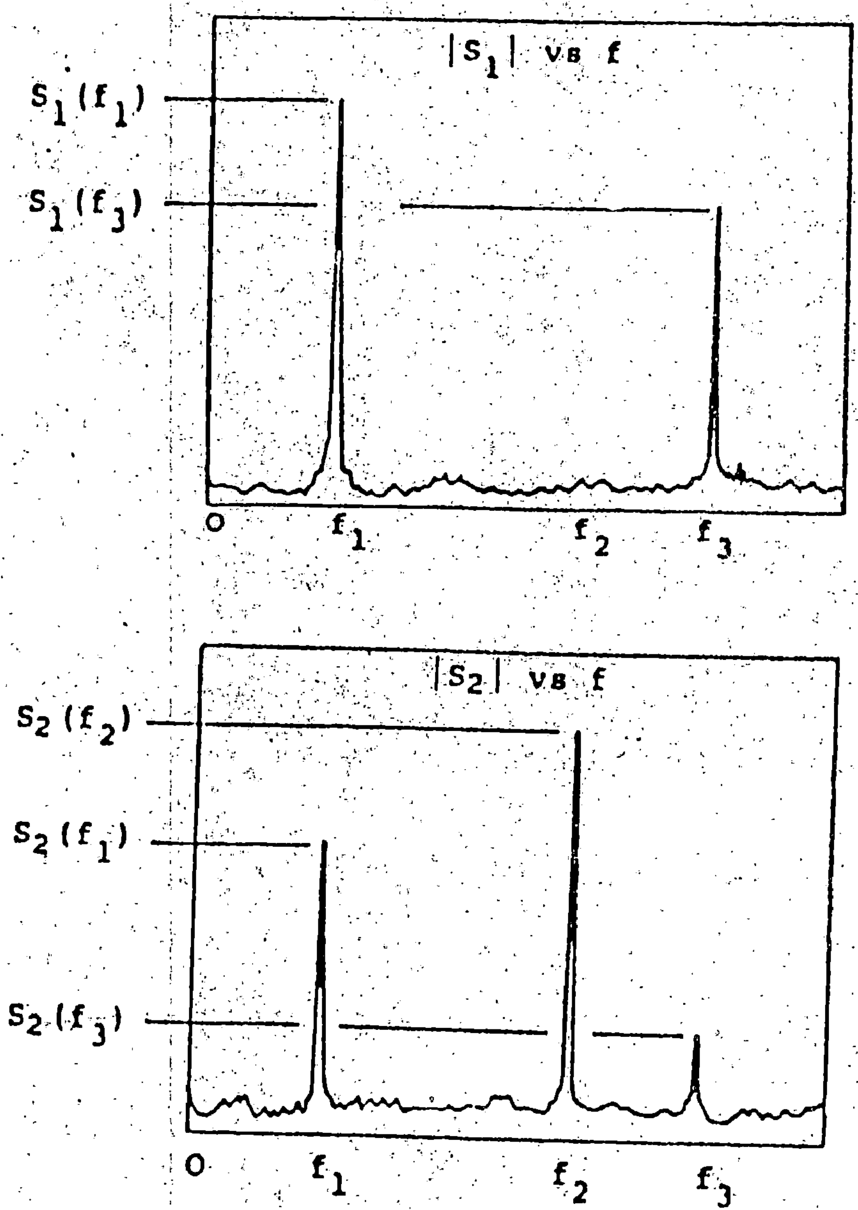


Figure 17 AMPLITUDE SPECTRA

Model For Roorkee Bridge

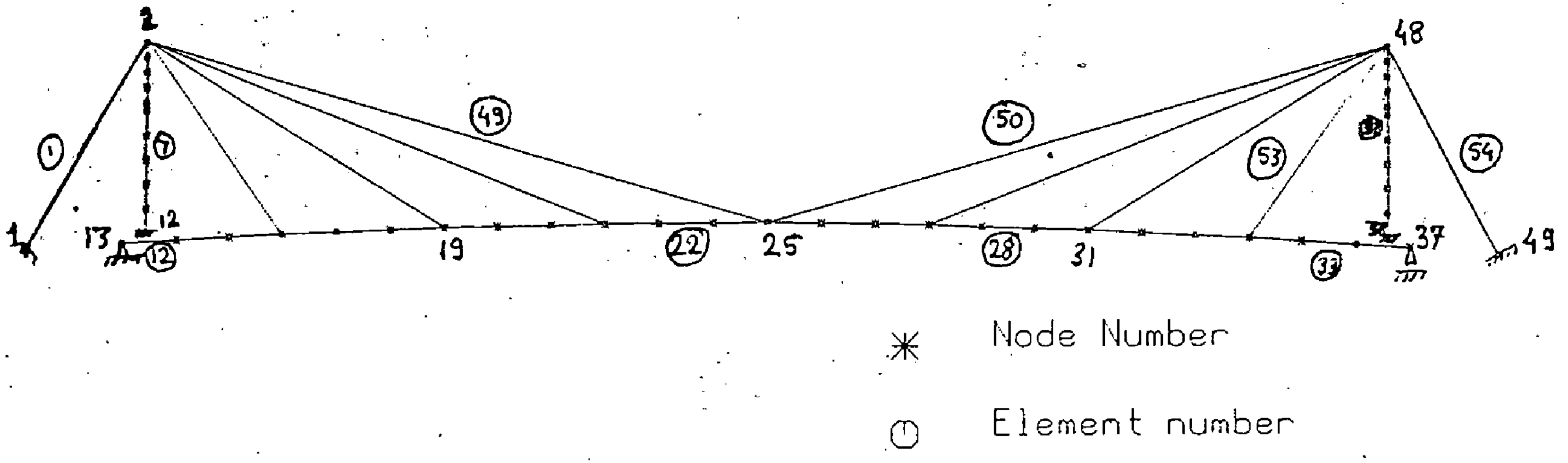


Fig 18 Mathematical Model For Roorkee Bridge

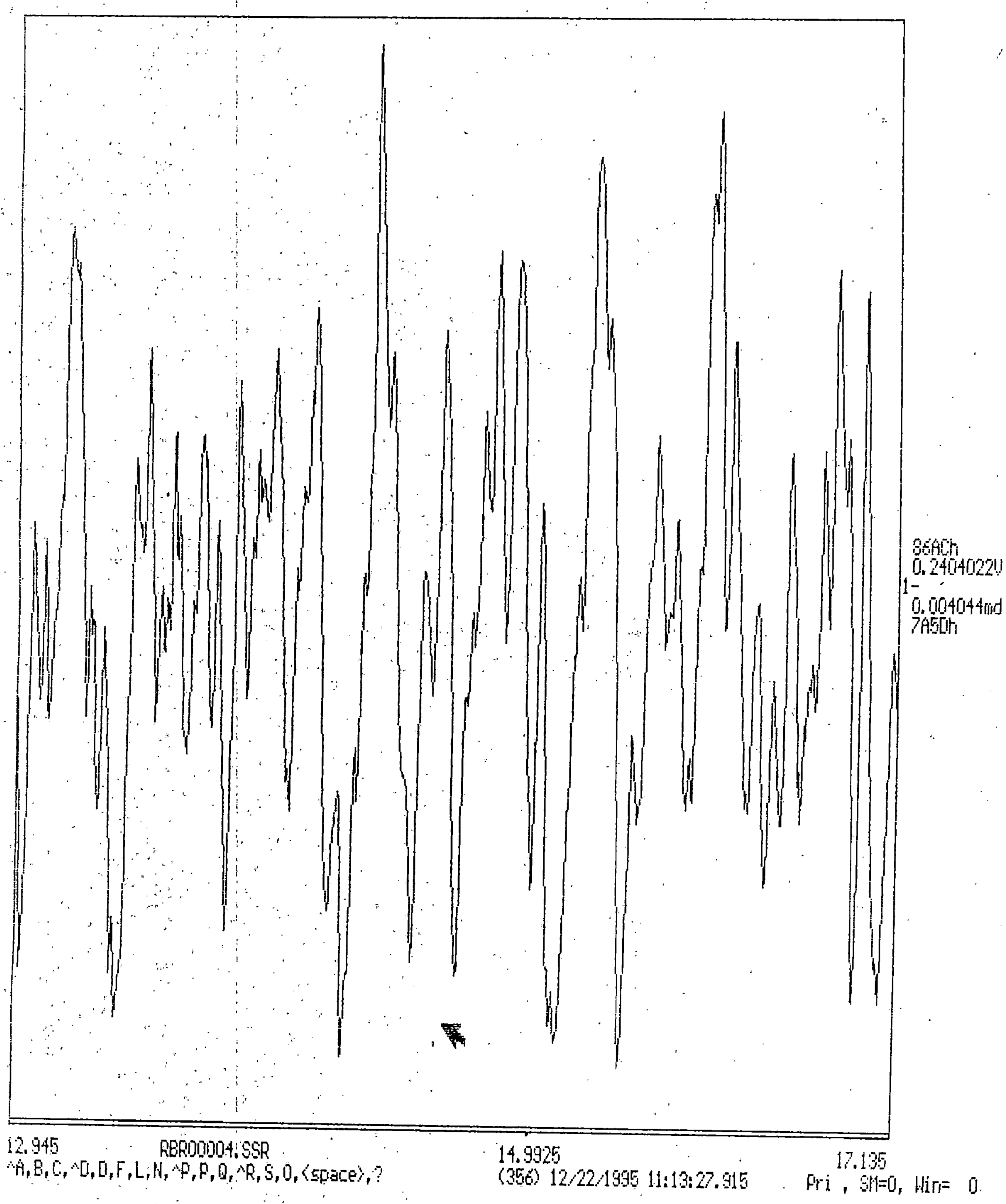


Fig 19 SSR Record For Roorkee Bridge

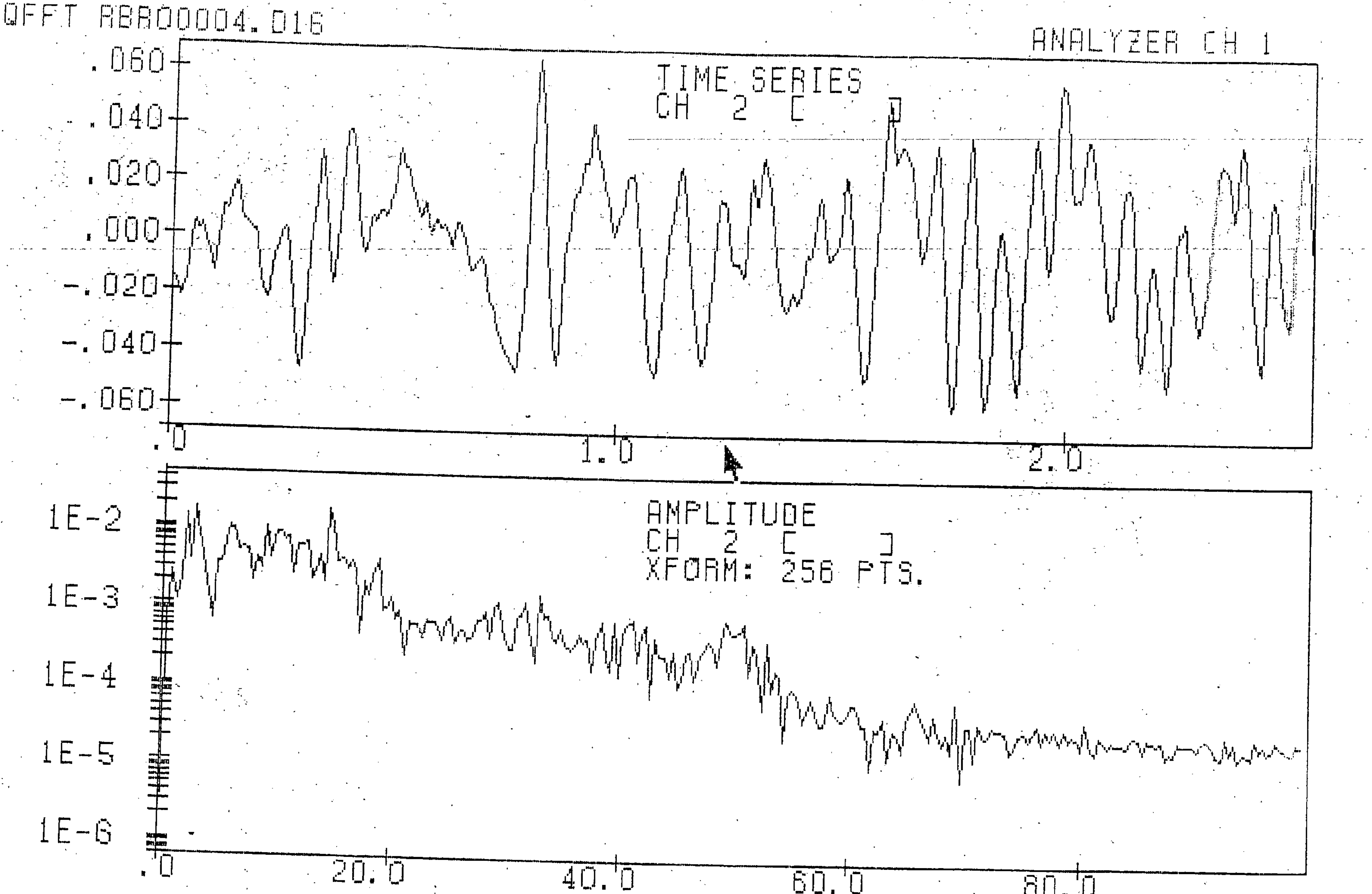


Fig 20 QFFT Plot For Roorkee Bridge

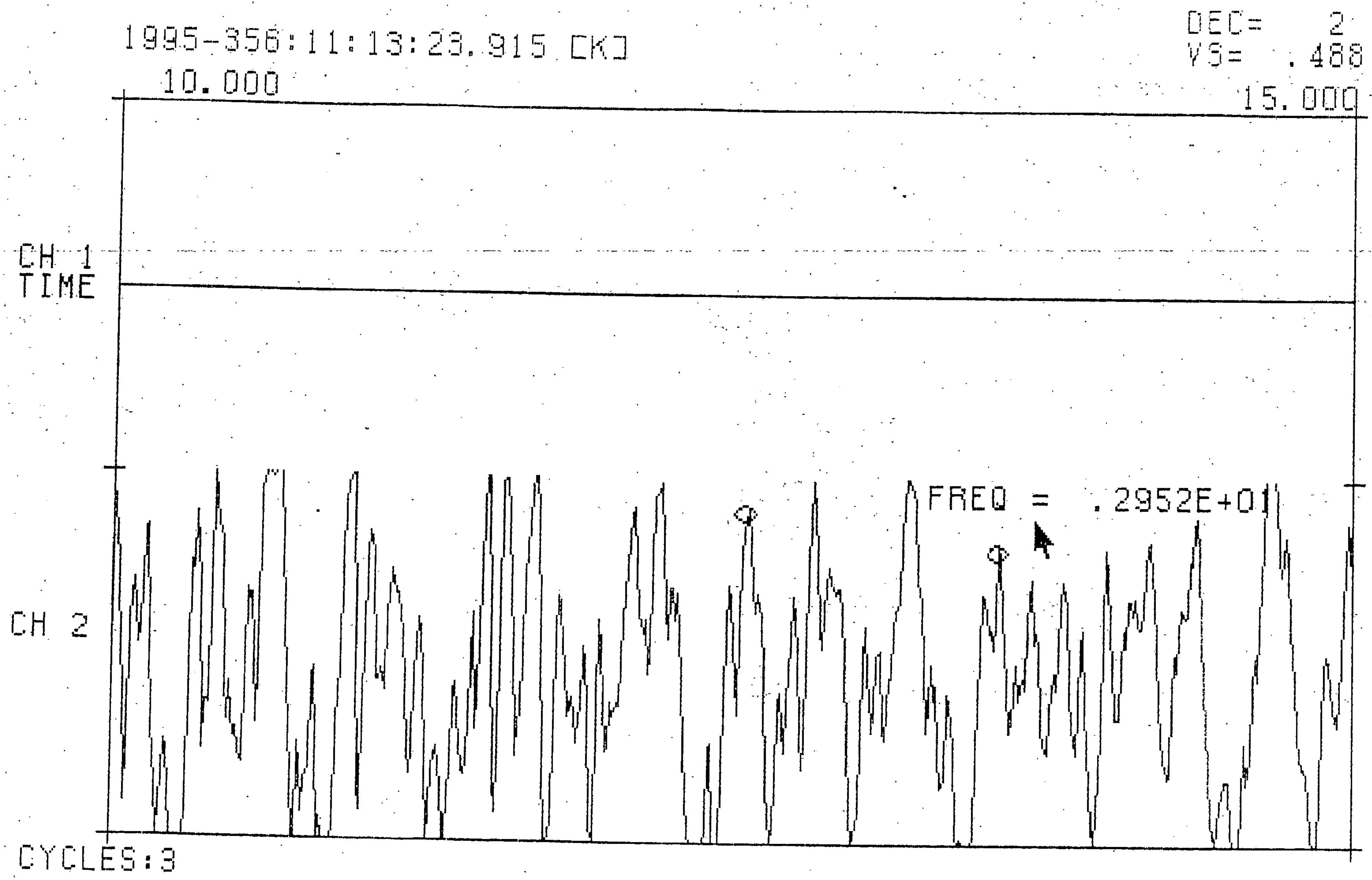
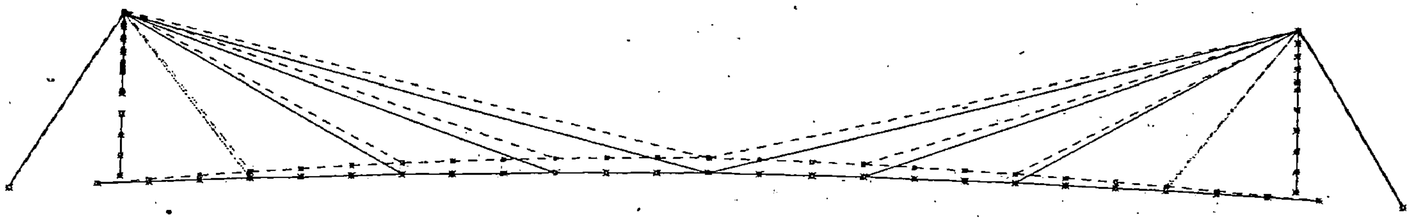


Fig. 21 Frequency Plot For Roorkee Bridge

FIRST MODE FOR ROORKEE BRIDGE



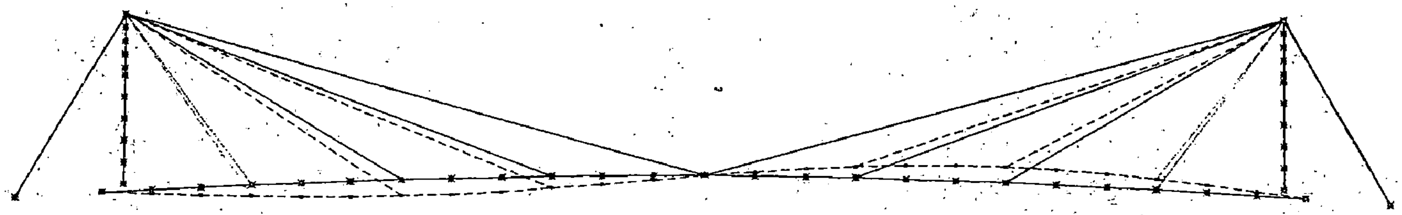
Time Period = 0.310 sec

Dash lines shows Deflected shape

Solid lines shows Undeflected shape

Fig 22 First Mode Shape For Roorkee Bridge

SECOND MODE FOR ROORKEE BRIDGE



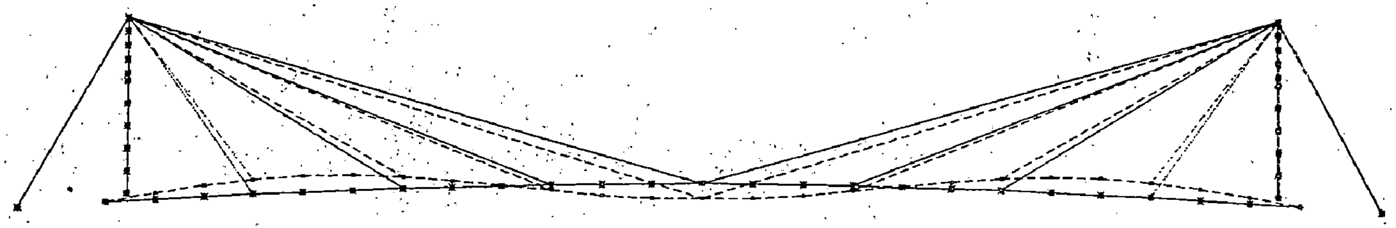
Time Period = 0.112 sec

Dash lines shows Deflected Shape

Solid lines shows undeflected shape

Fig 23 Second Mode Shape For Roorkee Bridge

THIRD MODE FOR ROORKEE BRIDGE



Time Period = 0.056 sec

Dash lines shoes Deflected shape

Solid lines shows Undeflected shape

Fig 24 Third Mode Shape For Roorkee Bridge

MODEL FOR HARDWAR BRIDGE

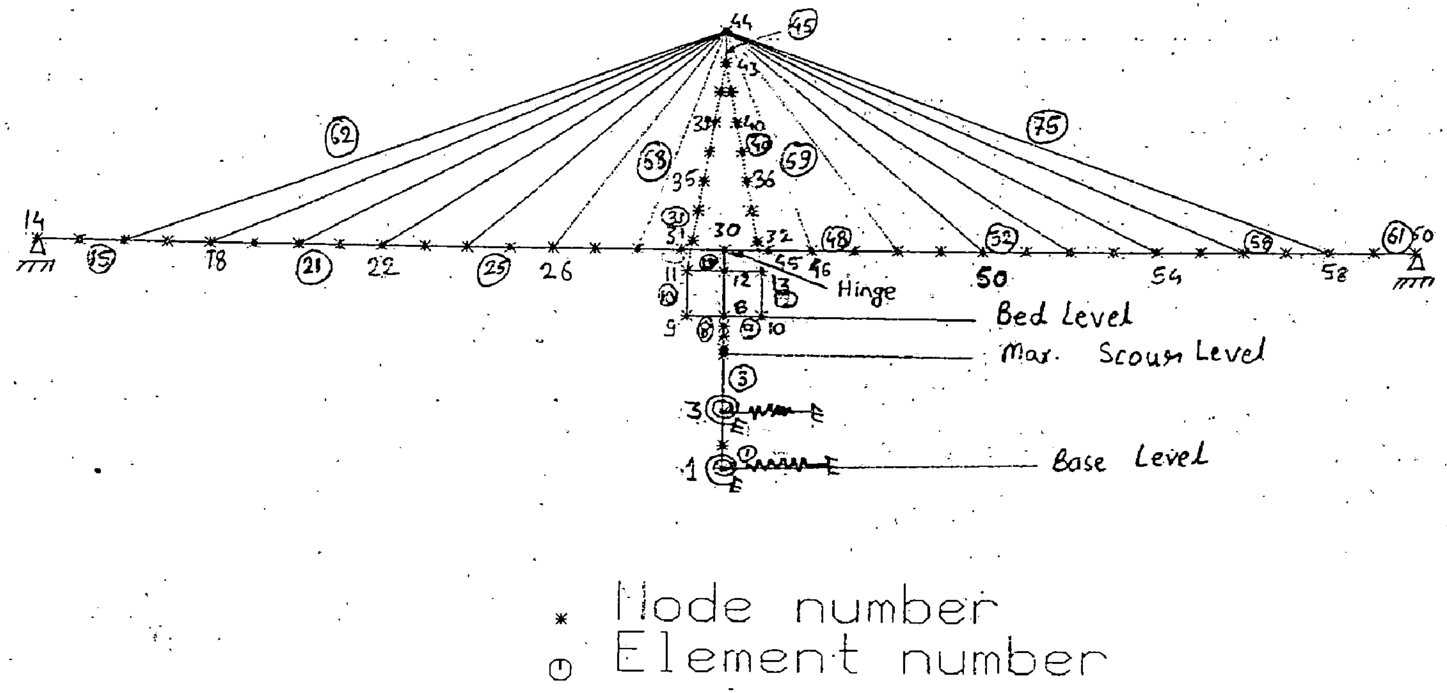


Fig 25 Mathmatical Model For Hardwar Bridge

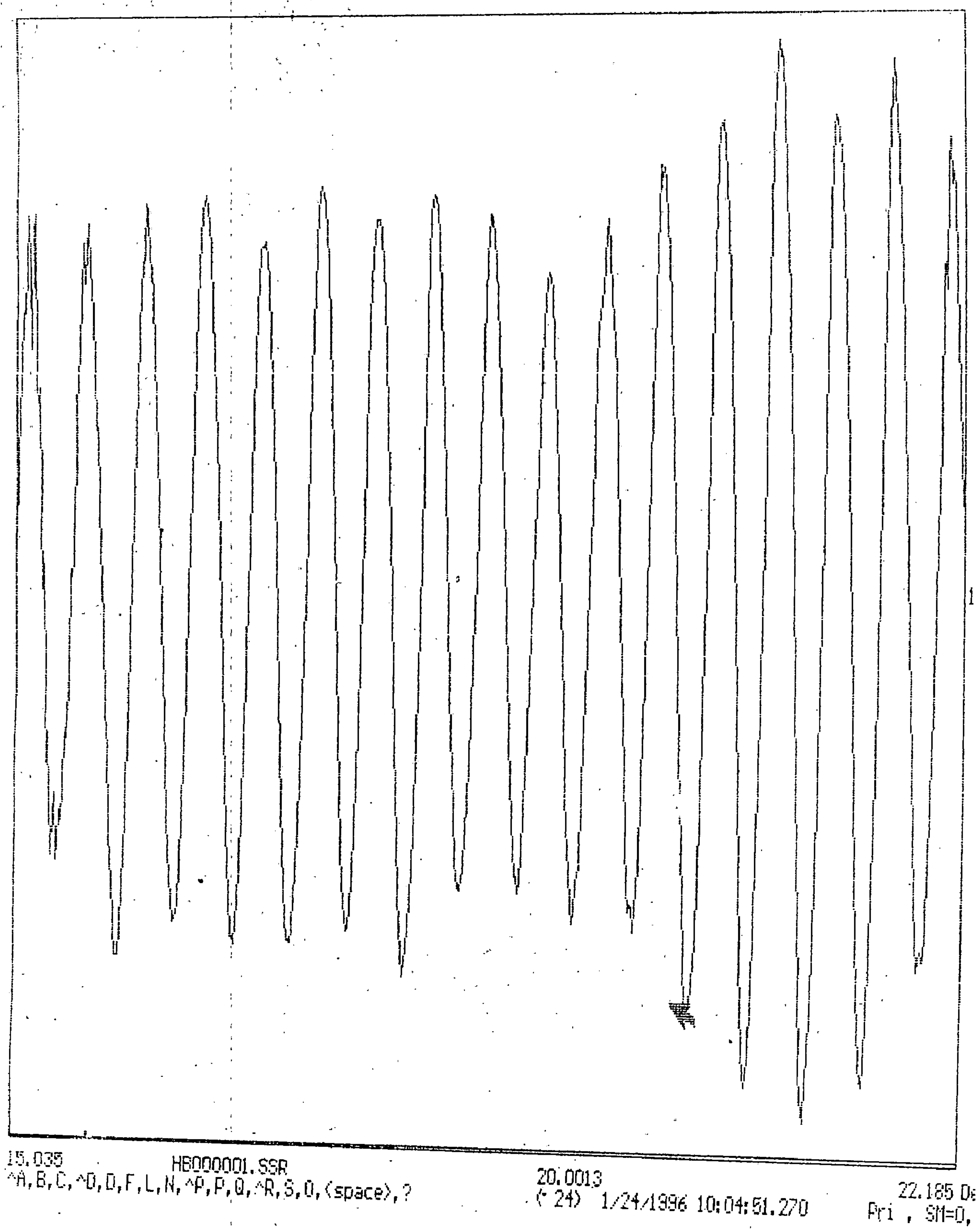


Fig 26 SSR Record For Hardwar Bridge

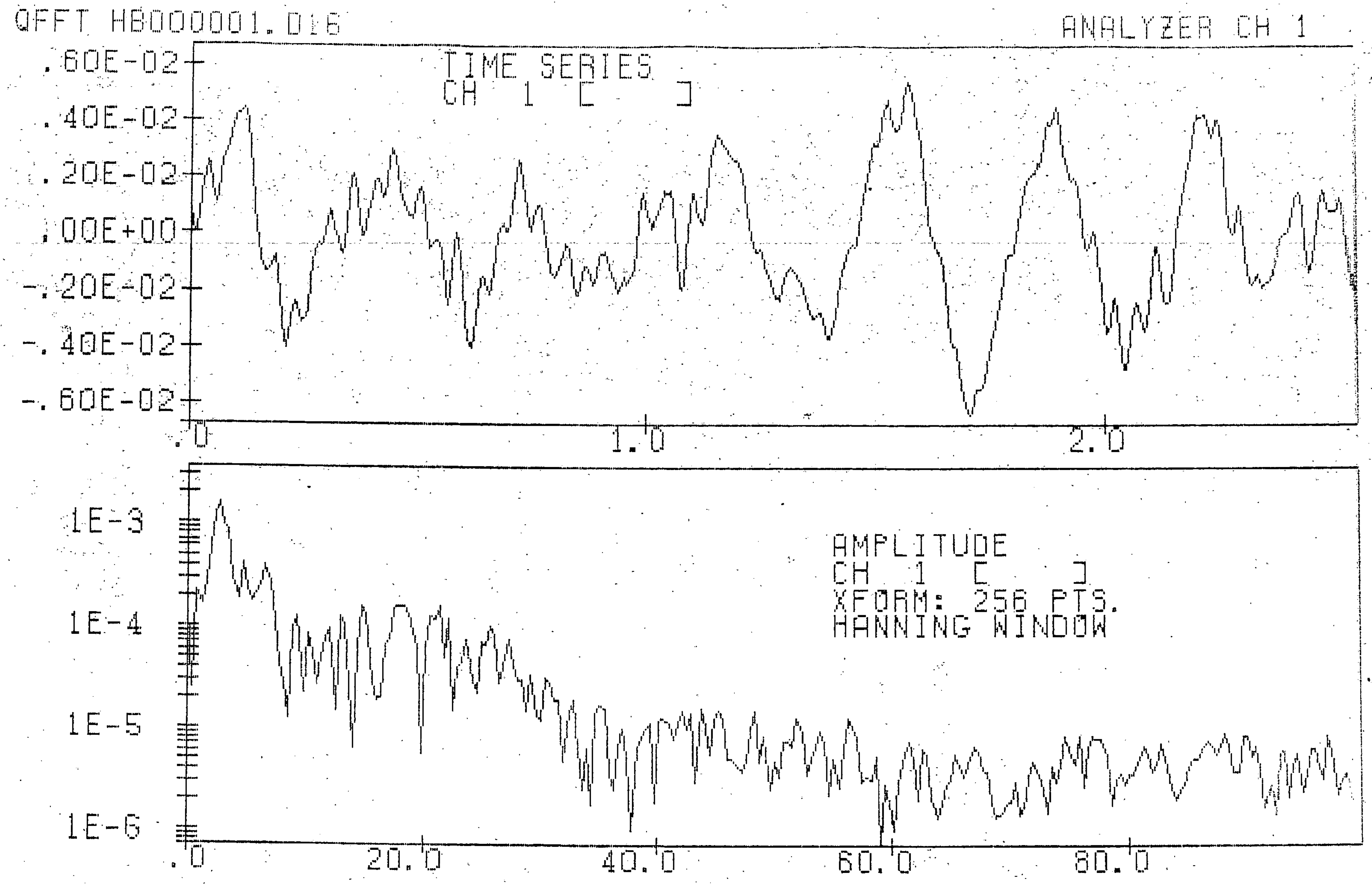


Fig 27 QFFT Plot For Hardwar Bridge

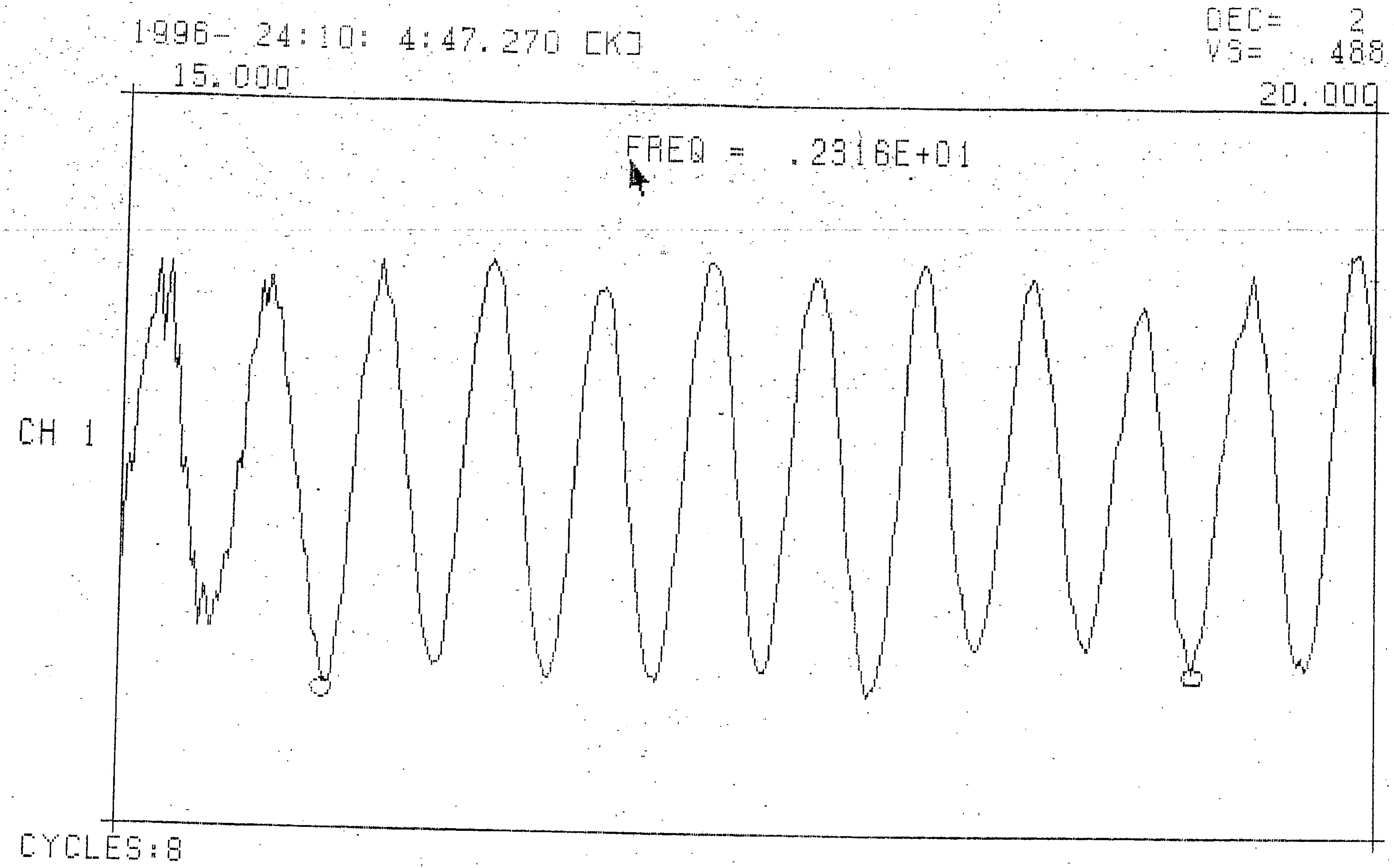
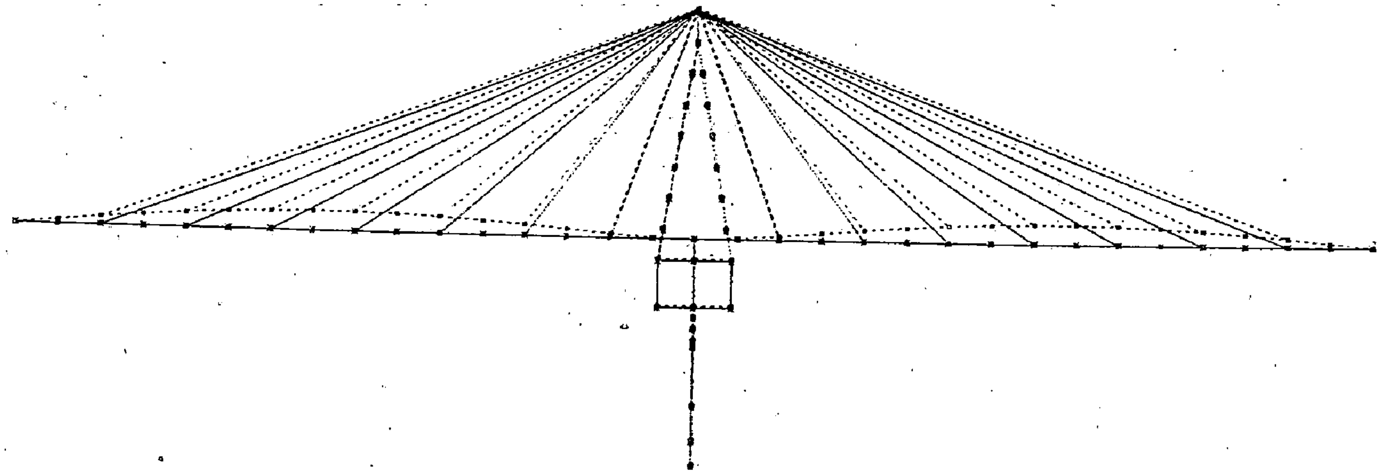


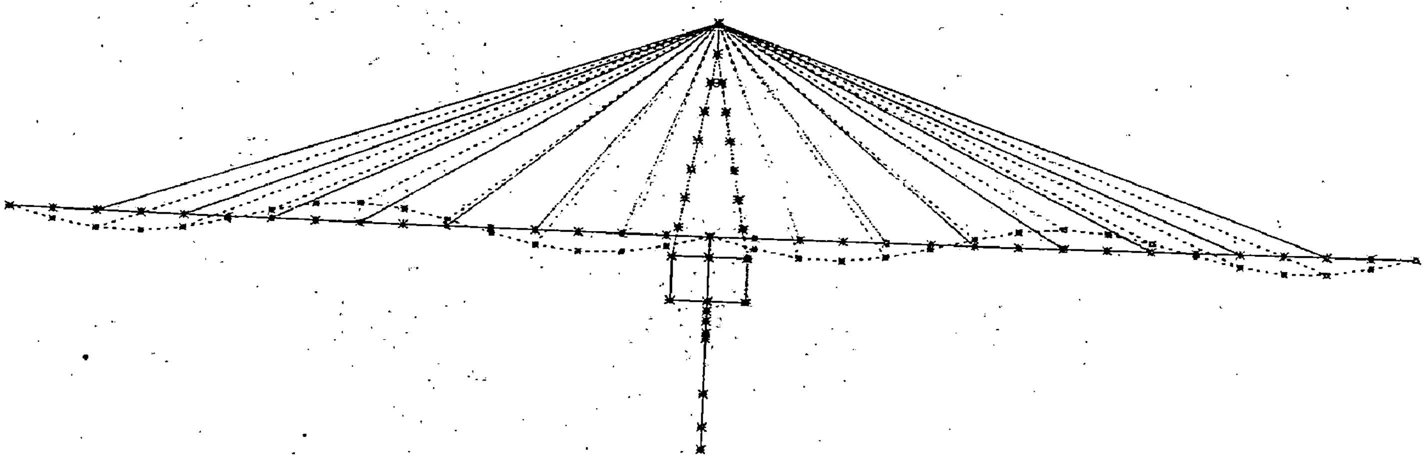
Fig 28 Frequency Plot For Hardwar Bridge

FIRST MODE FOR HARDWAR BRIDGE



Time Period = 0.470 sec
Solid lines showing the Undeflected Shape
Dashed Lines showing the Deflected Shape

Fig 29 First Mode Shape For Hardwar Bridge



THIRD MODE FOR HARDWAR BRIDGE

Time Period = 0.236 sec
Solid lines showing the Undeflected shape
Dashed Lines showing the Deflected Shape

Fig 31 Third Mode Shape For Hardwar Bridge