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Ambient Vibration Study of Berkeley Public Library: Report to the Berkeley Public Library

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AMBIENT VIBRATION STUDY OF BERKELEY PUBLIC LIBRARY

Report to Berkeley Public Library

BY

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AND

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Service to Industry
Project No. ES-2085

JULY 1997

DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING
UNIVERSITY OF CALIFORNIA, BERKELEY

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REPORT TO THE BERKELEY PUBLIC LIBRARY

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AMBIENT VIBRATION STUDIES OF BERKELEY PUBLIC LIBRARY

ABSTRACT

This report summarizes the results of ambient vibration tests performed on the Berkeley Public Library of the City of Berkeley, California. The tests were performed on May 19, 1997 by personnel of the Department of Civil & Environmental Engineering of the University of California at Berkeley. The motions of each floor of the main building and the library stacks due to ambient excitation (traffic, wind) were recorded using extremely sensitive velocity transducers. The acquired data was then processed to obtain the fundamental natural vibration modes and frequencies of the main building and the book stacks. In addition, in-plane response shapes of the roof of the building were estimated.

ACKNOWLEDGMENTS

The testing program was conducted by the Department of Civil and Environmental Engineering of the University of California at Berkeley (UCB) under Service to Industry Program Project No. ES-2085. Prof. James Kelly was the Principal Investigator.

The authors wish to express their gratitude to Prof. Vitelmo Bertero for his advice during the planning stage of the testing program and for his assistance during the initial field tests. Thanks are due to Mr. Bob Baty, Building Maintenance Supervisor of Berkeley Public Library, for providing building drawings and for facilitating the conduct of the tests. Chris Moy, of UCB, was responsible for the calibration of the instruments and the setup of the electronic equipment. Chris, Bill MacCracken, and Bruce Jacobsen, also of UCB, worked very hard during the tests, and their assistance is greatly appreciated.

1 INTRODUCTION

The objective of this study was to estimate the natural vibration modes and frequencies of the Berkeley Public Library. This information is extremely important because it characterizes the dynamic response of the building, and, therefore, can be used to predict its behavior during a future earthquake or to calibrate analytical models of the building.

A comprehensive program of ambient vibration tests was performed to determine the natural vibration frequencies and modes of the library. Ambient vibration testing has been used successfully to determine the dynamic characteristics of many buildings [1-3]. Testing consists of placing extremely sensitive instruments (seismometers) on each floor to measure the motions of the building due to external excitations such as wind and traffic. The natural vibration properties of the building are then estimated by comparing the relative motion of the floors at the dominant frequencies.

The Berkeley Public Library is a complicated building, with an independent structural system for the book stacks and a very irregular distribution of floor plans. Additional objectives of this test project were to characterize the dynamic behavior of the stacks, to measure the in-plane vibration of the roof, and to investigate the response of a building addition.

2 BRIEF DESCRIPTION OF THE BUILDING

The Berkeley Public Library is located at 2090 Kittredge St., in Berkeley, California. Figures 2.1 and 2.2 show views of the building from Kittredge St. and from Shattuck Ave., respectively. The library is a four-story building, with a basement and a small appendix on the roof. The main building was built in 1931. A three-story addition was built later on the West side of the building (Fig. 2.3).

The building has an almost rectangular shape measuring 170 feet in East-West direction (along Kittredge Street), and 96 feet in North-South direction (along Shattuck Ave.). The main entrance to the building is located in the first floor, on Kittredge St. The total height of the building is approximately 52 feet. Figure 2.4 shows the floor plan of the first floor. A plan of each floor is included in Appendix A.

Figures 2.5 and 2.6 show hand sketches of sections traced from the building drawings. These figures show that the floor plan distribution up the height of the building is very irregular. The book stacks are built in a four-level steel structure located inside the building. Only the basement and first floor of the building and the stacks are at the same level; the higher stack levels do not coincide with the library floors. The stacks are connected to the main building at each stack level by relatively flexible connectors and to some building floors by small stairs. The irregularity in floor plan distribution, the presence of a relatively independent structure for the stacks, the building addition, and the flexible roof are the main factors contributing to have an extremely complicated structural system. The identification of vibration characteristics of such a complex building via ambient vibration testing is a particularly challenging task.

Fig. 2.1 View of Berkeley Public Library from Kittredge St.

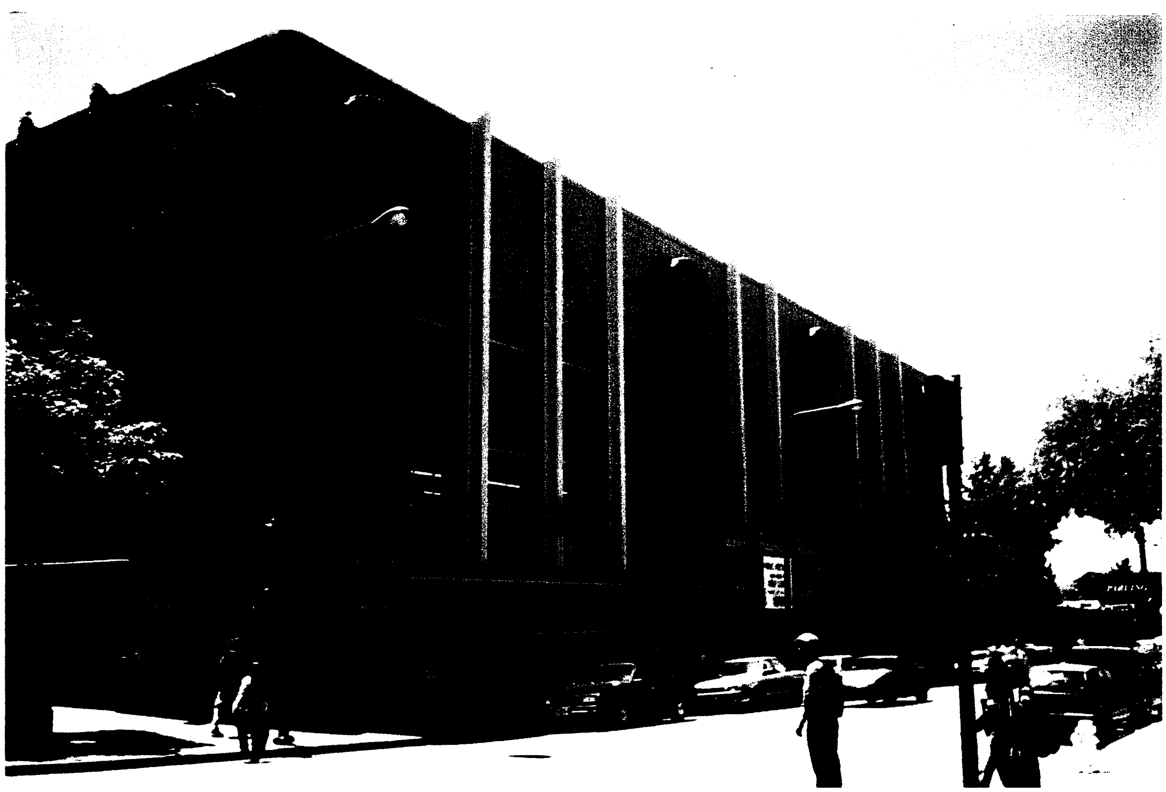


Fig. 2.2 View of Berkeley Public Library from Shattuck Ave.

Fig. 2.3 View of Building Addition from the Parking Lot on Kittredge St.

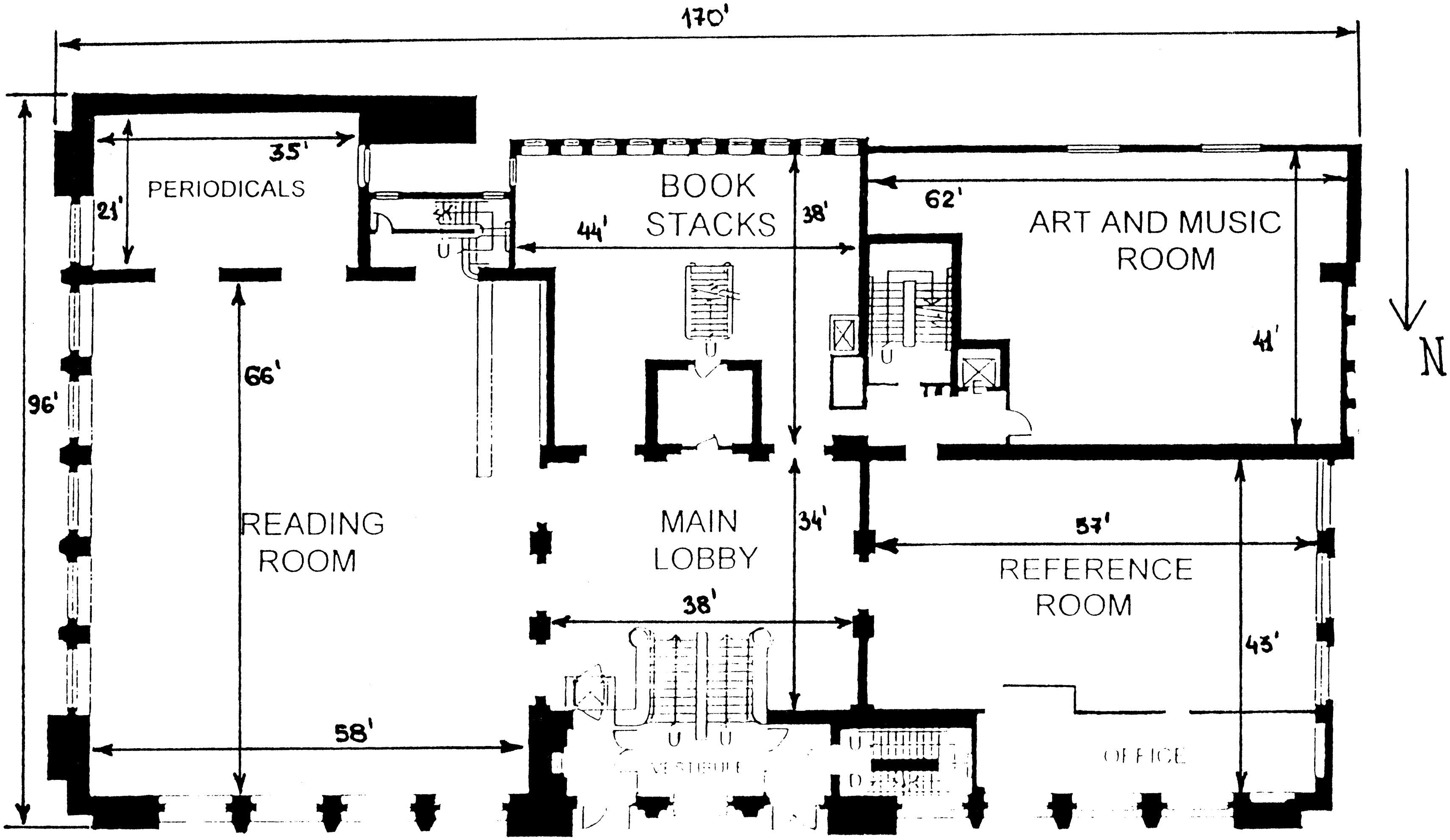


Fig. 2.4 Plan of First Floor

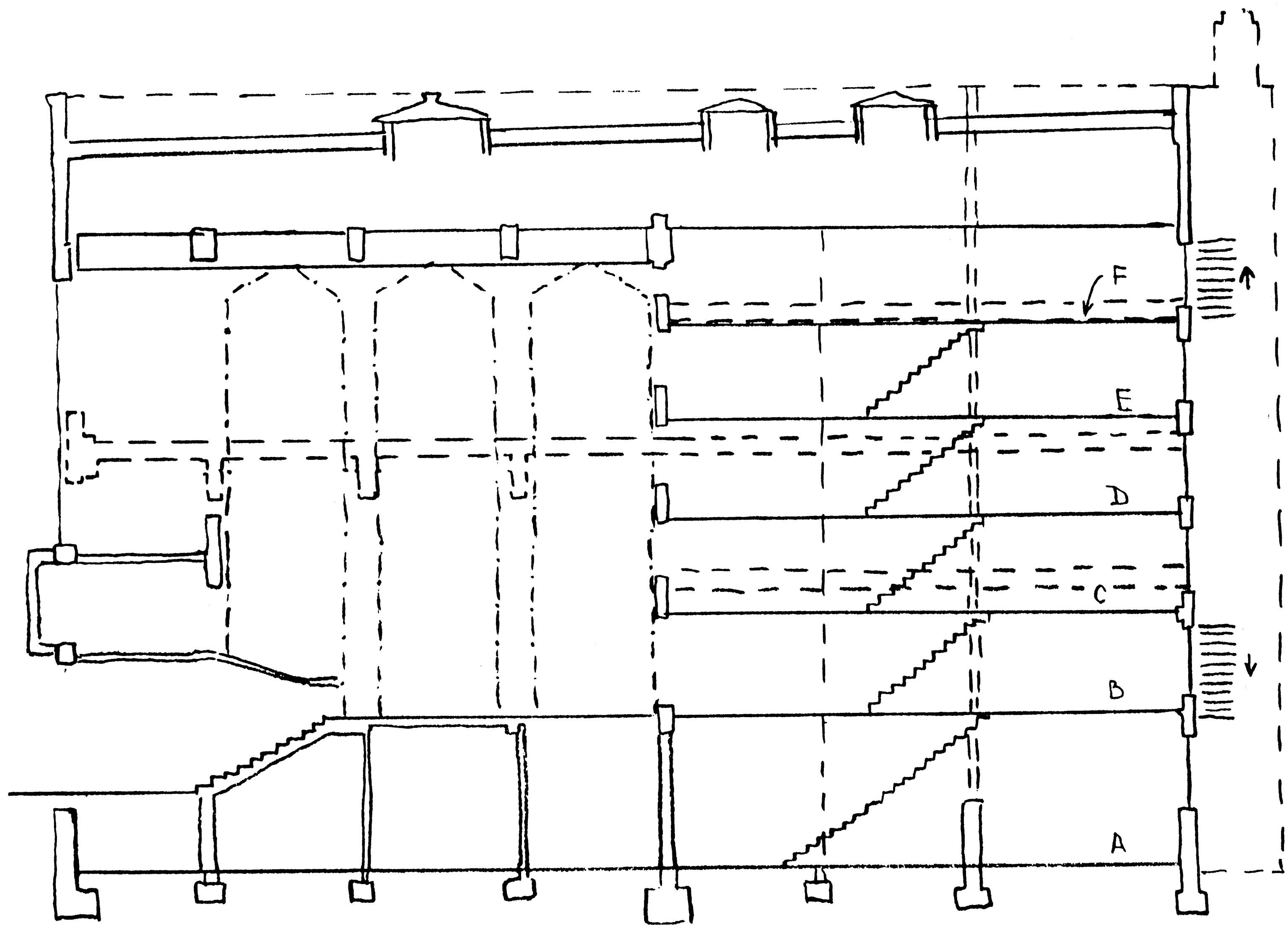


Fig. 2.5 Sketch of N-S Section of the Building

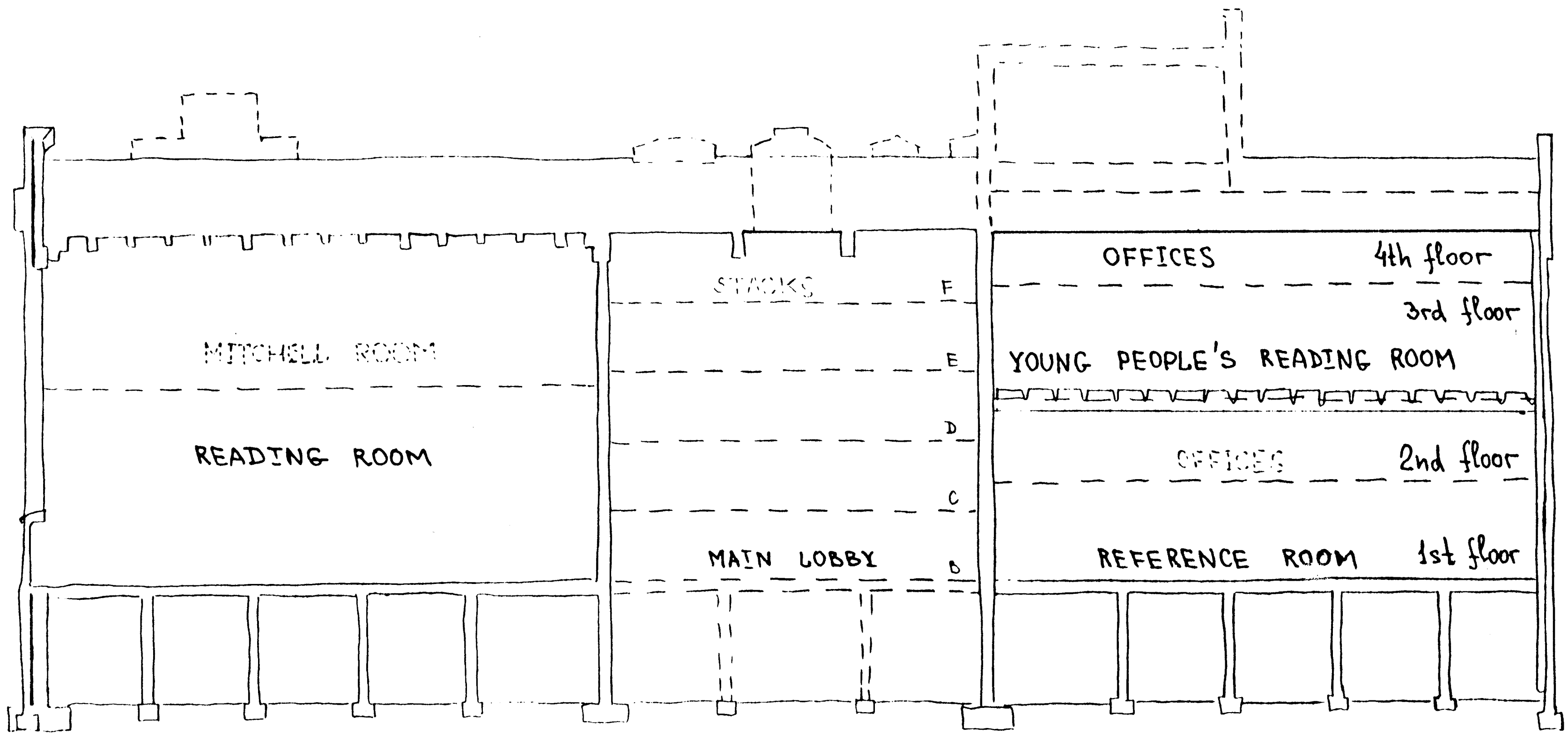


Fig. 2.6 Sketch of E-W Section of the Building

3 *INSTRUMENTATION & TESTING*

The response of the building was measured with eight Kinemetrics SS1 Ranger seismometers (named S1 through S8). The signals from these sensitive velocity transducers were low-pass filtered at 100 Hz and attenuated to 30 dB with Kinemetrics SC-1 Signal Conditioners. The measurements were recorded in mm/sec with a Megadac portable data acquisition system and transferred to a laptop computer after each test. The scanning rate was set at 200 Hz. Memory constraints of the data acquisition system limited each test to approximately two and half minutes of recording. Additionally, a HP 3582A spectrum analyzer was used to monitor frequency response of the structure.

The main objective of the project was to determine the global dynamic characteristics of the building in three directions: horizontal translation of each floor level in the N-S and E-W directions, and floor rotation around a vertical axis. To characterize floor motion in these three directions, a set of four instruments was placed on each floor; two oriented in the N-S direction and two in the E-W direction. These sensors were placed as far apart as possible. That way, the sum of the readings of each pair (N-S or E-W) was dominated by the floor translation and their difference was dominated by the floor rotation.

Throughout the testing program a set of four seismometers was kept on the roof to serve as reference instruments. Sensors S1 and S3 measured motion in the N-S direction; S2 and S4 in the E-W direction. A second group of four seismometers was moved from floor to floor, starting at the highest level of the building and ending at the basement. Sensors S5 and S7 were located in the N-S direction; S6 and S8 in the E-W direction.

Table 3.1 lists all the tests performed. Measurements were taken in all the main building floors and all the stacks levels. In order to ensure repeatability of measurements, at least three tests were conducted for each sensor configuration. The testing program is represented schematically in Fig. 3.1, which shows a three dimensional sketch of all floors tested and the instrumentation configuration for a typical test (3rd Floor). This drawing also captures some of the complexity of the structure due to the uneven size and distribution of the floors. The location of the seismometers at each level tested is presented in figures A.1 through A.10 of Appendix A.

The command center was set up on the 3rd floor, in the Young People's Reading Room. During each test, the response of all sensors was monitored in real time on the laptop screen to ensure that the data was adequate. The frequency response of selected seismometers was also monitored on the frequency analyzer screen and plotted using an X-Y recorder. A clear signal was obtained from each seismometer at each floor, indicating that the main response modes of the building were excited during the tests. Figures 3.2 to 3.5 show photographs taken during testing.

The first test performed was a calibration check of the seismometers. All eight instruments were placed side by side and oriented in the same direction (N-S) on the third floor in the Young People's Room. All sensors measured very similar motions, indicating that they were correctly calibrated. This is corroborated in Fig. 3.6, which shows the Fourier amplitudes of all seismometers and phase angles of transfer functions (reference is S1) for this test. The frequency response of the seismometers is very close in the frequency range of interest, 2 to 10 Hz.

Table 3.1 Testing Program

Test Number	Description	File Name
1 a-c	Instrument Check (3rd Floor)	Alibrary.001-003
2 a-c	Roof Flexibility	Alibrary.004-006
3 a-c	4th Floor	Alibrary.007-009
4 a-e	Stacks Level F	Alibrary.010-014
5 a-c	Stacks Level E	Alibrary.015-017
6 a-c	3rd Floor	Alibrary.018-020
7 a-c	Addition (3rd Floor)	Alibrary.021-023
8 a-c	Mitchell Room (3rd Floor)	Alibrary.024-026
9 a-c	Stacks level D	Alibrary.027-029
10 a-c	2nd Floor	Alibrary.030-032
11 a-d	Stacks Level C	Alibrary.033-036
12 a-c	Stacks Level B	Alibrary.037-039
13 a-c	1st Floor	Alibrary.040-042
14 a-c	Basement	Alibrary.043-045

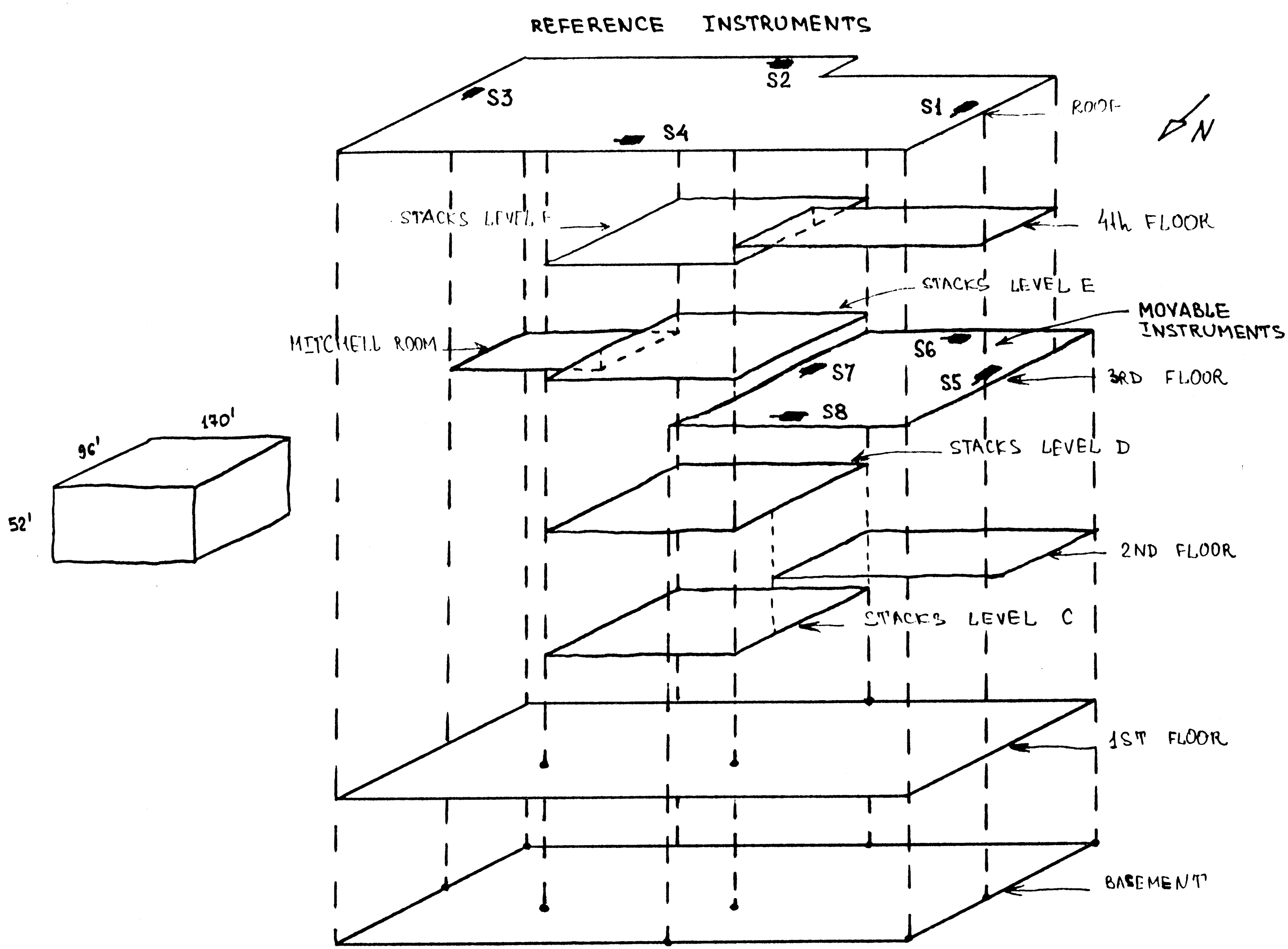


Fig. 3.1 3-D Sketch of Testing Locations

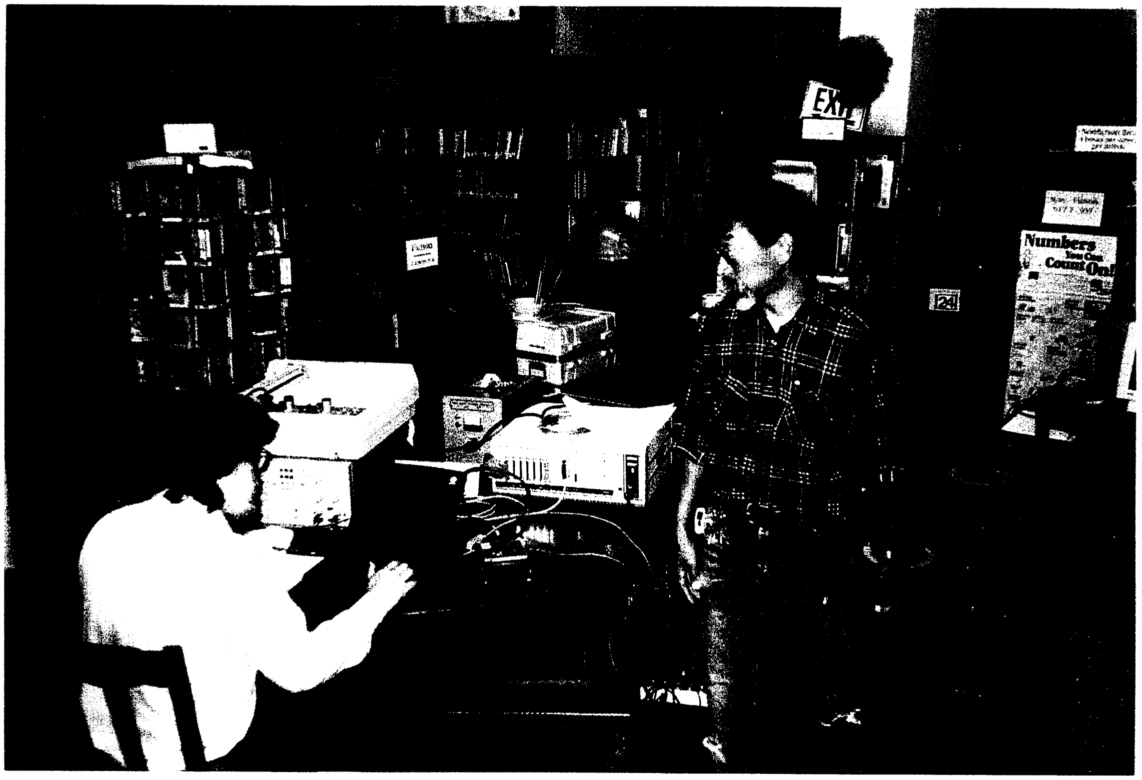


Fig. 3.2 Testing Command Center on 3rd Floor (Young People's Reading Room)

Fig. 3.3 Photo of Two Seismometers During Roof Flexibility Test

Fig. 3.5 Photo of Seismometers S5 to S8: Addition Test

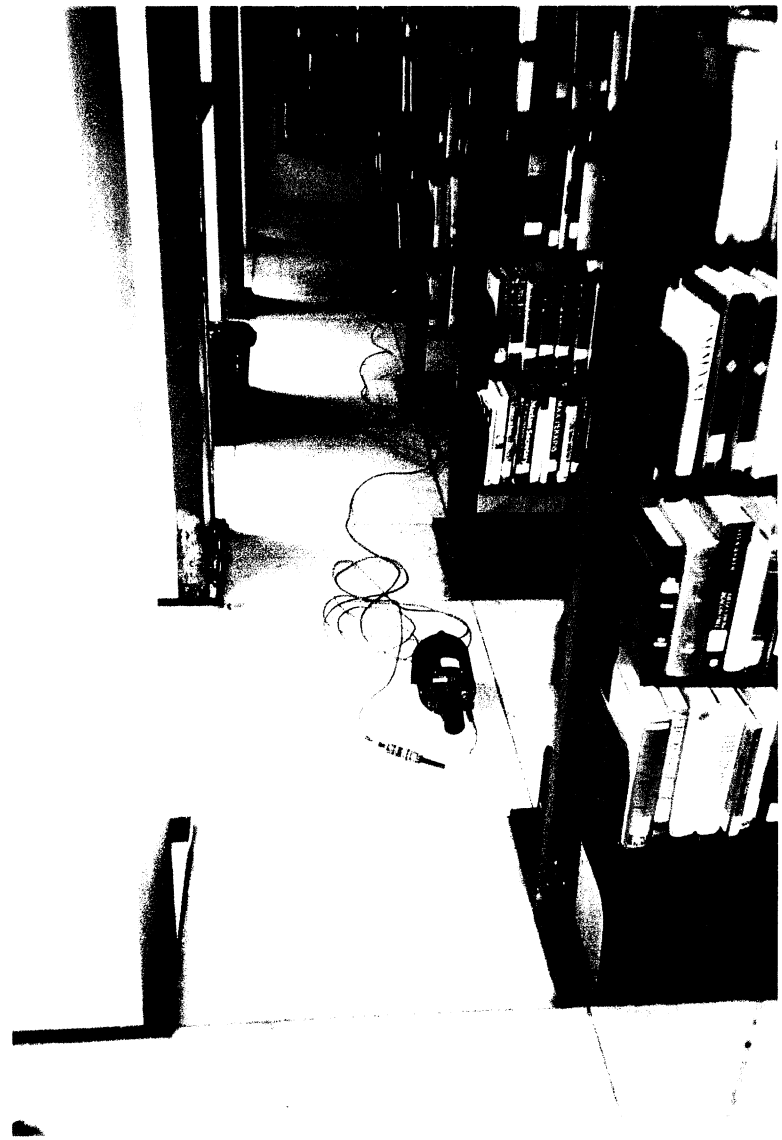


Fig. 3.4 Photo of Seismometer S5 During Stacks Test

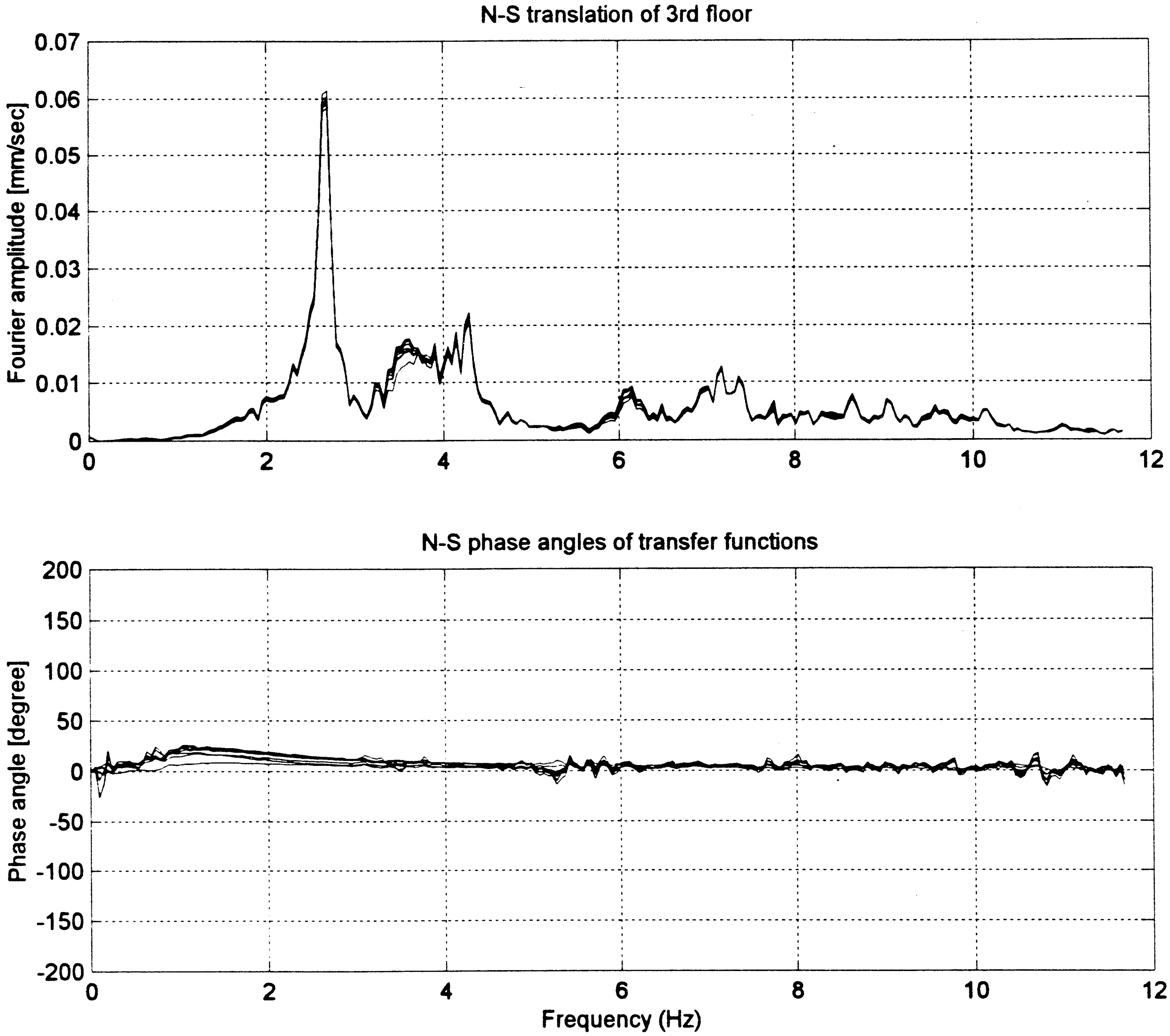


Fig. 3.6 Instrument Calibration Check – 3rd Floor Frequency Response

4 *DATA PROCESSING*

The computer program MATLAB [4] and its signal processing Toolbox [5] were used to process the experimental data. Each data channel consisted of approximately 25,000 points sampled at a time interval of 0.005 seconds.

Floor translation time histories were estimated as the average of records from two opposite seismometers. The corresponding floor rotation records were obtained by subtracting these two records and dividing the result by the distance between the sensors. Figure 4.1 shows typical translation time histories calculated for all floors of the main building.

Frequency domain data were obtained by dividing the floor response time histories in overlapping segments (or windows) of 4096 data points. Window duration was 20.48 seconds; thus, the frequency resolution was approximately 0.05 Hz. Segment overlap was 1000 points. A Hanning window was applied to all segments to prevent frequency leakage due to finite window duration. The MATLAB 'spectrum' function was used to compute the Power Spectral Density (PSD) of each floor response time history and to compute the Complex Transfer Function (CTF) from a roof record (reference) to each floor record.

Fourier amplitude spectra of each level response record (including the roof) were estimated as the square root of the corresponding PSDs. Natural vibration frequencies were detected by identifying significant peaks appearing at each level. For example, Figure 4.2 a) shows the Fourier amplitude spectra of the main building floors in the N-S direction. Peaks at 2.6 Hz appear in all floors, increasing in amplitude up the height of the building. This suggests that the first translational mode might occur at this frequency. To ascertain this suggestion, it was necessary to examine the relative phase angle of each floor at this frequency. A small phase angle indicates that the floor considered is moving in the same sense as the roof (i.e. floor and roof are in phase). A phase angle close to 180 degrees indicates that the floor is moving in an opposite sense to the roof (i.e. floor and roof are out of phase).

Phase angles were calculated from the phase of the CTF of each level relative to the roof. For instance, Figure 4.2 b) shows phase angles of the N-S response of all floors with respect to the roof. All floors have very small phase angles at 2.6 Hz, indicating that they are all moving in phase with the roof at this frequency. This means that the first translational mode in the N-S direction of the main building floors occurs indeed at 2.6 Hz. The corresponding mode shape was obtained by normalizing the Fourier amplitudes measured at 2.6 Hz to a unit value on the roof.

This method was used to estimate the fundamental mode shapes and frequencies of the building, a few higher modal frequencies and modes, and response shapes of the in-plane motions of the roof.

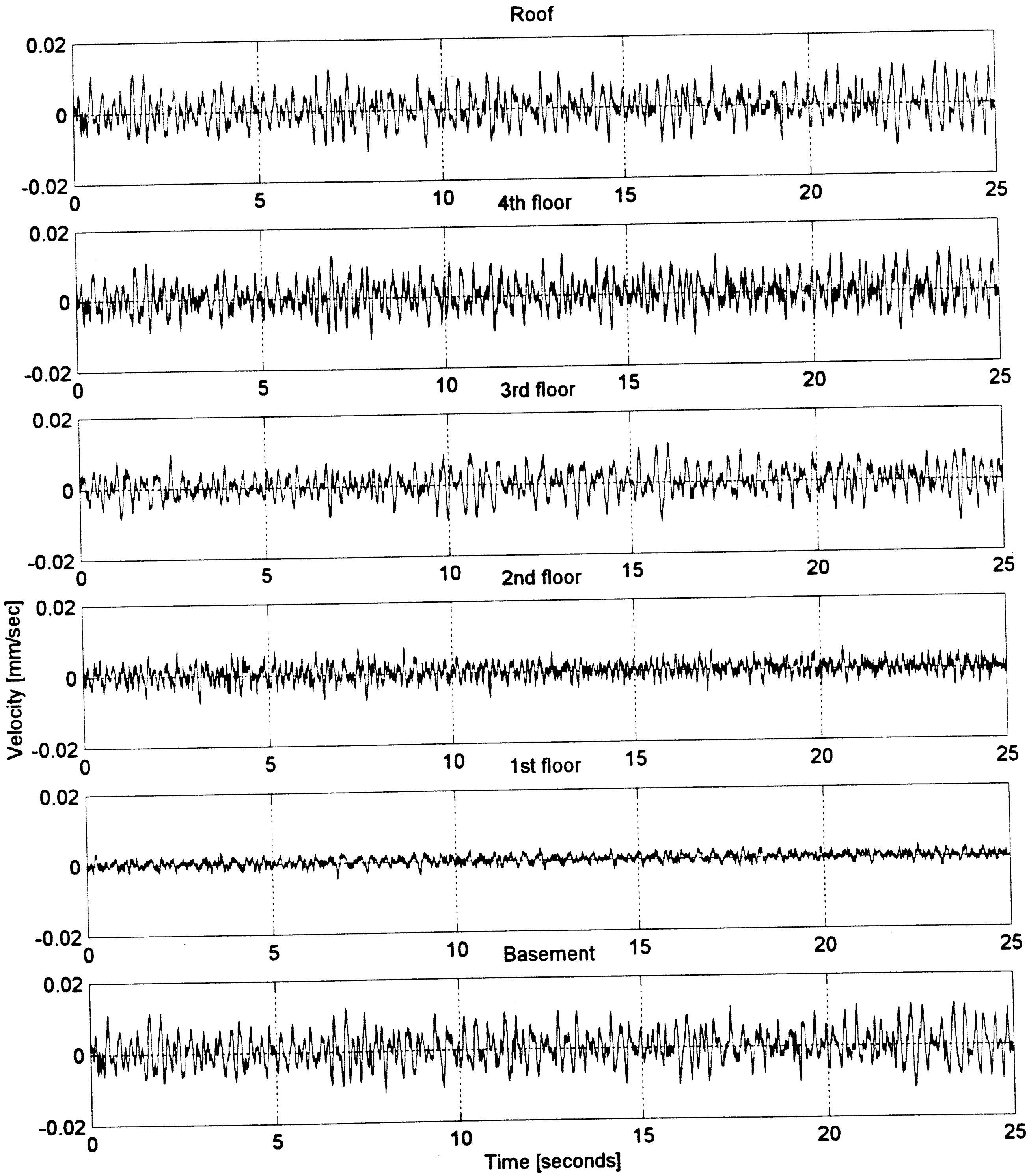


Fig. 4.1 Time Domain Records of N-S Translation of Main Building Floors

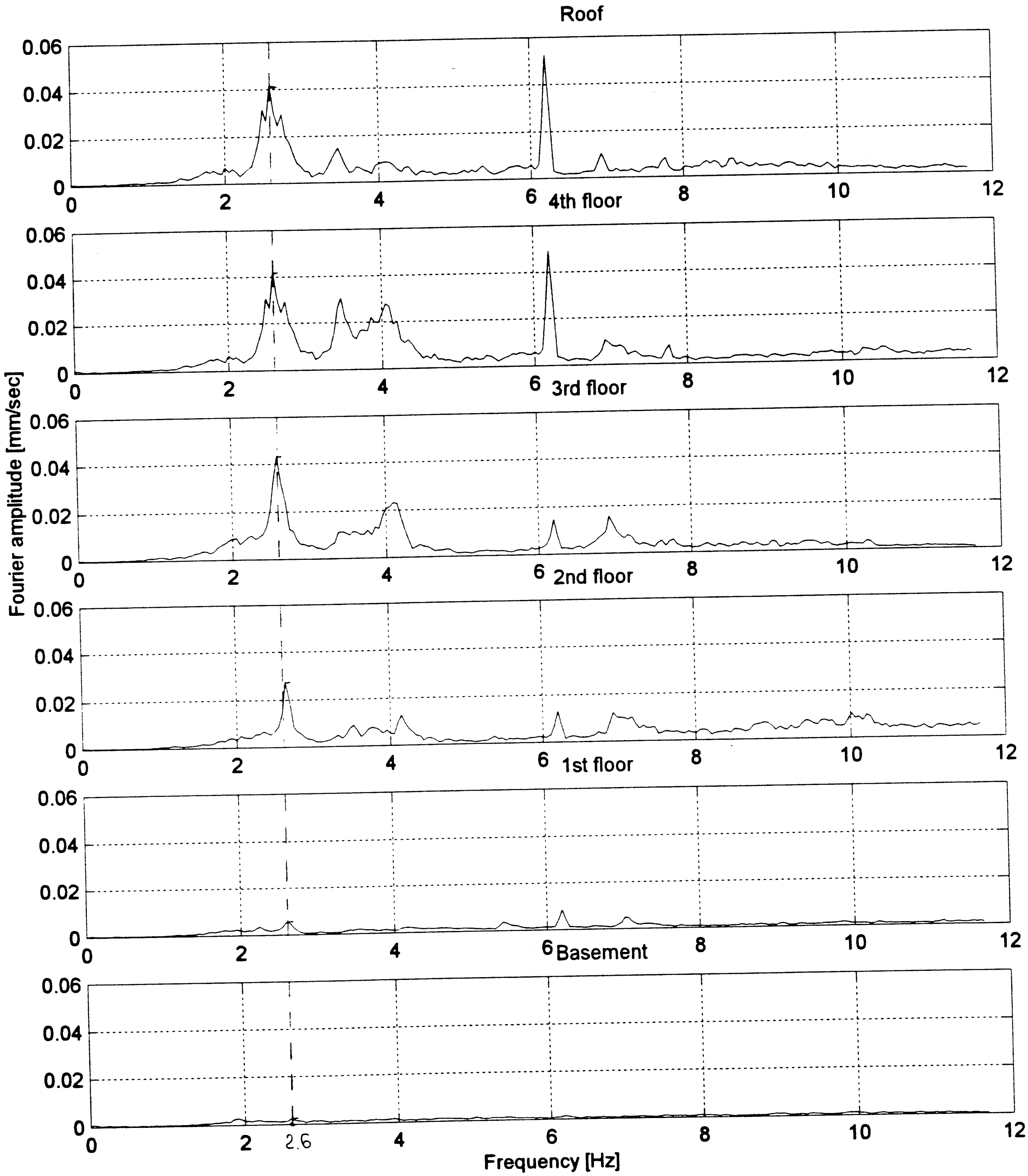


Fig. 4.2 a) Amplitude of Frequency Response of N-S Floor Translation

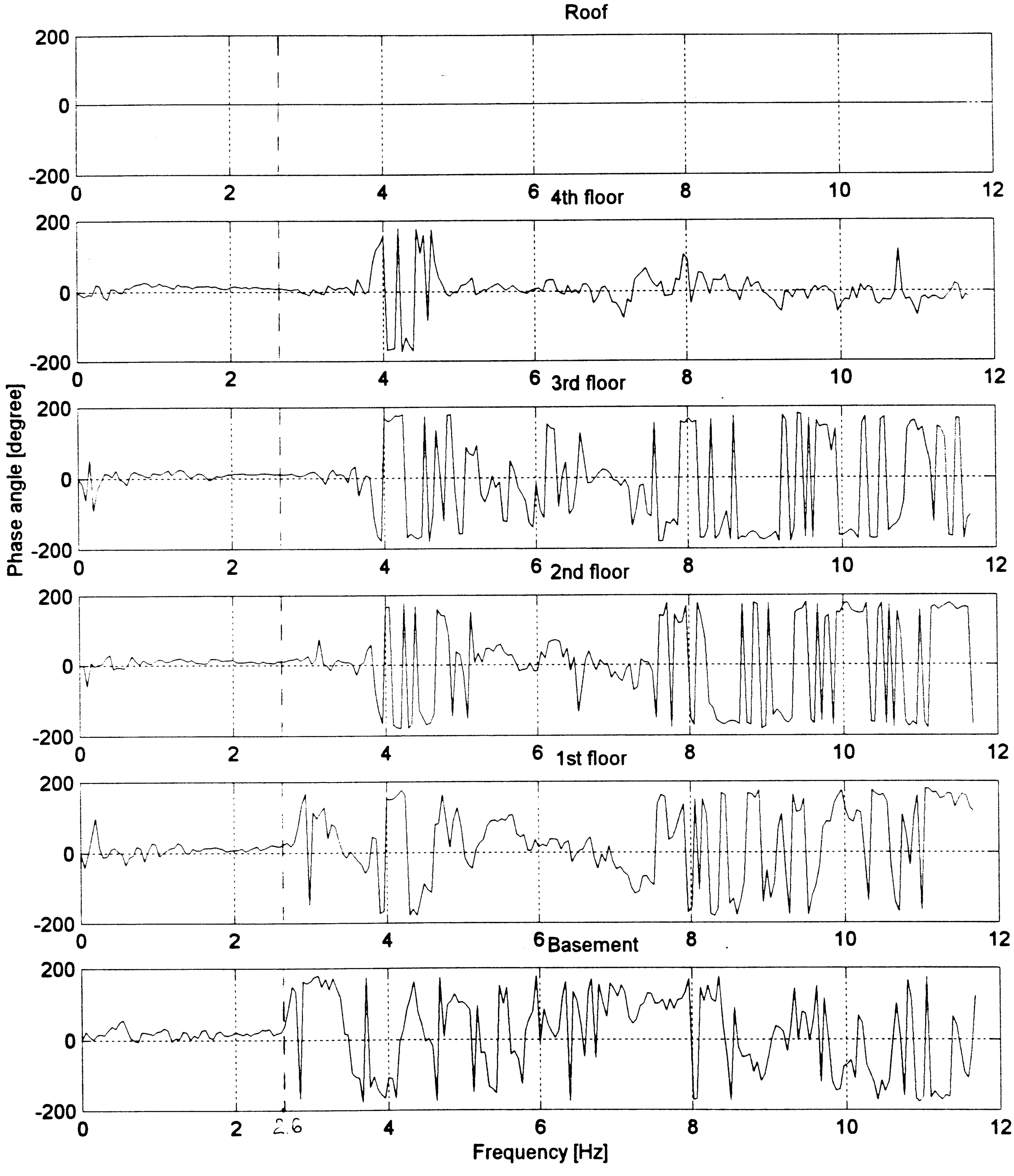


Fig. 4.2 b) Phase of Frequency Response of N-S Floor Translation

5 *ROOF & ADDITION TESTS*

5.1 Roof Flexibility Test

This test was performed to evaluate the in-plane response of the roof. Six seismometers were placed in the N-S direction (S3, S5, S6, S7, S8, and S1); two seismometers were placed in the E-W direction (S2 and S4). The frequency response in the N-S direction can be visualized in Figs. 5.1 a) and b) which show the Fourier amplitude and relative phase (S1 is reference) of all records. Figure 5.2 shows the corresponding information for the instruments placed in the E-W direction. These figures show meaningful peaks at 2.6 Hz, 3.4 Hz, 4.1 Hz and 6.2 Hz.

As expected, the roof showed a flexible in-plane response, mainly along its longest axis (E-W). At 2.6 Hz, the roof moved in the N-S direction, with significant flexural in-plane deformation (Fig. 5.3 a - top). At 3.4 Hz, the roof moved rigidly in the E-W direction, with a pronounced shear distortion along the E-W axis (Fig. 5.3 a - bottom). This response shape does not include a rotational component because the two opposite E-W sensors are in phase with each other. A clear torsional response was observed at 4.1 Hz, with some in-plane deformation (Fig 5.3 b –top). Finally, at 6.2 Hz, the roof moved rigidly in the E-W direction, with a complicated in-plane distortion shape.

The results from this test indicated that the fundamental vibration frequencies of the building were most probably at 2.6 Hz for N-S floor translation, 3.4 Hz for E-W floor translation, and 4.1 Hz for floor rotation.

5.2 Test of Building Addition

This test was scheduled to verify whether or not the library addition responded together with the main building. The test was performed on the third floor. Two seismometers were placed on the addition floor, in two orthogonal directions, and a similar set of two seismometers was located nearby, but on the floor of the main building.

Fig. 5.4 shows the calculated Fourier amplitudes and phase angles for the translations in the N-S and E-W directions. The addition and the main building clearly moved together during the ambient vibration tests.

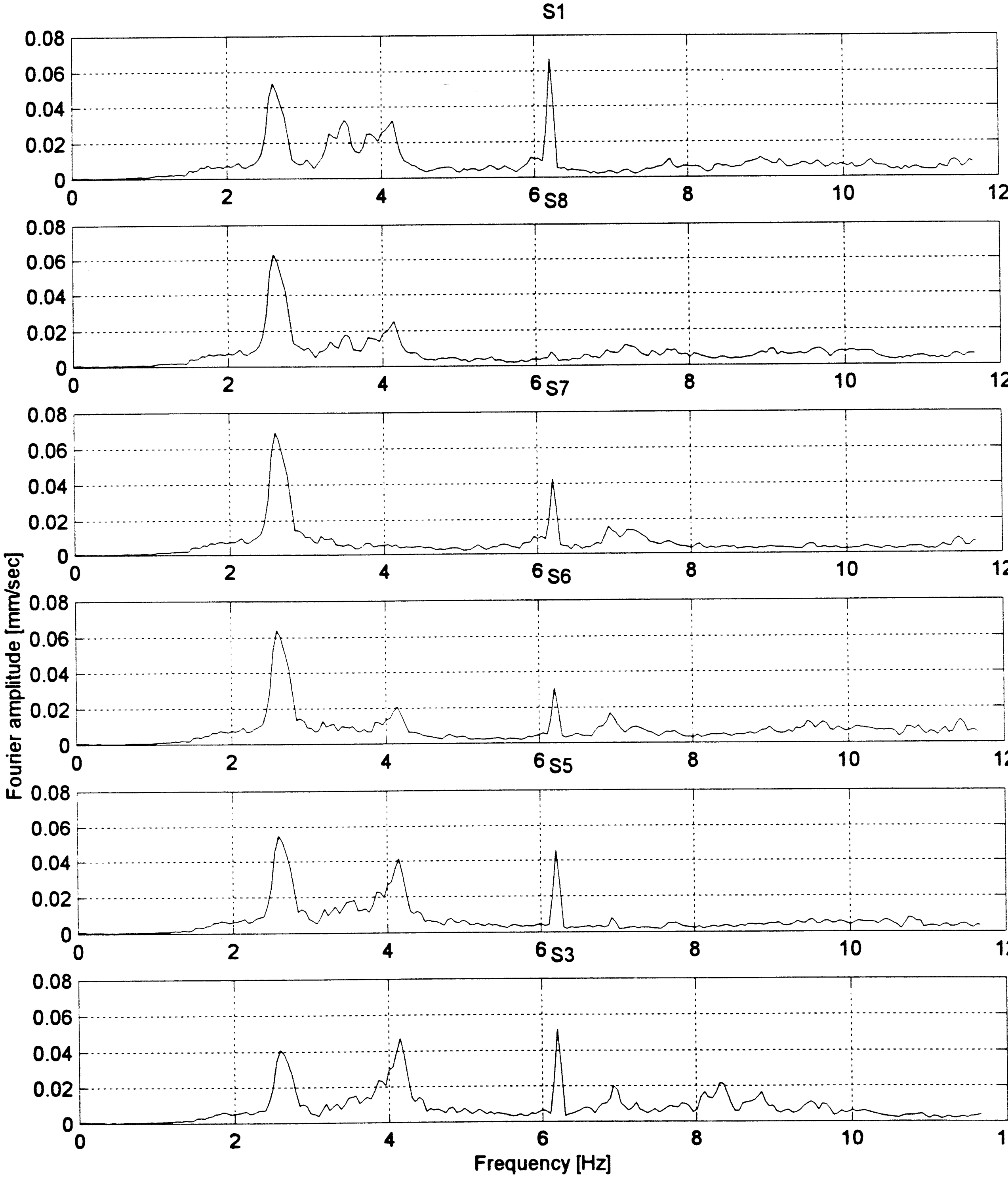


Fig. 5.1 a) Roof Flexibility Test: N-S Translation Frequency Response Amplitude

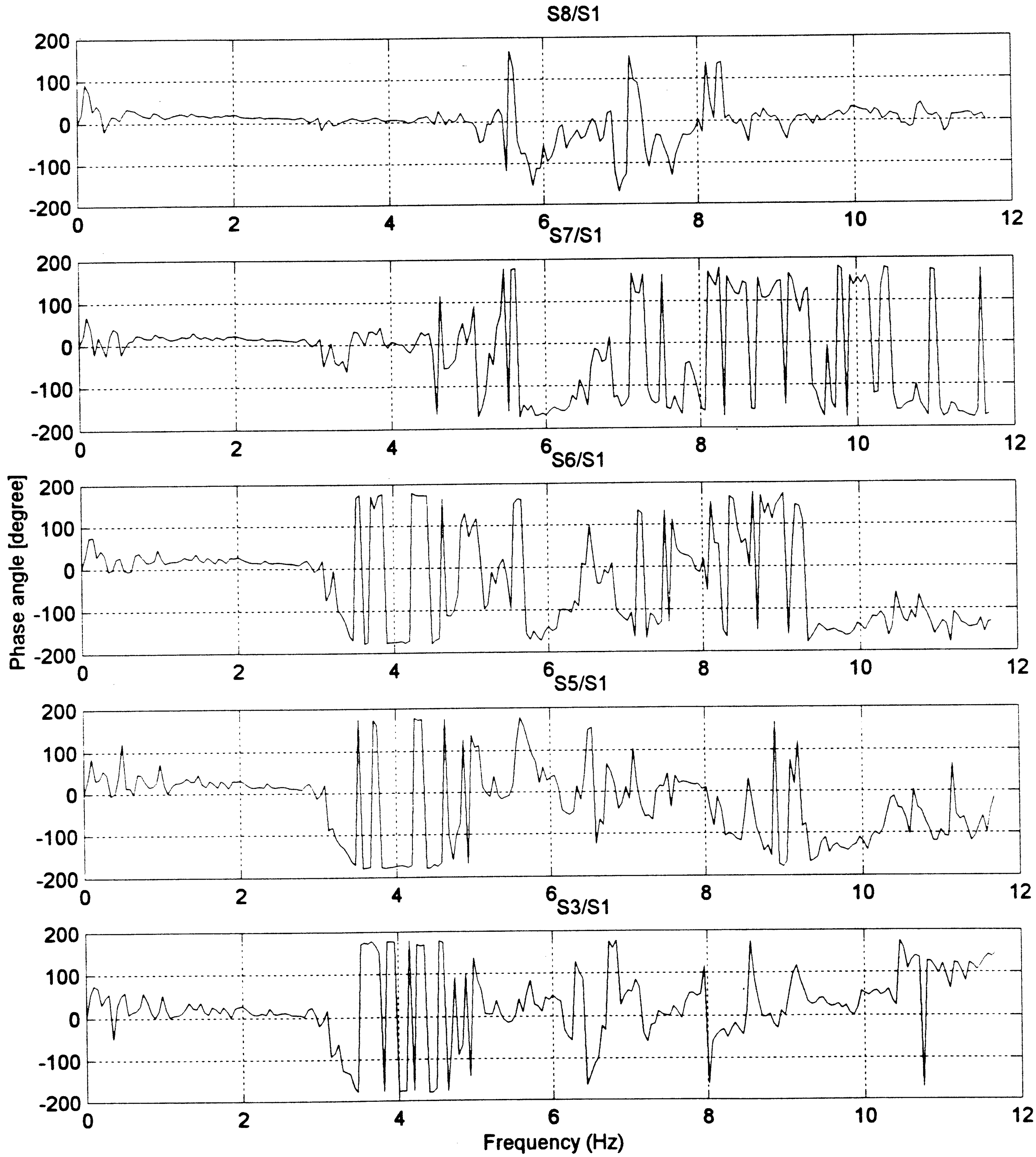


Fig. 5.1 b) Roof Flexibility Test: N-S Translation Frequency Response Phase

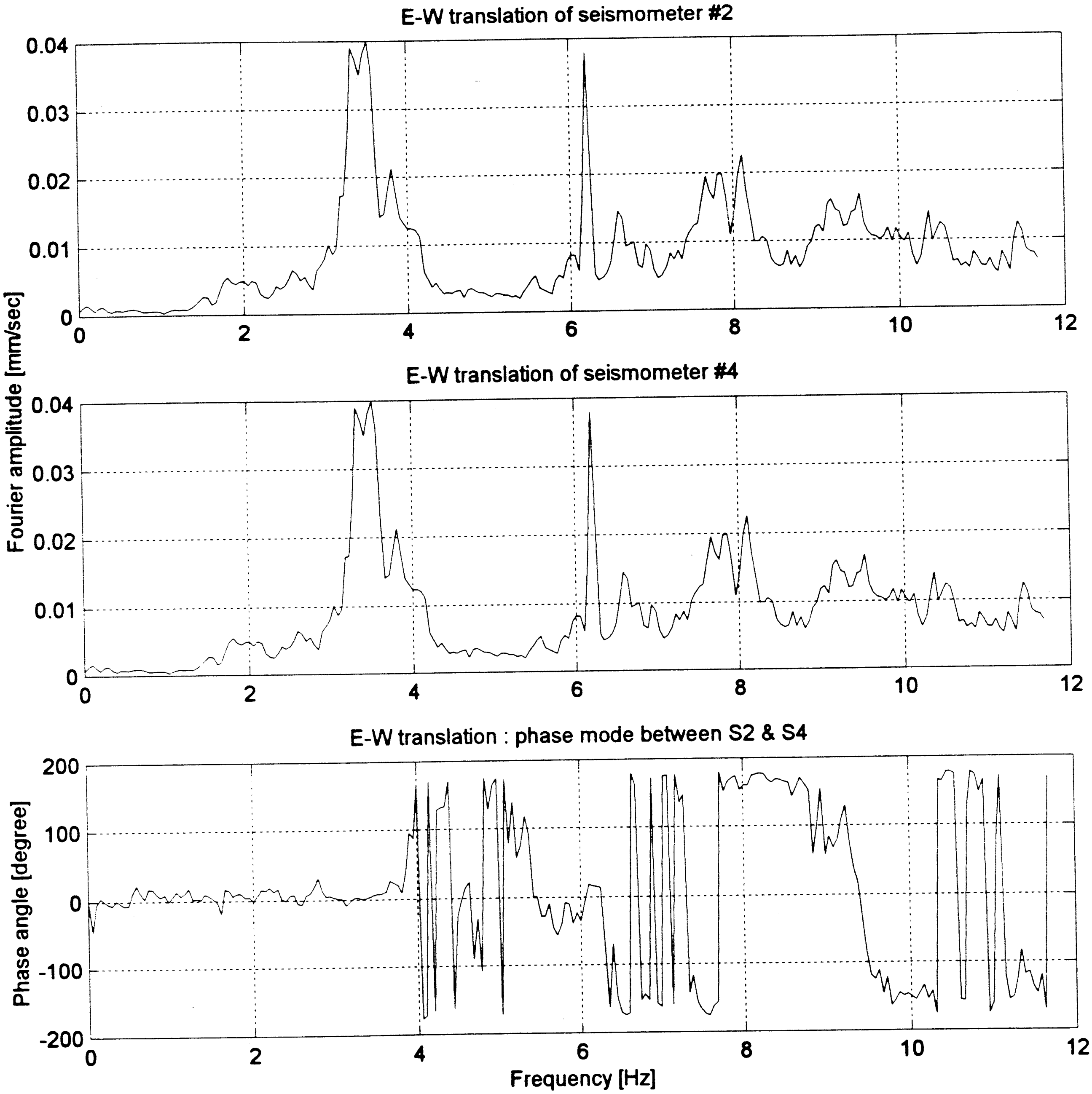
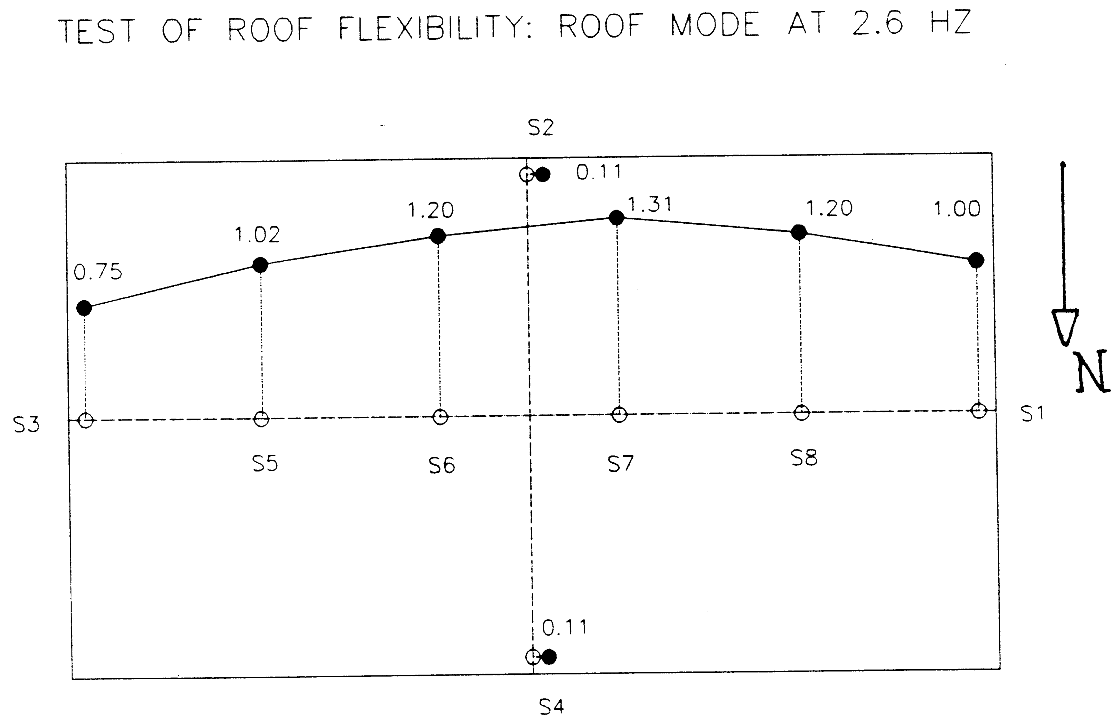


Fig. 5.2 Roof Flexibility Test: E-W Translation Frequency Response



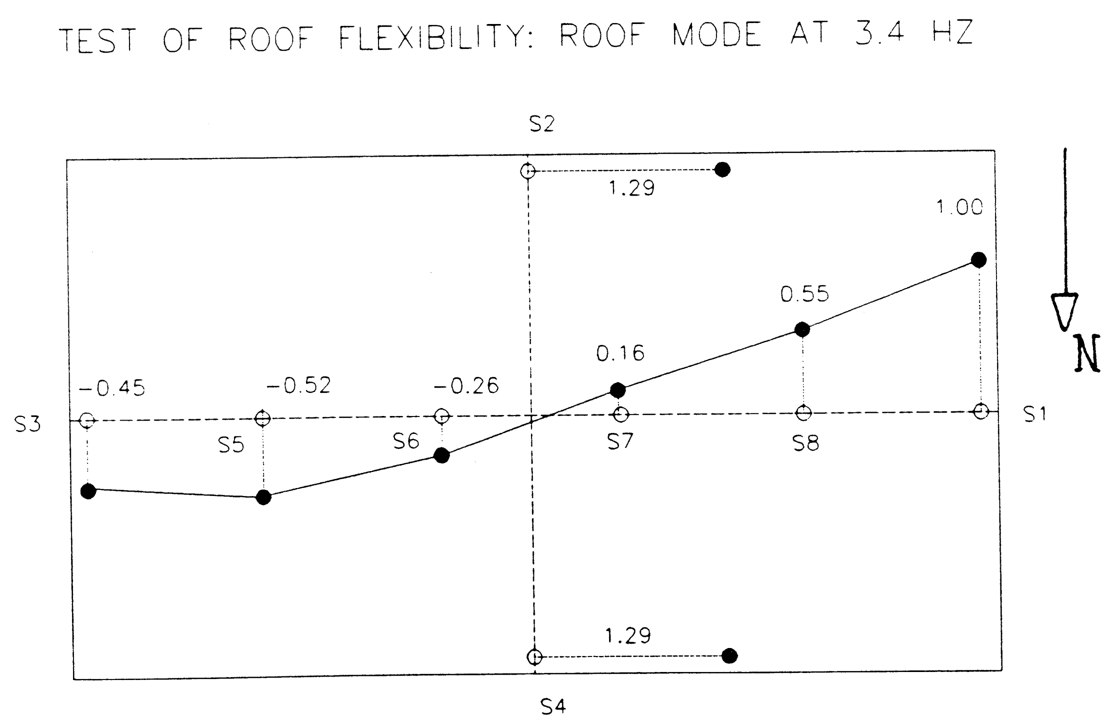
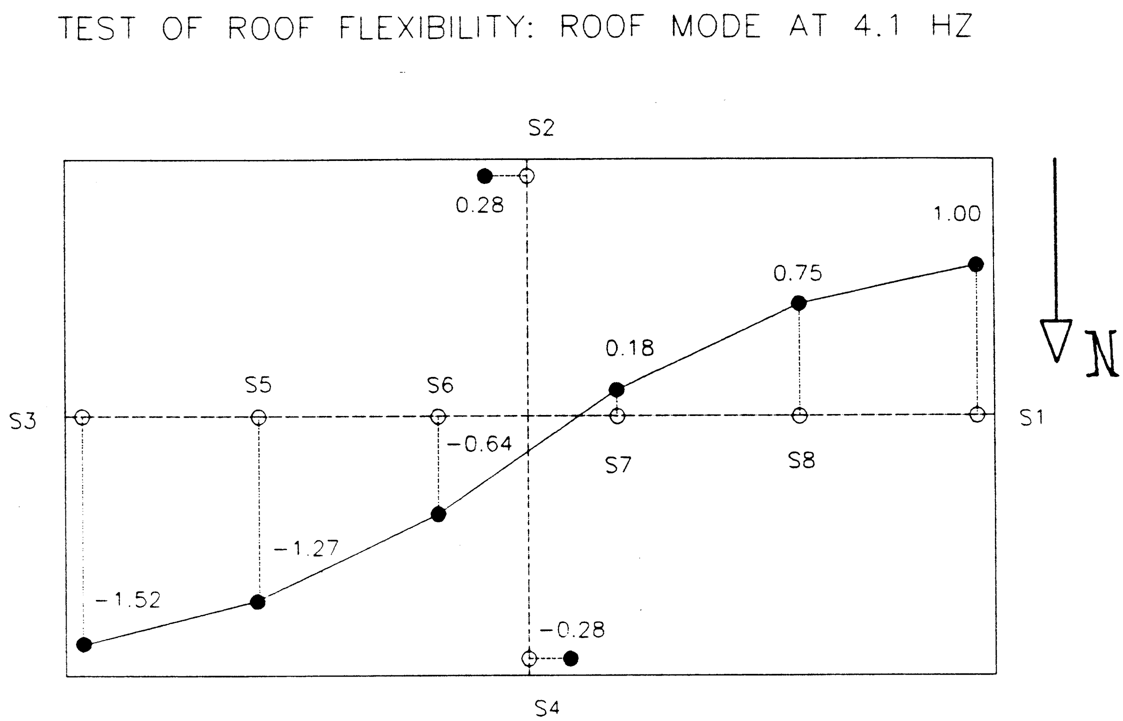


Fig. 5.3 a) Roof In-Plane Response Shapes at 2.6 Hz and 3.4 Hz



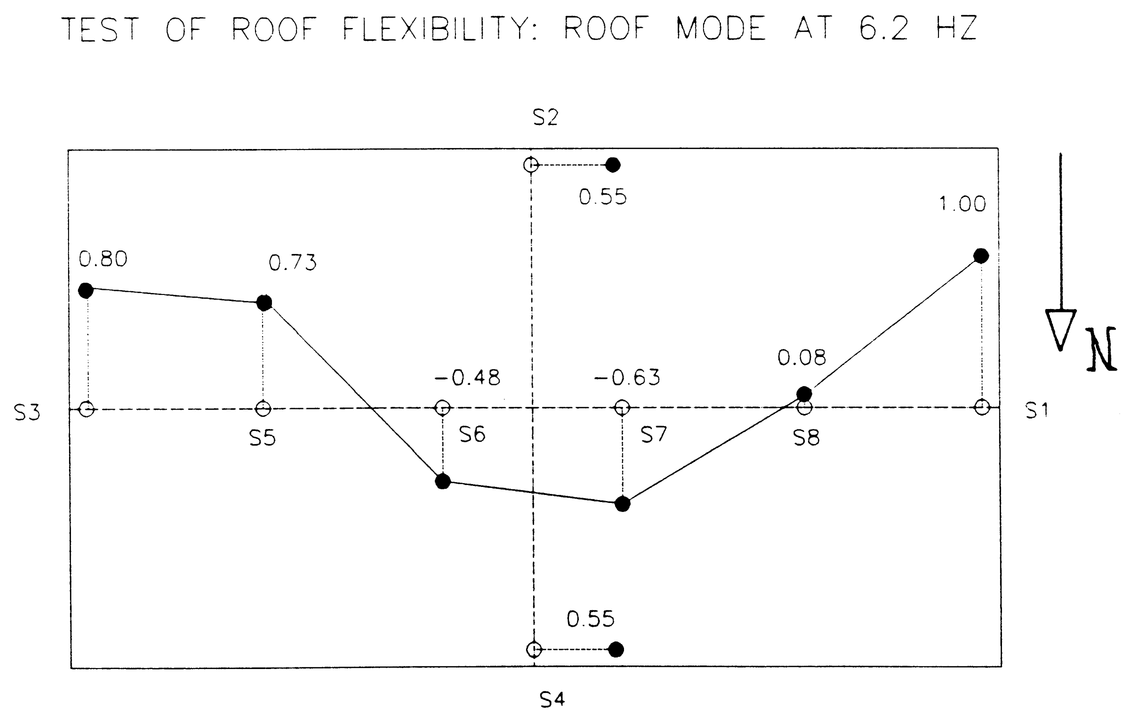


Fig. 5.3 b) Roof In-Plane Response Shapes at 4.1 Hz and 6.2 Hz

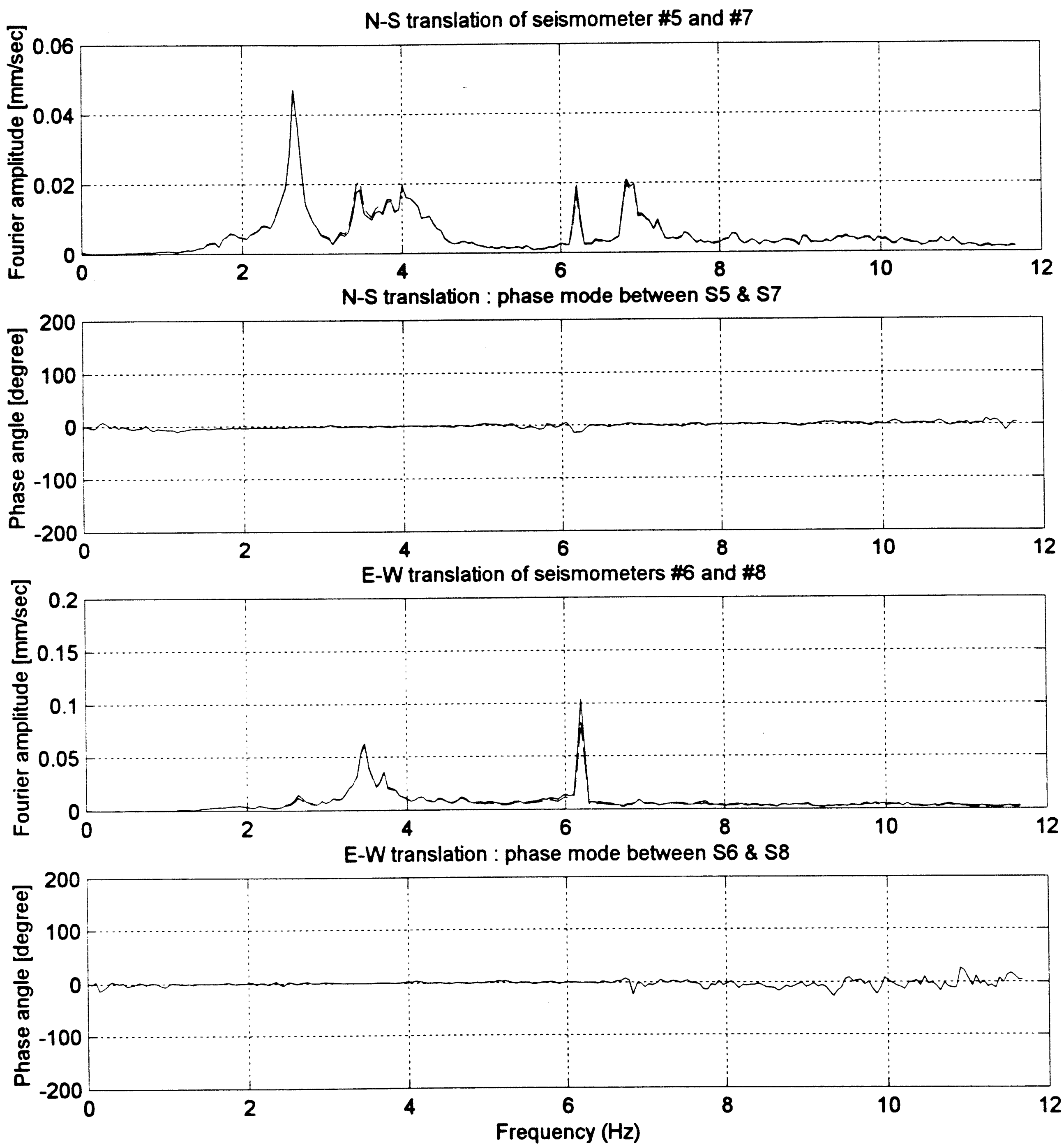


Fig. 5.4 **3rd Floor Frequency Response**
(Solid Line: Addition, Dashed Line: Main Floor)

6 *NATURAL MODES AND FREQUENCIES*

The main objective of this testing program was to estimate at least the fundamental natural modes and frequencies of the main building. It was also hoped that the recorded data would help to determine whether the stacks and the building respond together or they vibrate independently of each other.

The fundamental frequencies of the main building and the stacks were found to be 2.6 Hz for the translational response in the N-S direction, 3.4 Hz for the translational response in the E-W direction, and 4.1 Hz for the torsional response. These results are in accordance with those obtained during the roof flexibility test, and indicate that the main building and the stacks respond together, at least for small excitation levels. The corresponding fundamental mode shapes were calculated reliably because all levels were found to be clearly in phase at each fundamental frequency.

Figure 6.1 shows the mode shapes of the main building floors and the stack levels for the fundamental translational modes of vibration in the N-S direction at 2.6 Hz. Modal shapes are smooth, with the characteristic 1st mode response outline. The modal amplitudes of the stacks at the higher levels are larger than those of the main building.

Figure 6.2 shows the corresponding information for the fundamental translational mode in the E-W direction at 3.4 Hz. The modal amplitude for the 3rd floor is smaller than what would be expected in a more regular building. Modal amplitudes of main building and stacks are similar up the height of the building.

The fundamental rotational mode shapes obtained at 4.1 Hz are presented in Fig. 6.3. The modal amplitudes of the 2nd through 4th floors of the main building are significantly larger than that of the roof, and the modal amplitudes of the stacks are somewhat smaller than those of the main building.

Modal parameters for higher modes of vibration were significantly more difficult to estimate than those for the fundamental modes of vibration. The results presented below must not be considered to be completely reliable.

Fig. 6.4 shows the estimated mode shapes and frequencies for building and stacks corresponding to the 2nd translational mode in the N-S direction. Building and stacks vibrate at different frequencies: 4.1 Hz for the building and 5.3 Hz for the stacks. Notice that 4.1 Hz is also the calculated 1st mode rotational frequency for both building and stacks, and that roof response was mainly rotational at 4.1 Hz. This seems to indicate that the response of the building at 4.1 Hz is not a "pure" translational or rotational mode, but a mixed mode of vibration including both translational and rotational components.

Finally, Fig. 6.5 shows the response shapes at 6.2 Hz. They seem to correspond to the 2nd mode of vibration in the E-W direction for building and stacks. As in the case of the 1st E-W mode, the amplitude for the 3rd floor is smaller than expected.

Table 6.1 summarizes the computed modal parameters. Appendix B presents graphs of the Fourier amplitudes and phase angles for all levels of the main building and stacks.

Table 6.1 Modal Properties and Frequencies

Mode No.	Frequency	Description
1	2.6 Hz	Main Building and Stacks N-S Translation, 1st Mode
2	3.4 Hz	Main Building and Stacks E-W Translation, 1st Mode
3	4.1 Hz	Main Building and Stacks Rotation, 1st Mode
4?	4.1 Hz	Main Building N-S Translation, 2nd mode
5?	5.3 Hz	Stacks N-S Translation, 2nd mode
6?	6.2 Hz	Main Building and Stacks E-W Translation, 2nd mode

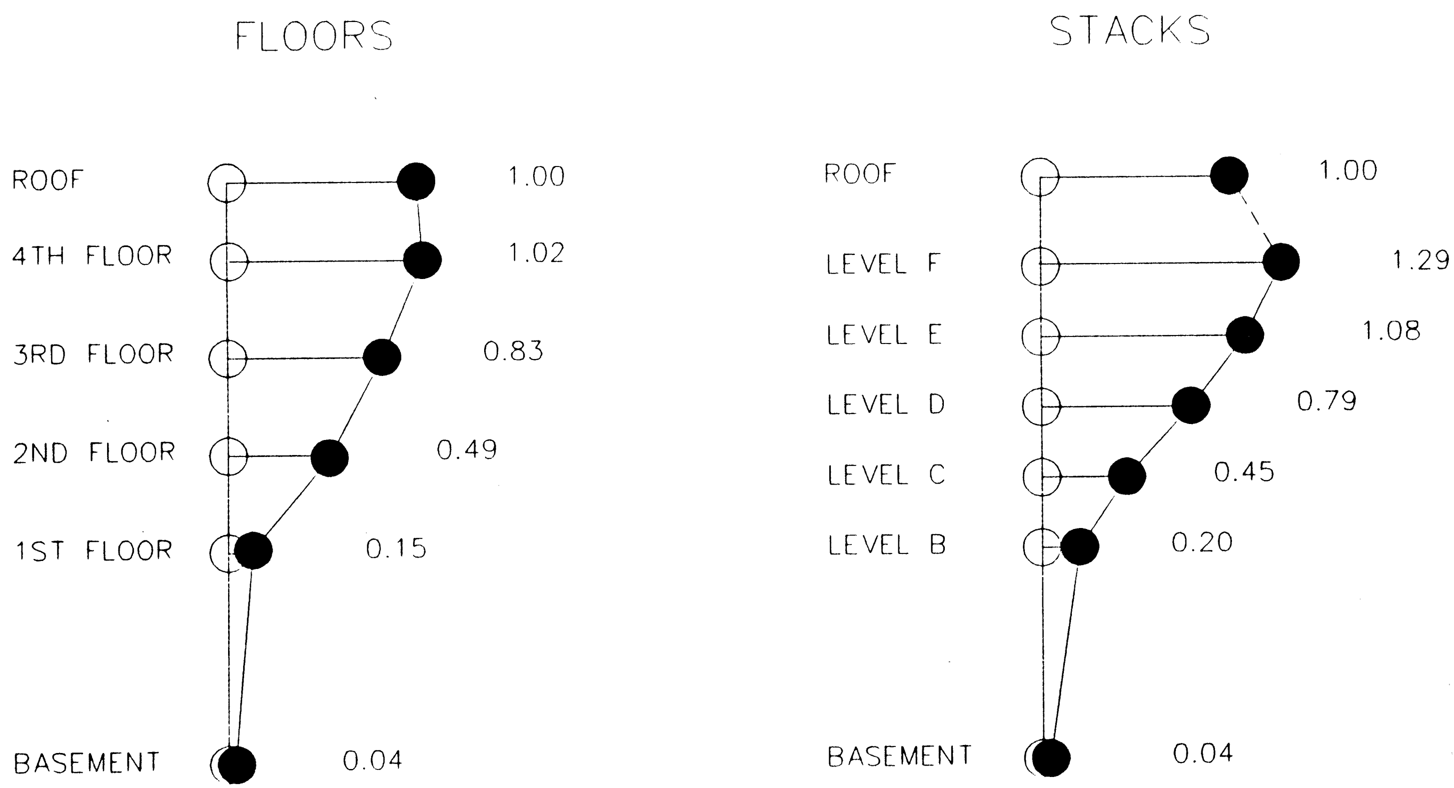


Fig. 6.1 1st Translational Mode of Vibration in N-S Direction
Frequency = 2.6 Hz

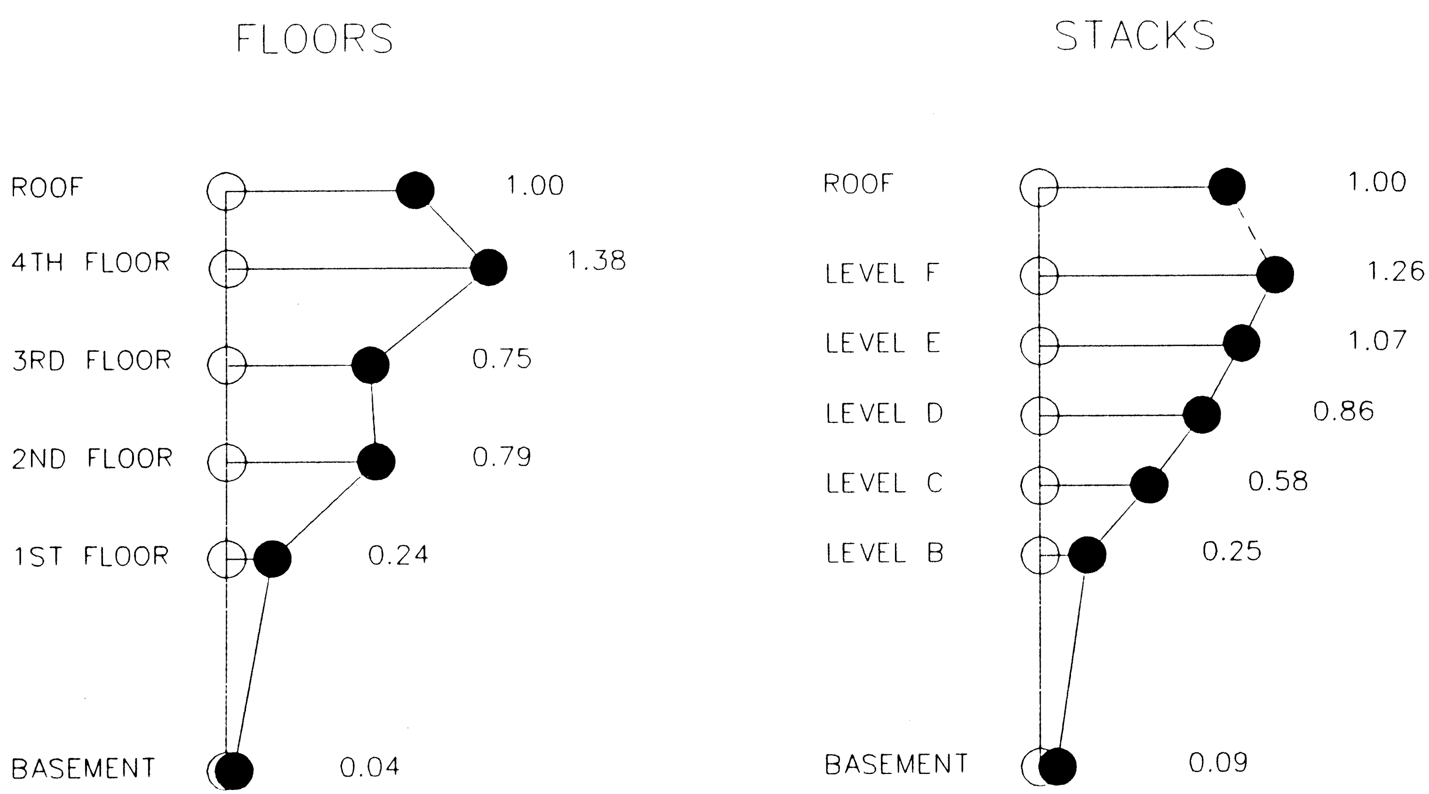


Fig. 6.2 1st Translational Mode of Vibration in E-W Direction Frequency = 3.4 Hz

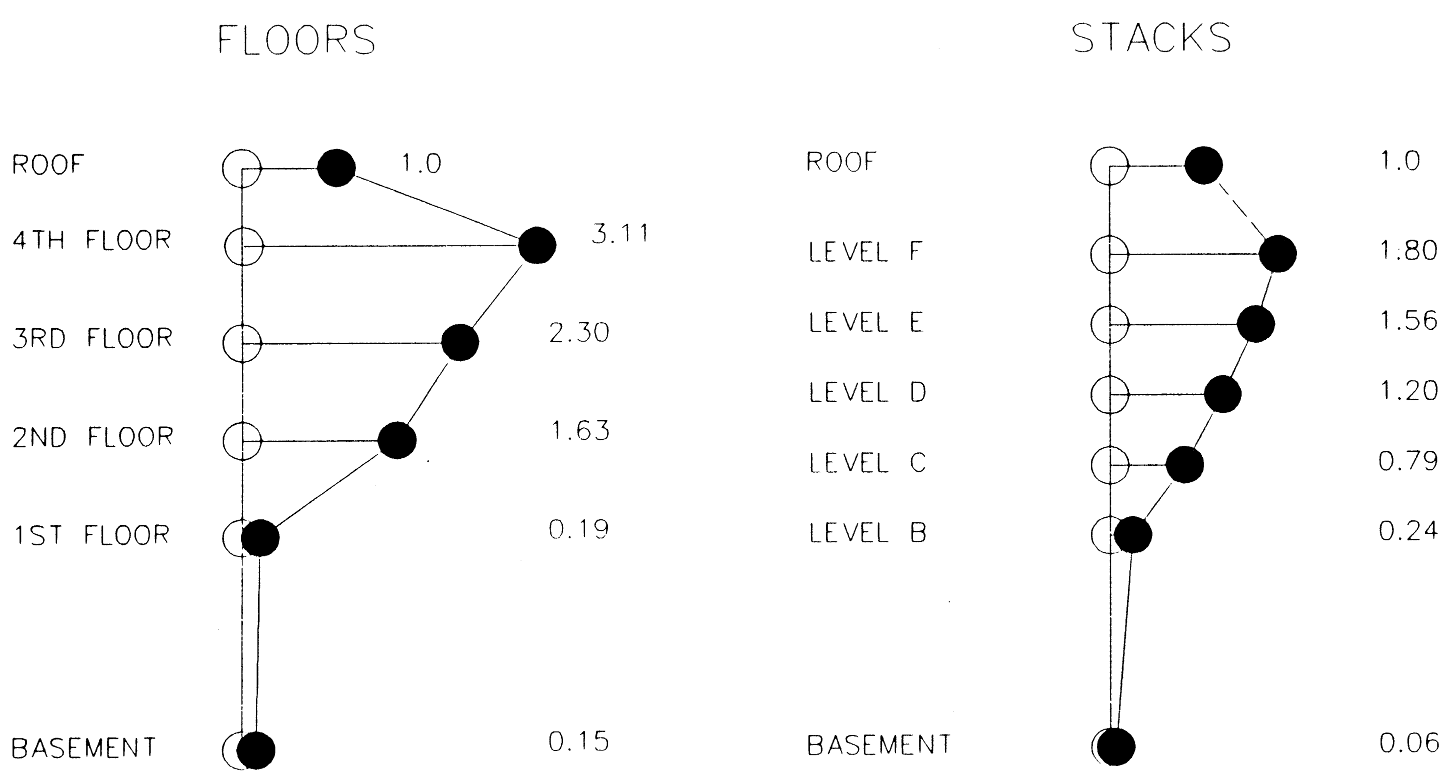


Fig. 6.3 1st Rotational Mode of Vibration — Frequency = 4.1 Hz

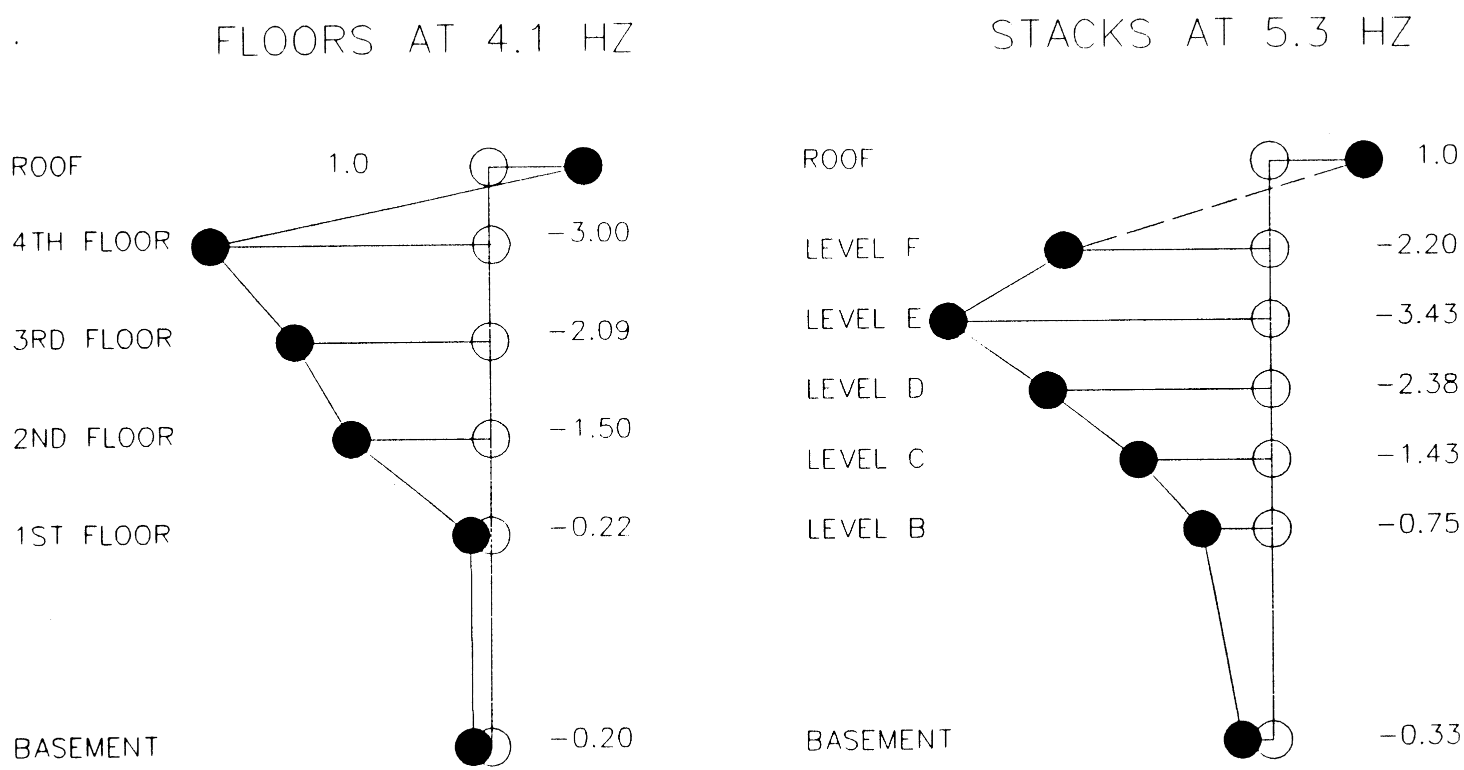


Fig. 6.4 2[nd] Translational Mode of Vibration in N-S Direction
Building Frequency = 4.1 Hz Stacks Frequency = 5.3 Hz

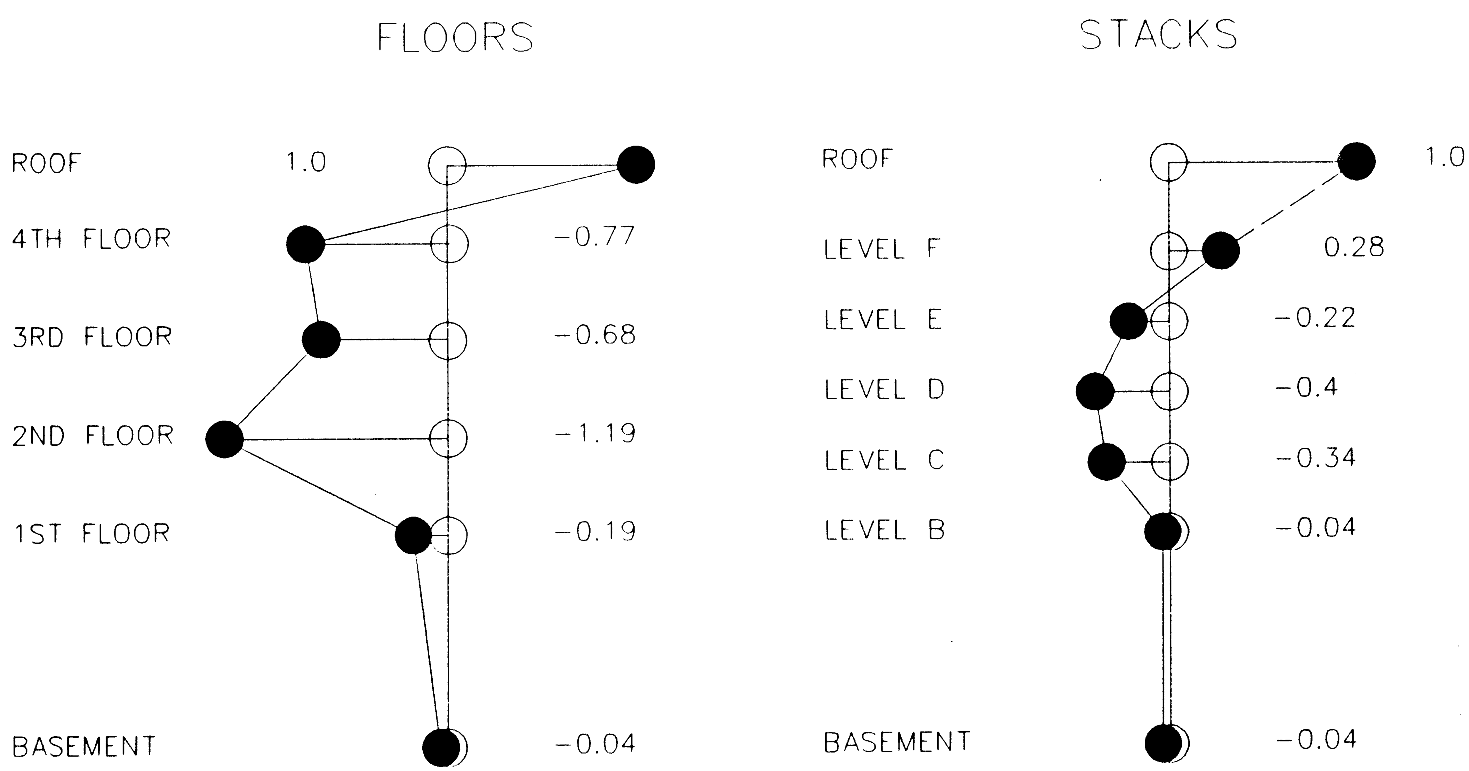


Fig. 6.5 **2nd Translational Mode of Vibration in E-W Direction**
Frequency = 6.2 Hz

7 *REFERENCES*

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APPENDIX A

BUILDING FLOOR PLANS

& SEISMOMETER LOCATIONS

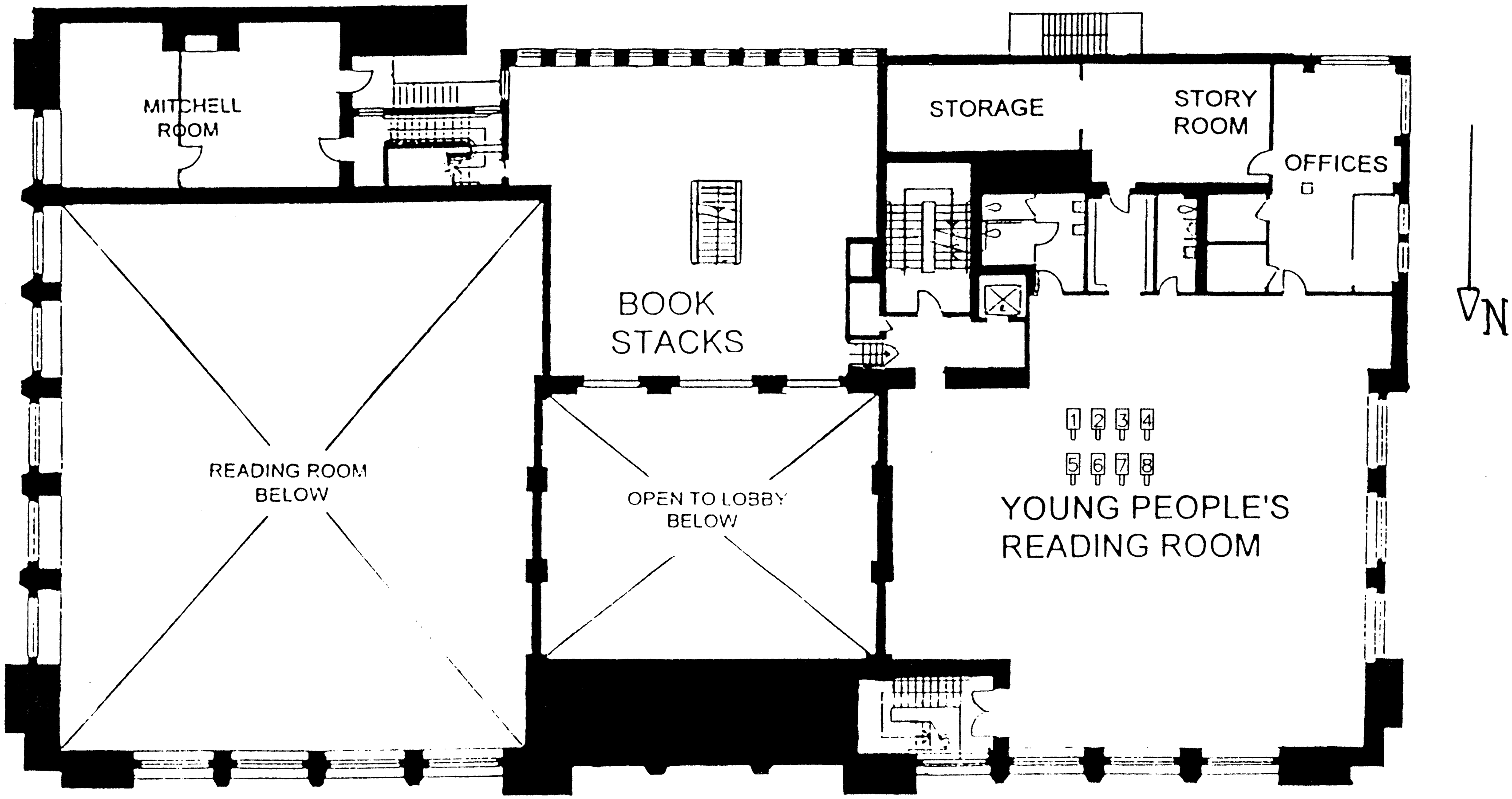

Fig. A.1 Test No. 1: Instrument Check (3rd Floor)

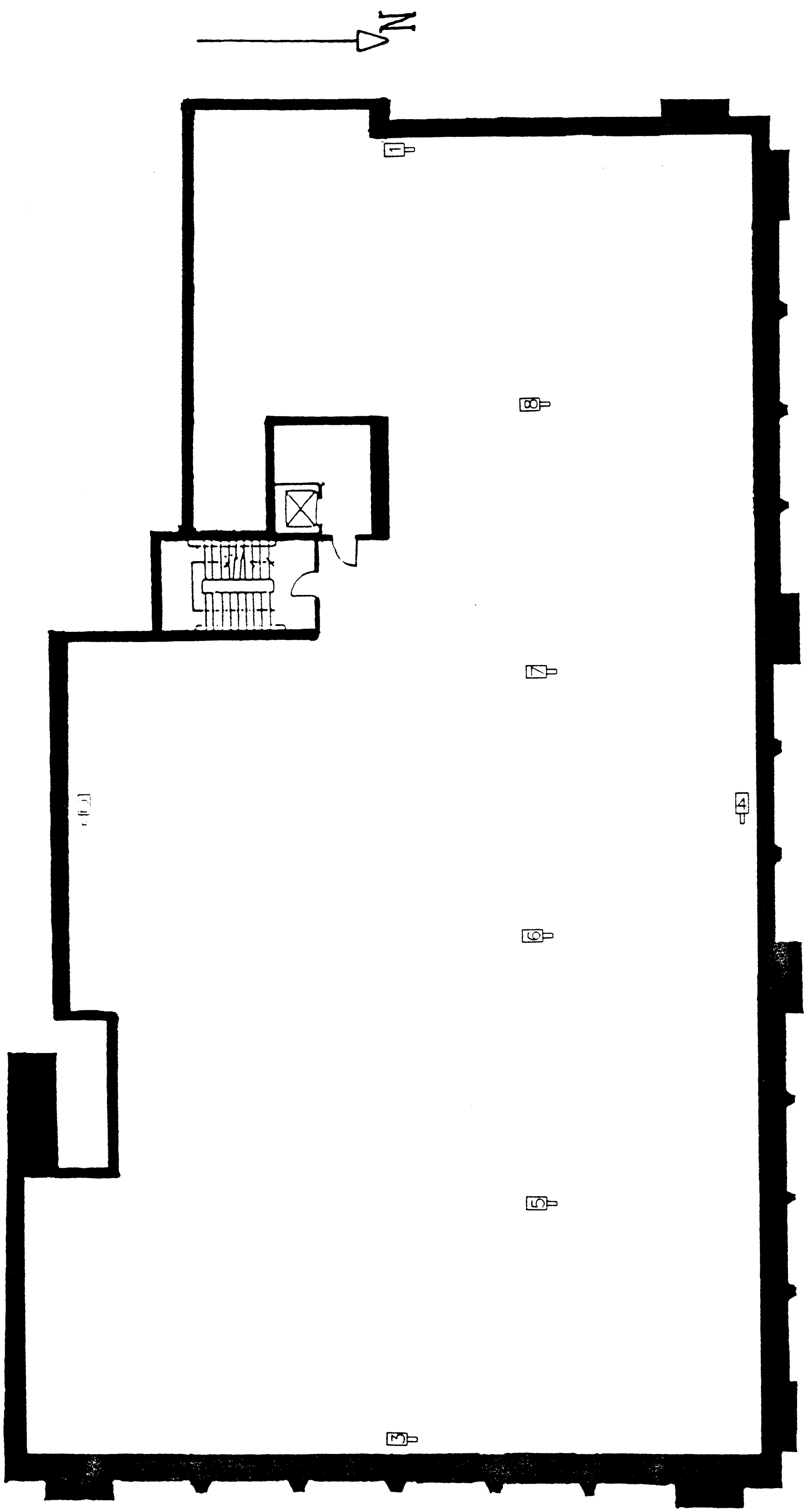

Fig. A.2 Test No. 2: Roof Flexibility Test

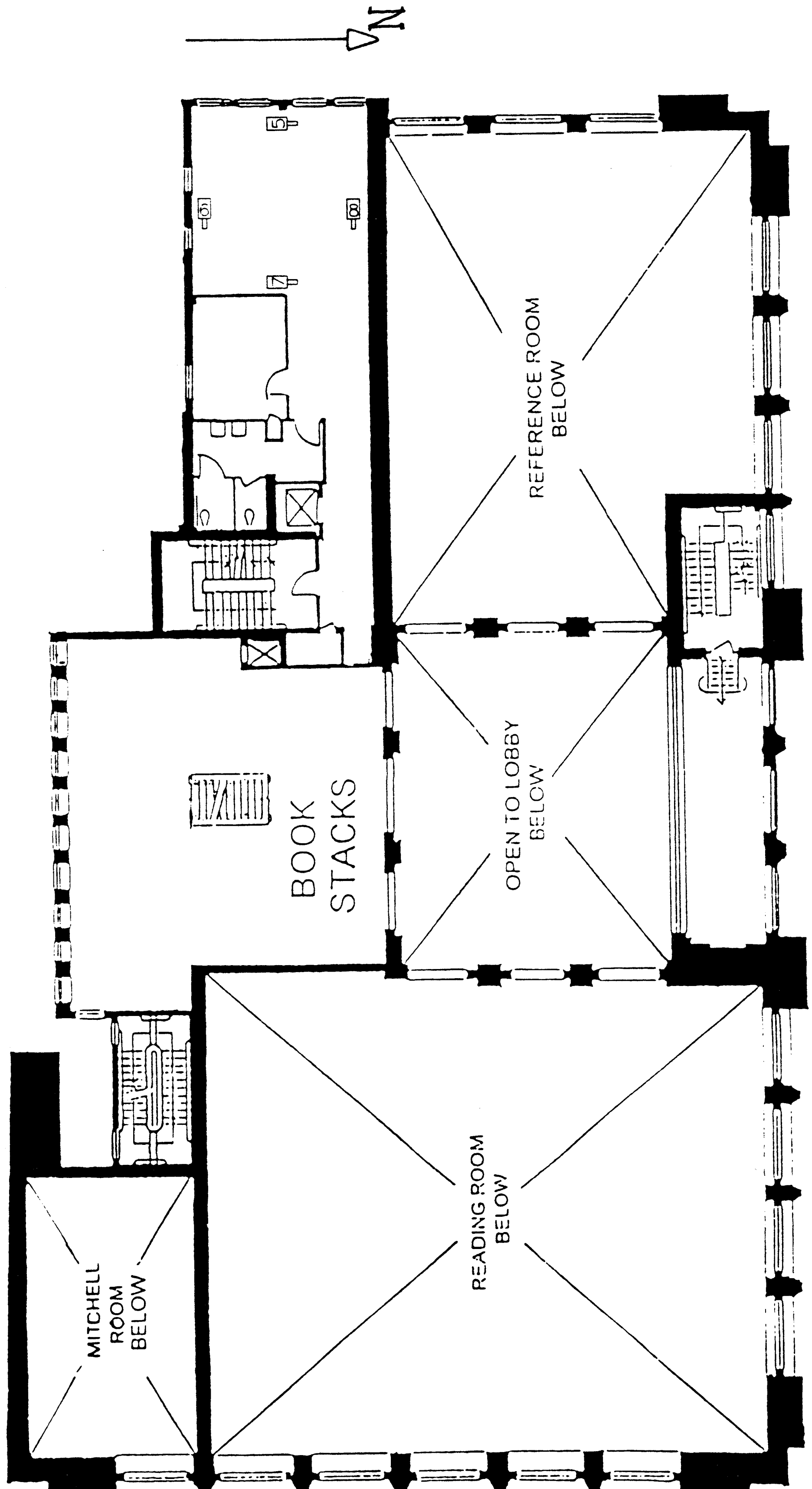

Fig. A.3 Test No. 3: 4th Floor Test

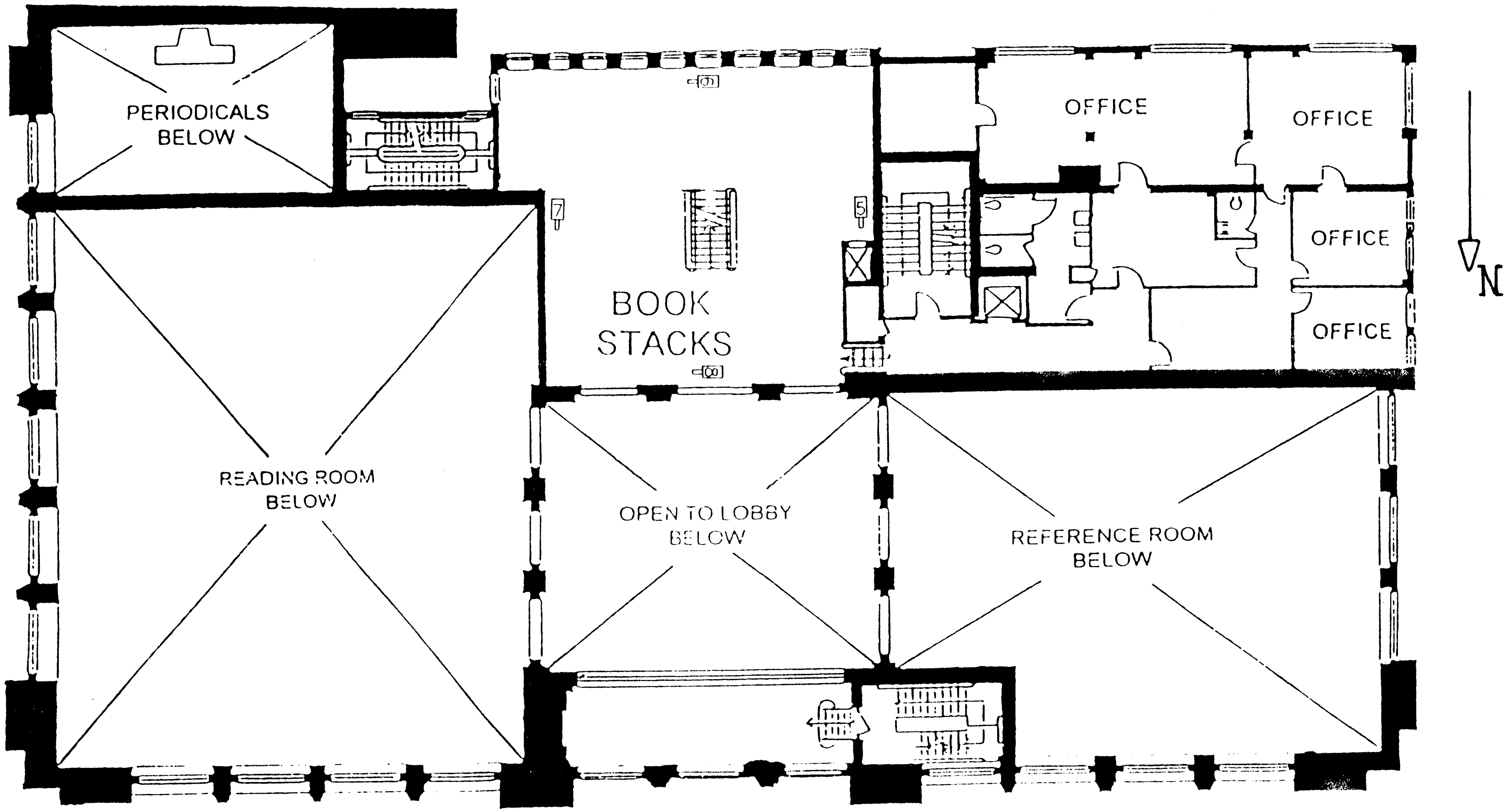

Fig. A.4 Tests No. 4, 5, 9, 11, 12: Stack Tests

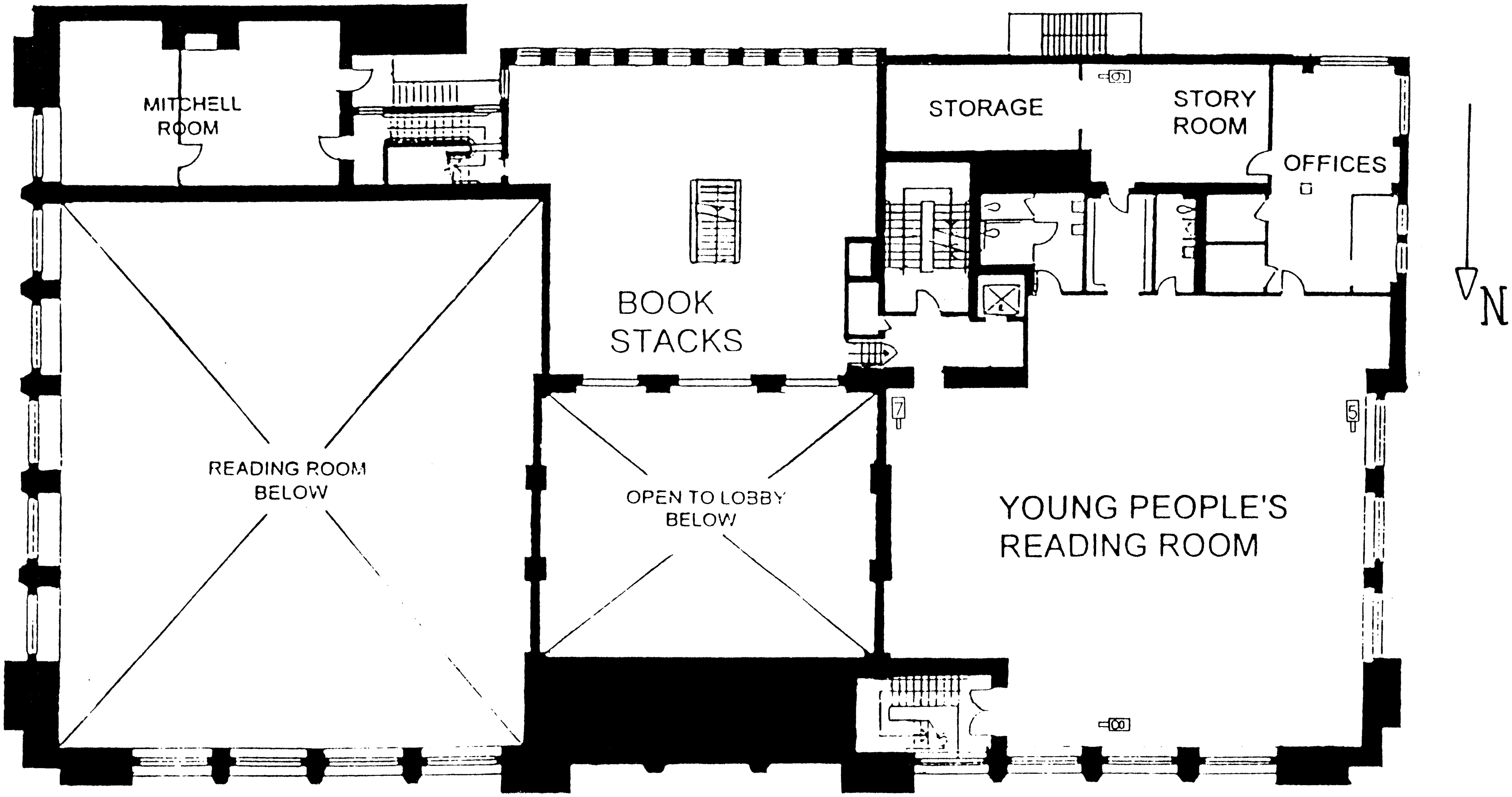

Fig. A.5 Test No. 6: 3rd Floor Test

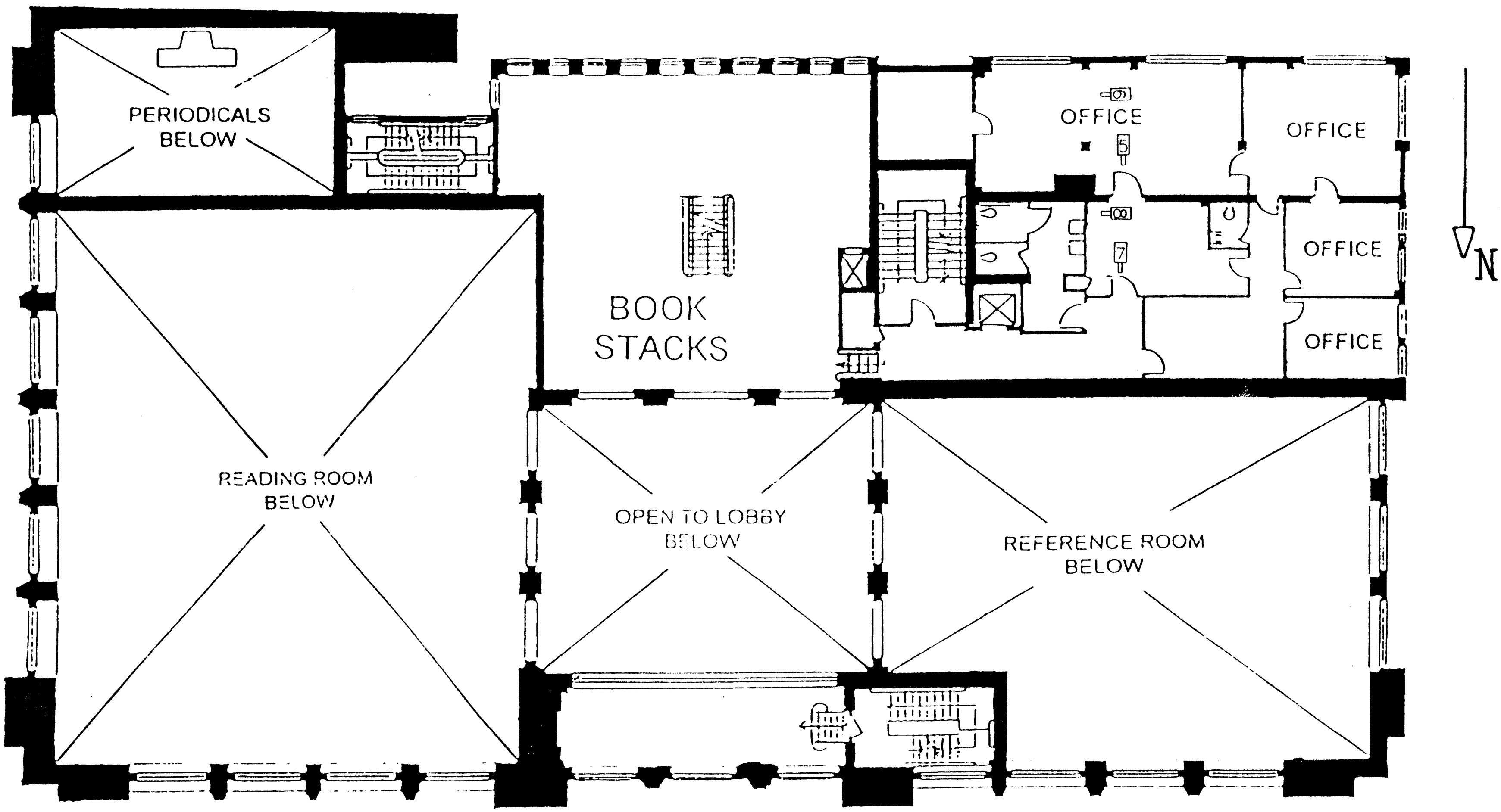

Fig. A.6 Test No. 7: Addition Test (3rd Floor)

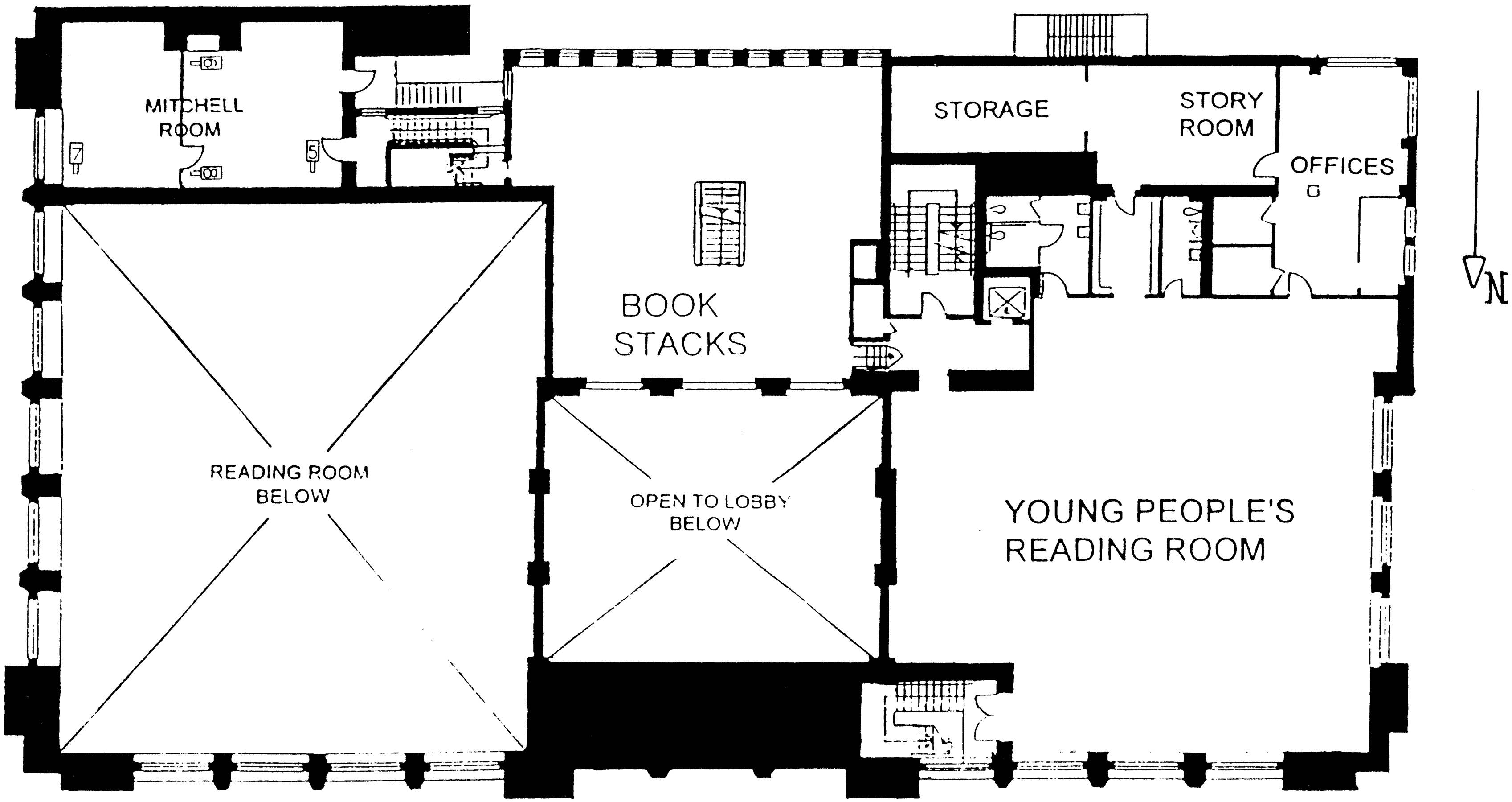

Fig. A.7 Test No. 8: Mitchell Room Floor Test

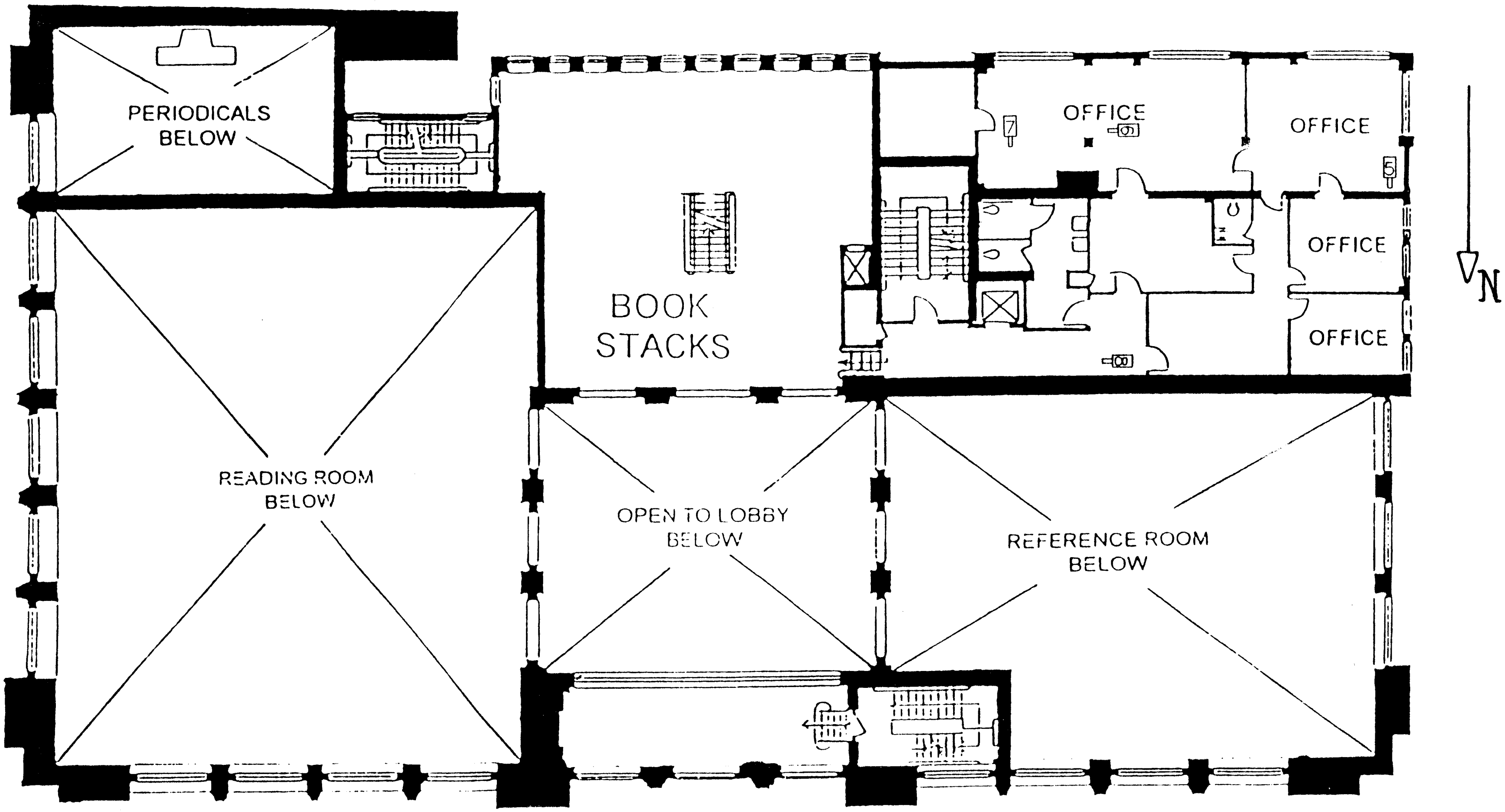

Fig. A.8 Test No. 10: 2nd Floor Test

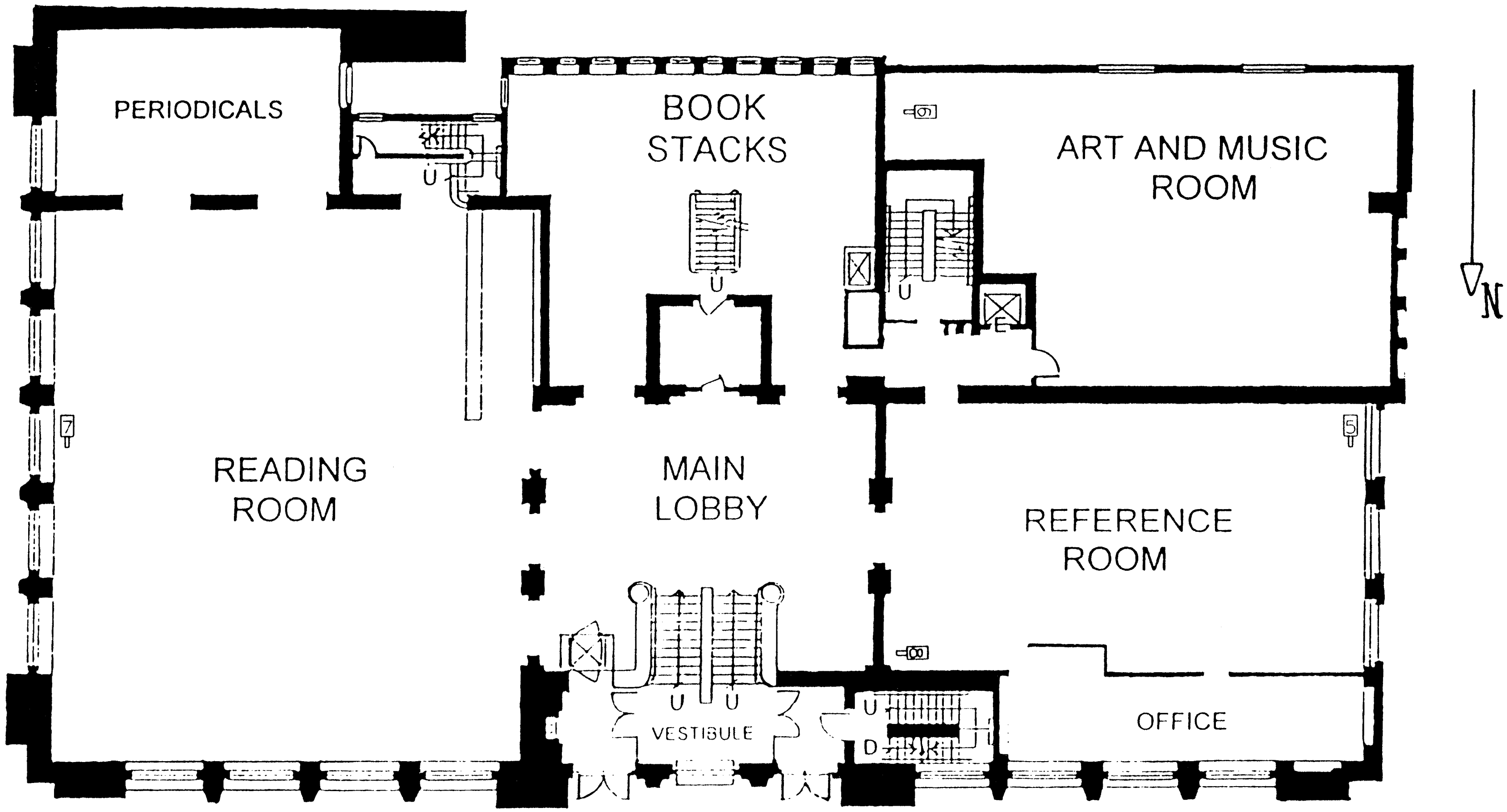

Fig. A.9 Test No. 13: 1st Floor Test

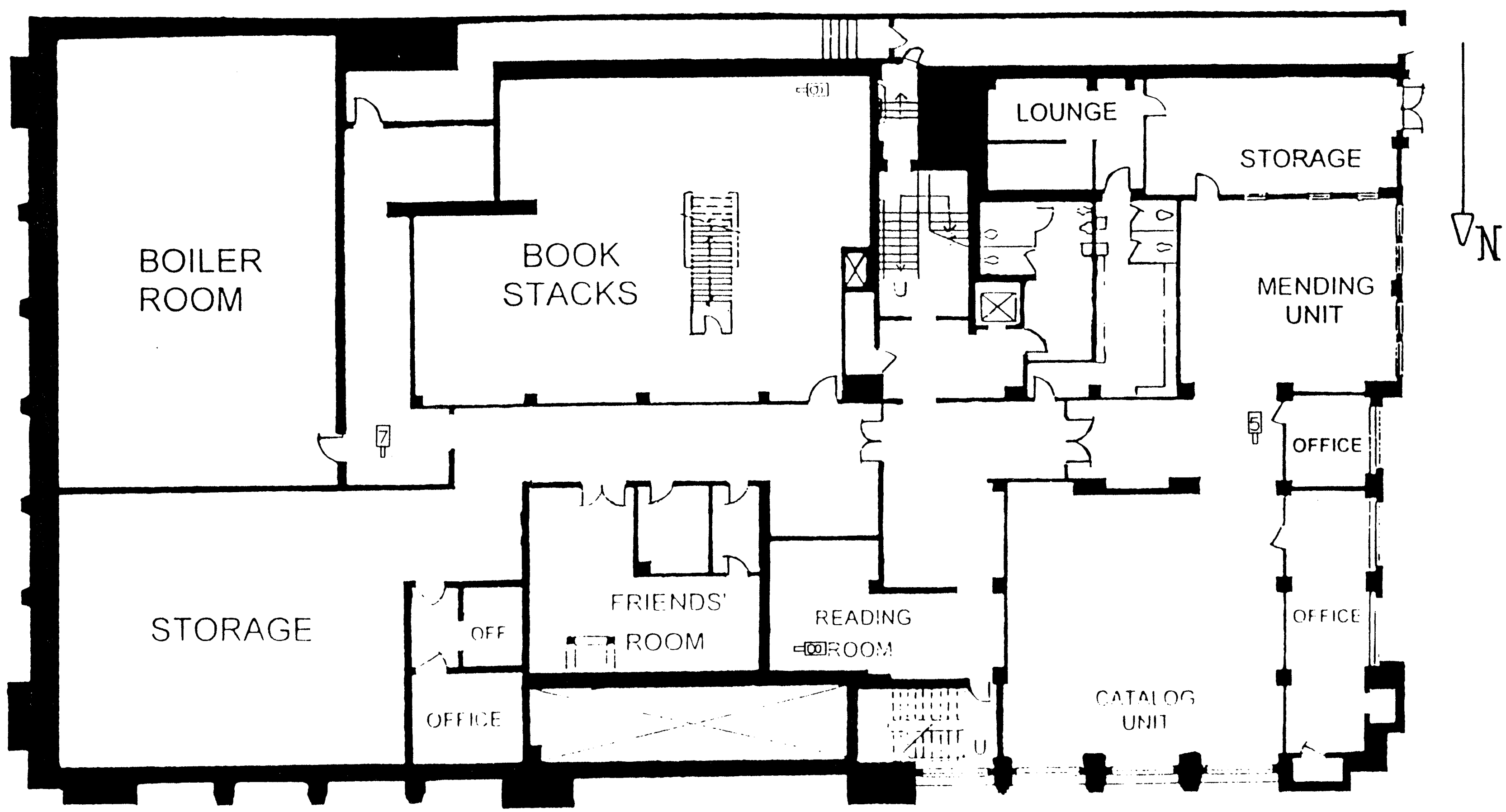

Fig. A.10 Test No. 14: Basement Test

APPENDIX B

FREQUENCY DOMAIN RESPONSE

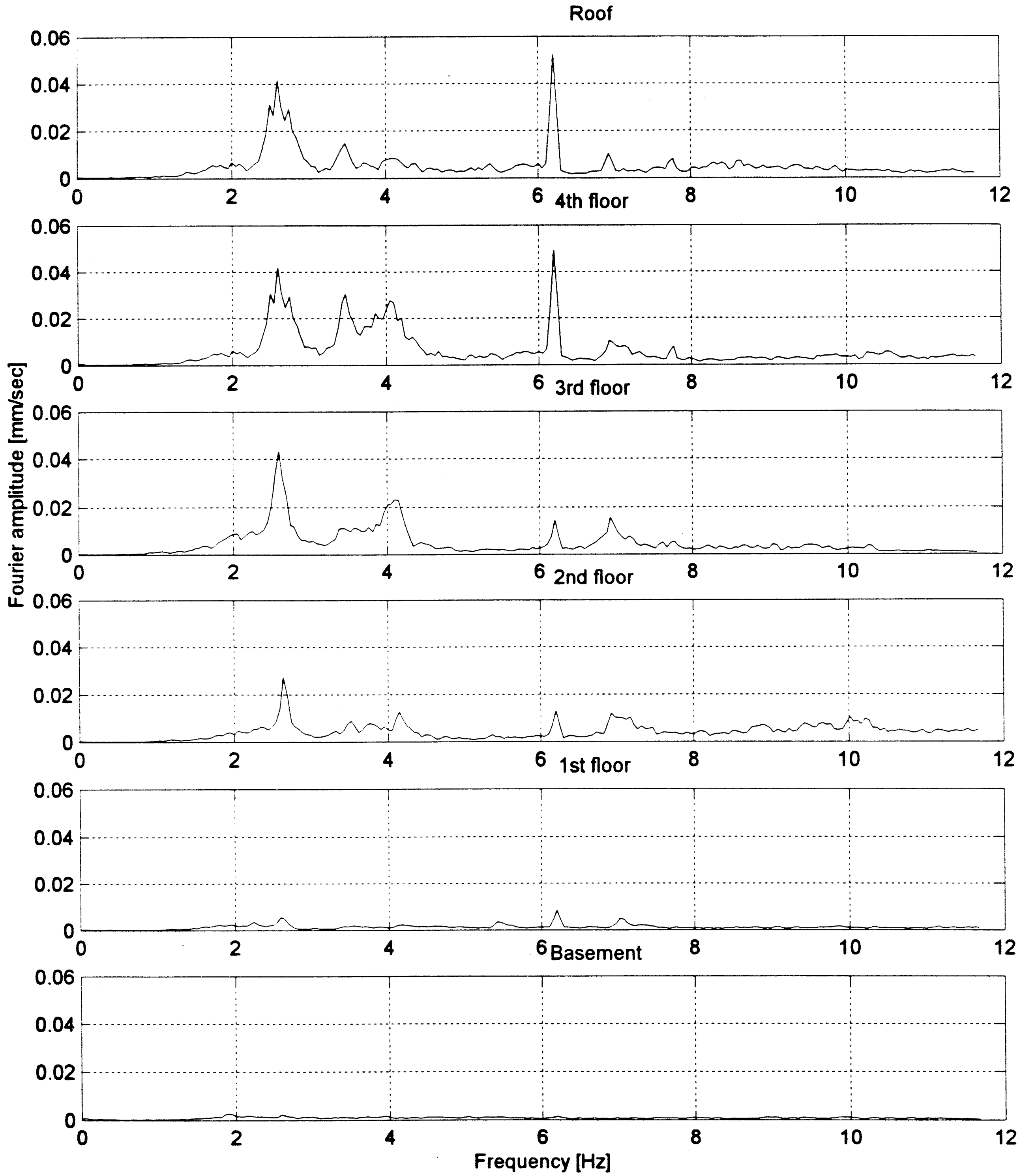

Fig. B.1 Fourier Amplitudes for N-S Translation of Floors

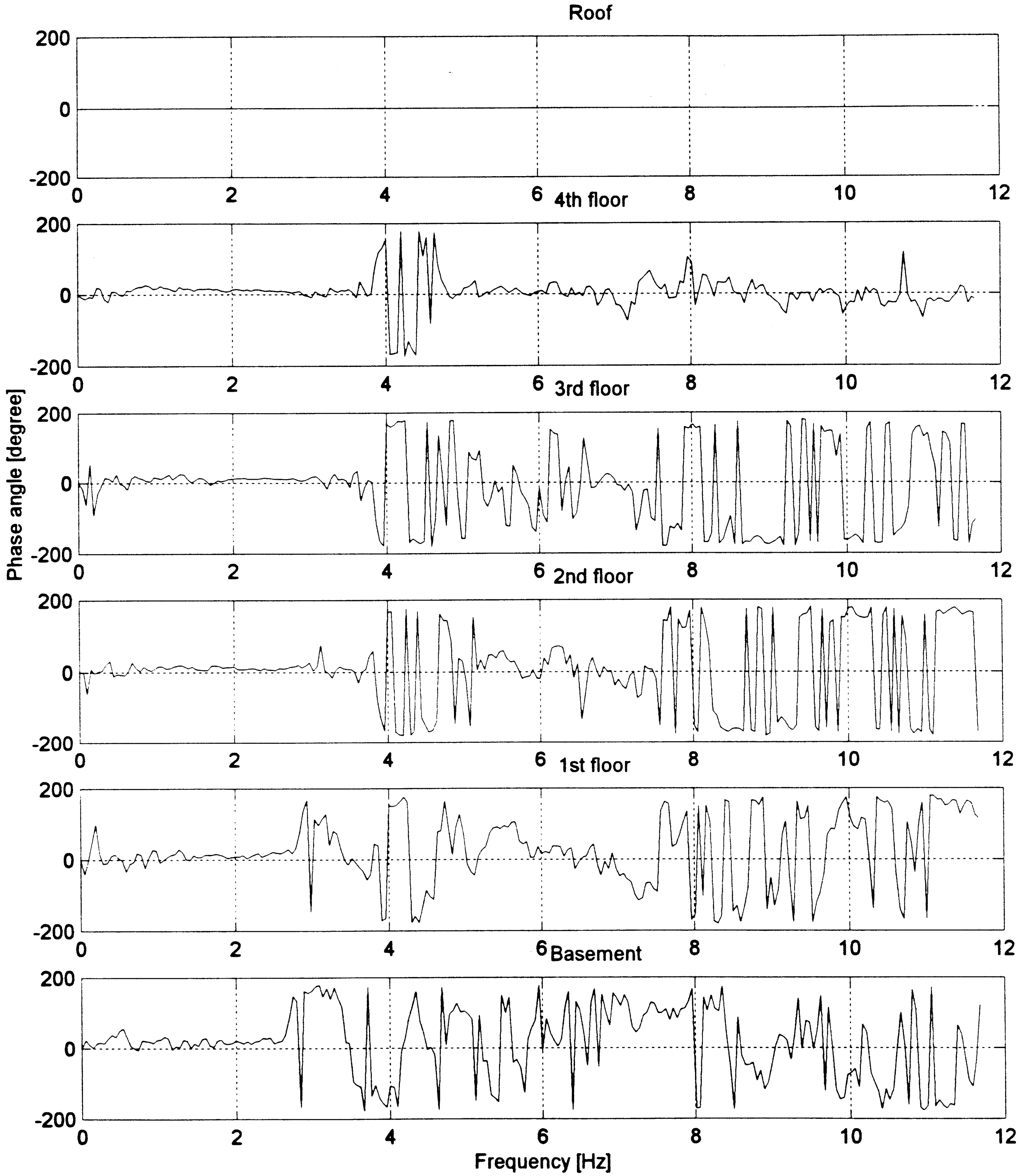

Fig. B.2 Phase Angles for N-S Translation of Floors

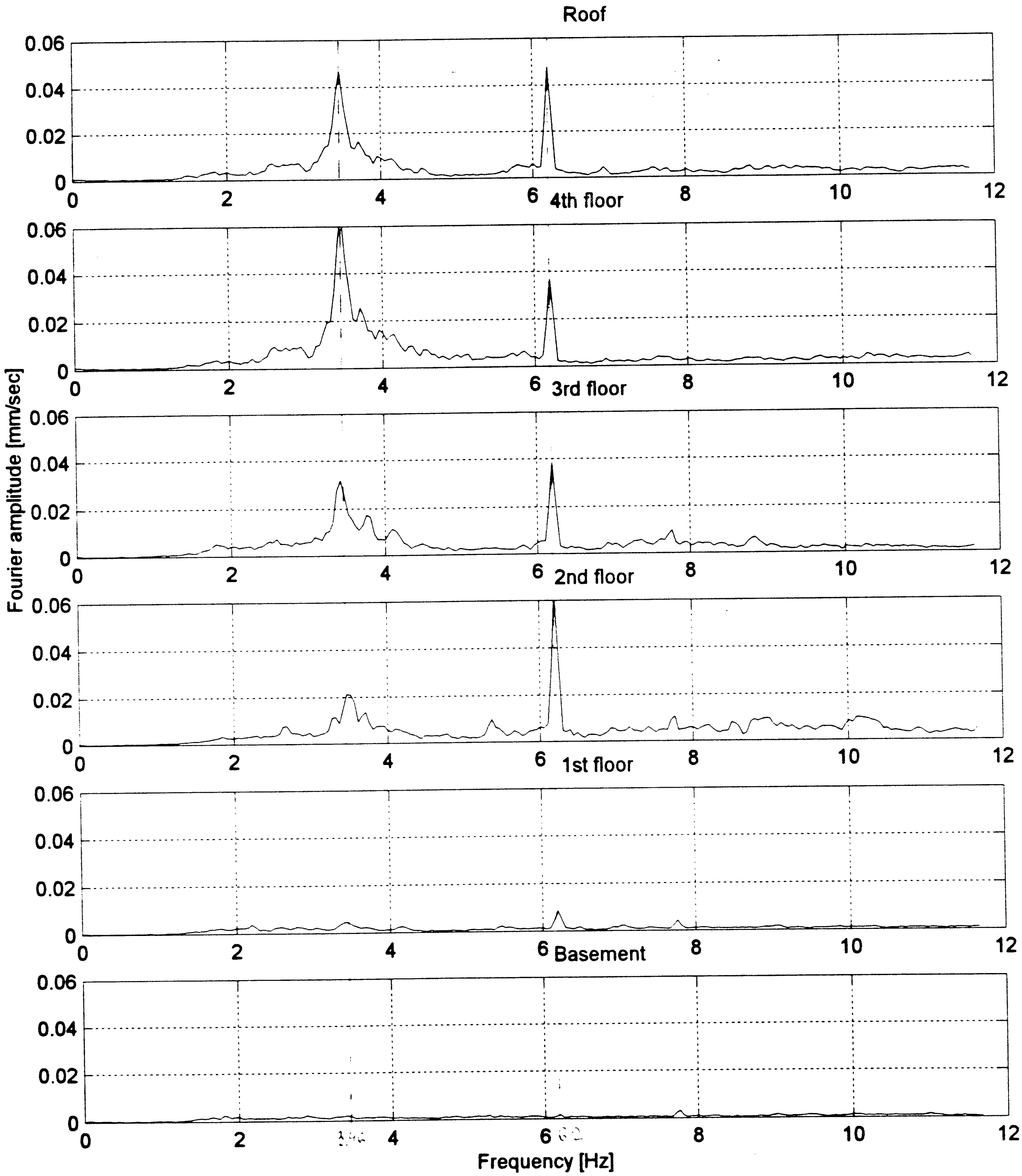

Fig. B.3 Fourier Amplitudes for E-W Translation of Floors

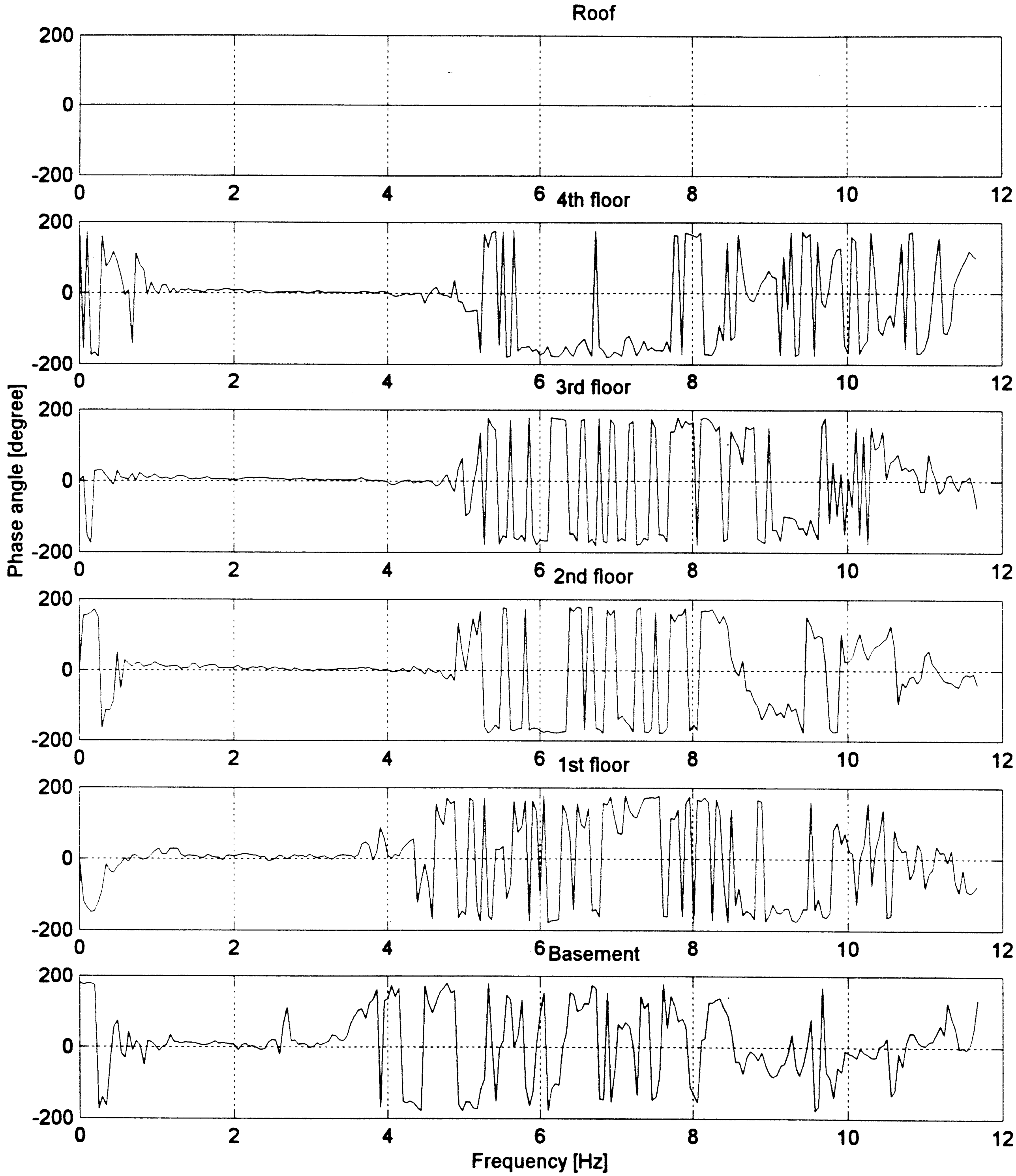

Fig. B.4 Phase Angles for E-W Translation of Floors

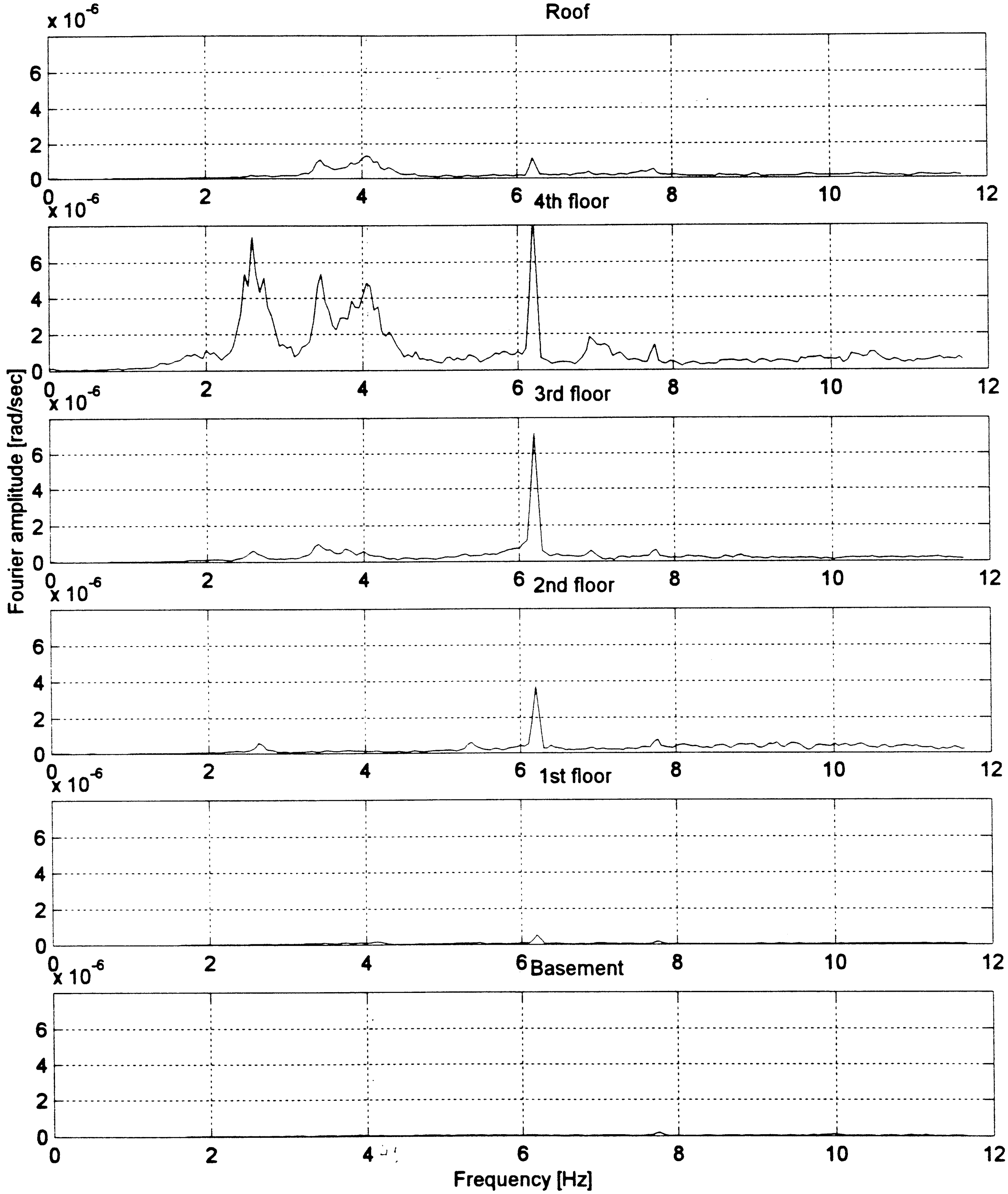

Fig. B.5 Fourier Amplitudes for Floor Rotations

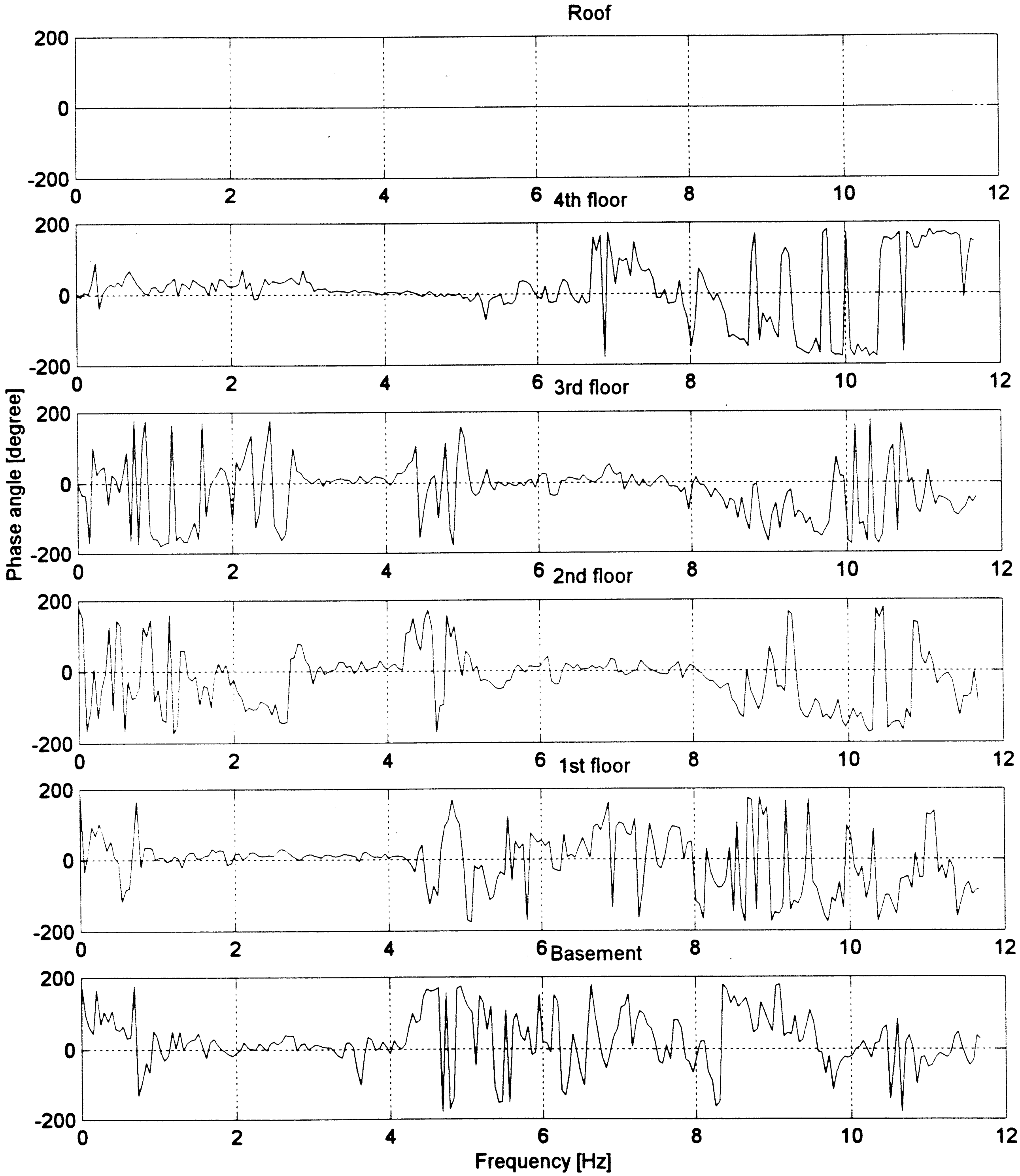

Fig. B.6 Phase Angles for Floor Rotations

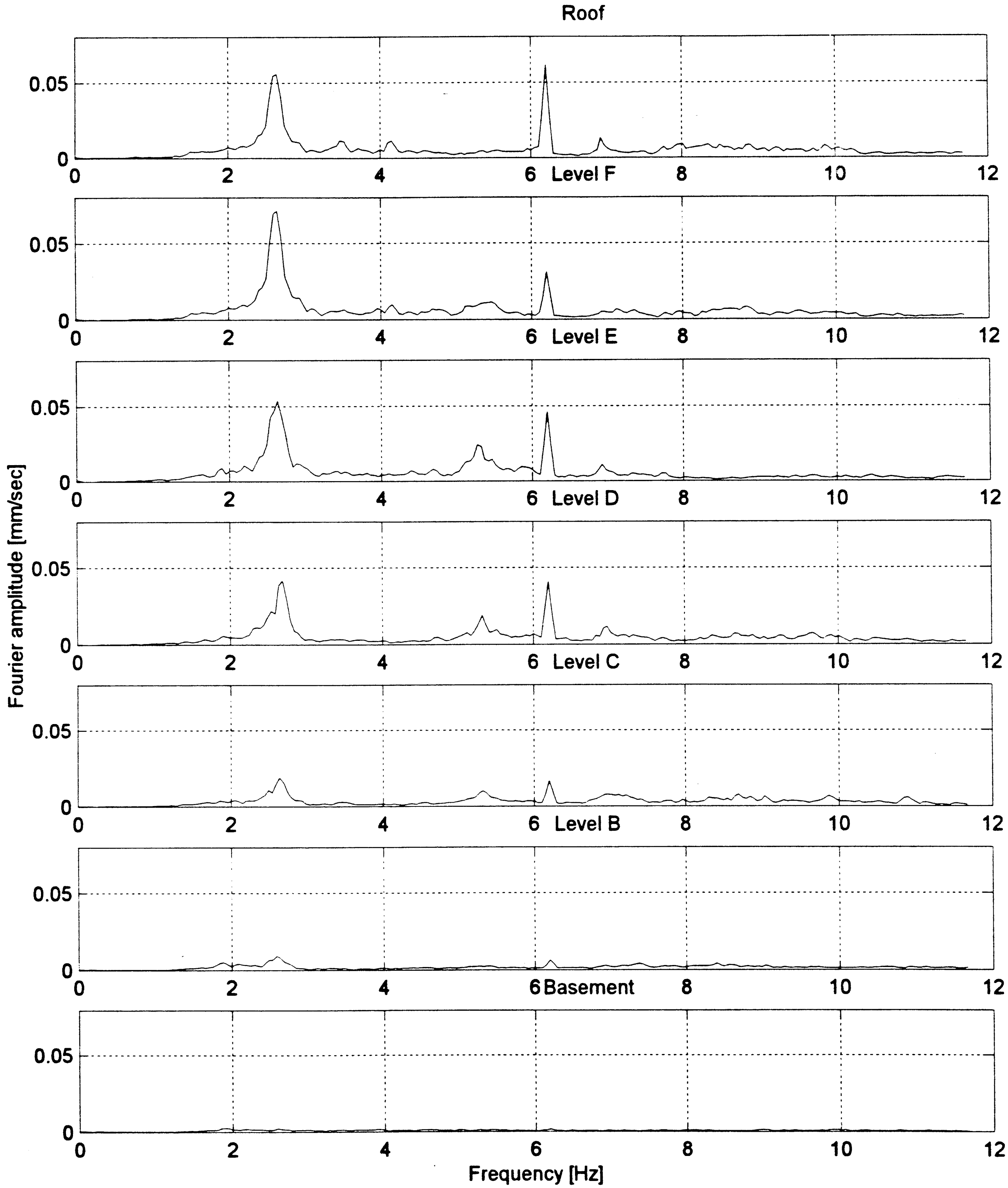

Fig. B.7 Fourier Amplitudes for N-S Translation of Stacks

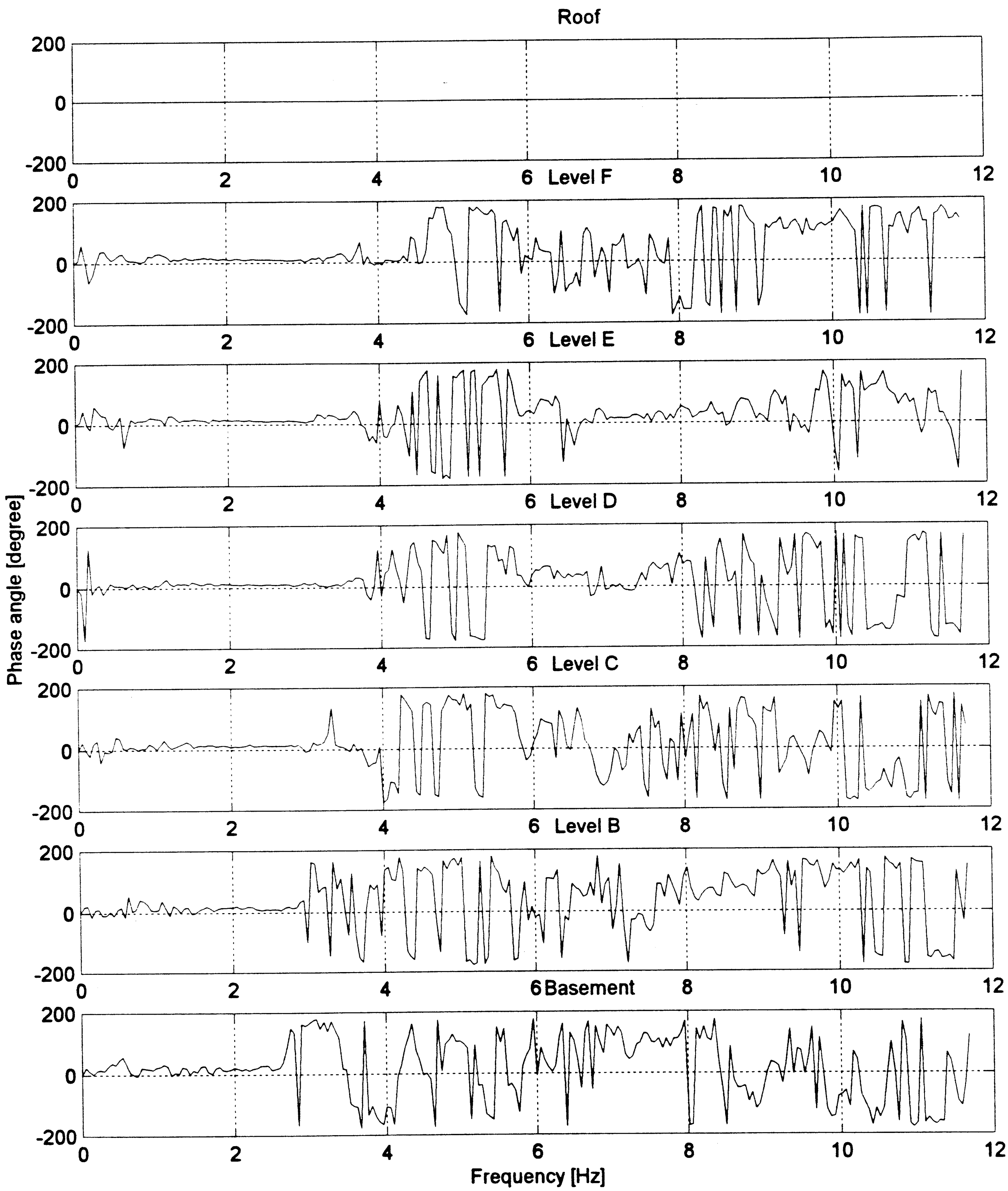

Fig. B.8 Phase Angles for N-S Translation of Stacks

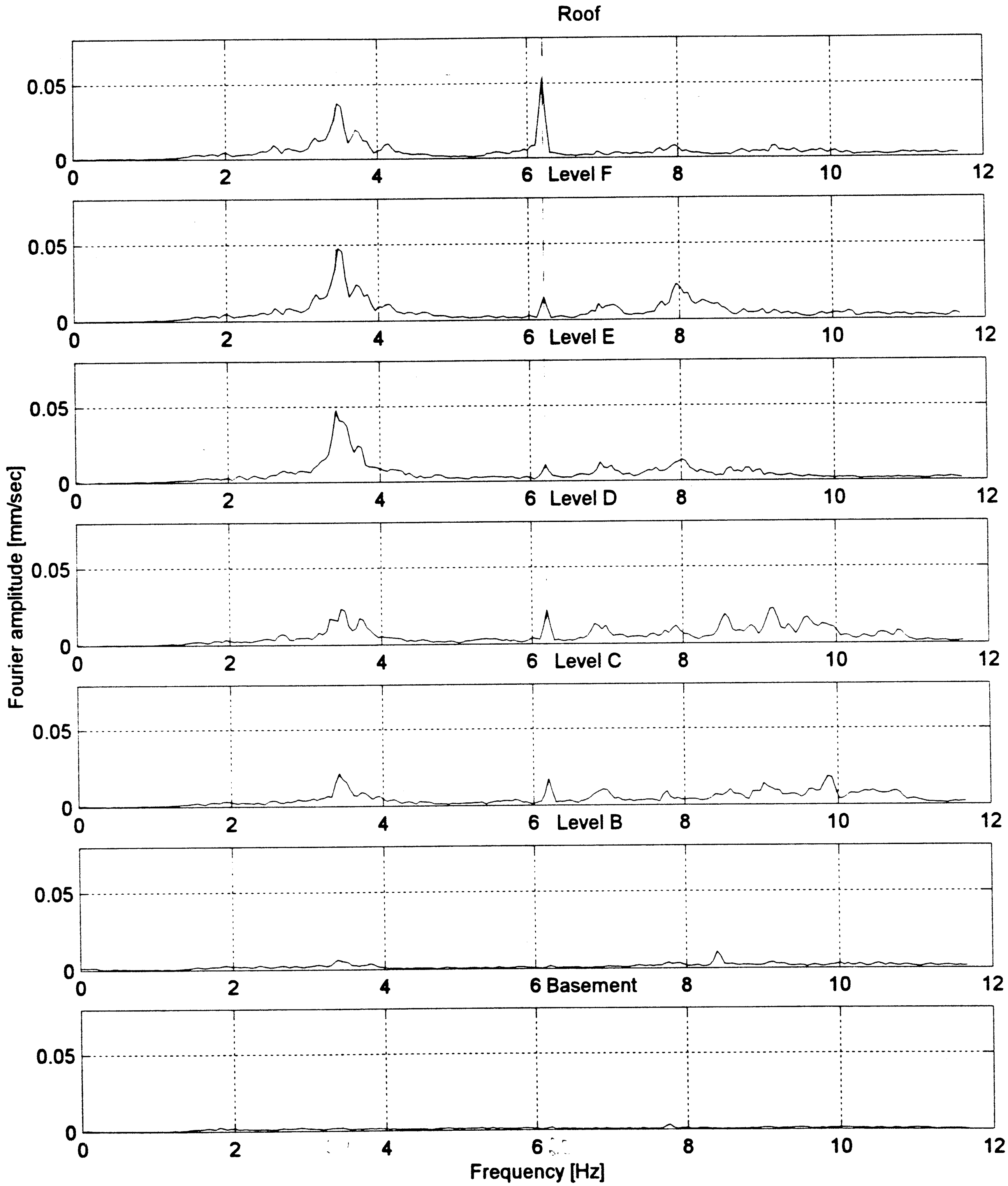

Fig. B.9 Fourier Amplitudes for E-W Translation of Stacks

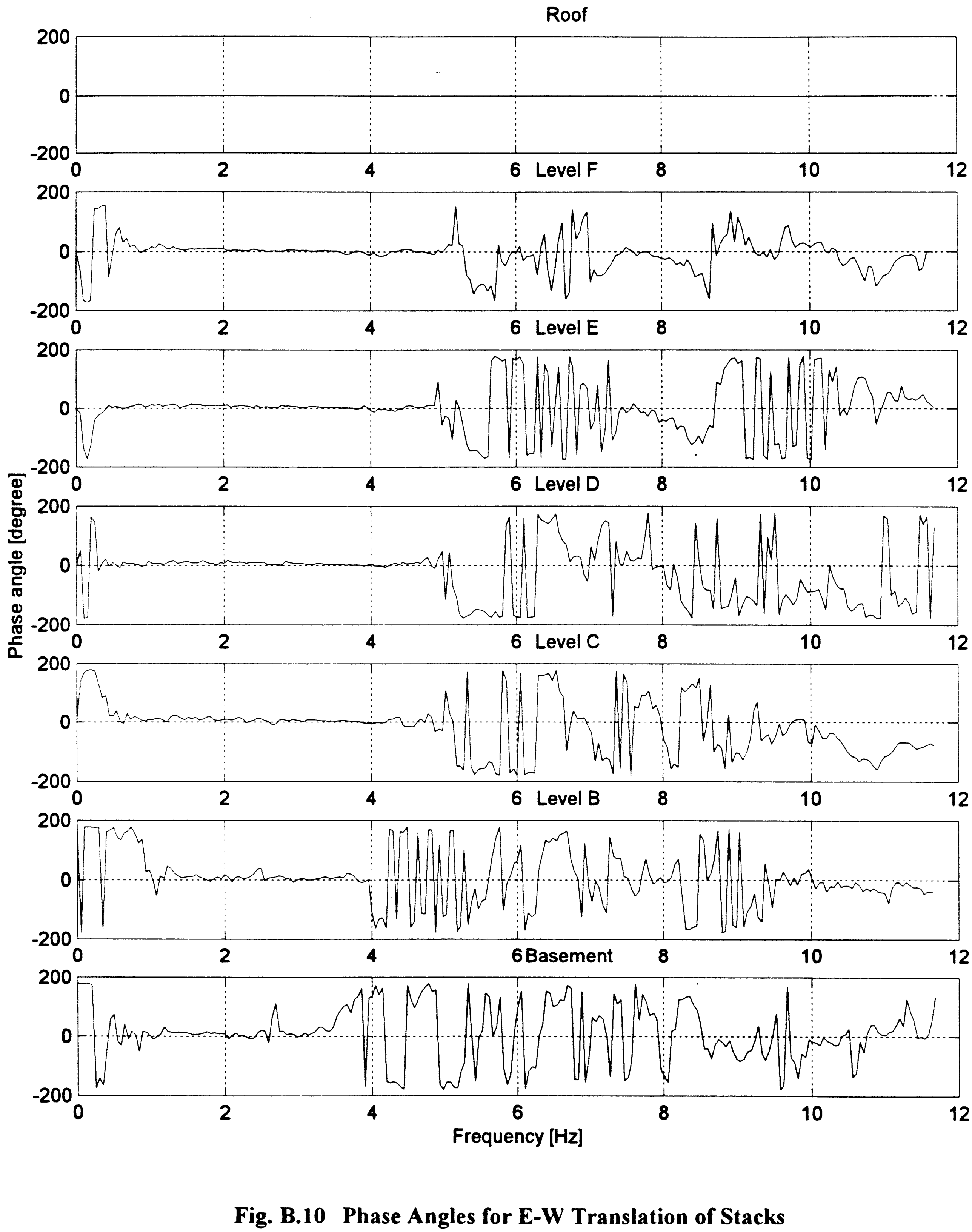

Fig. B.10 Phase Angles for E-W Translation of Stacks

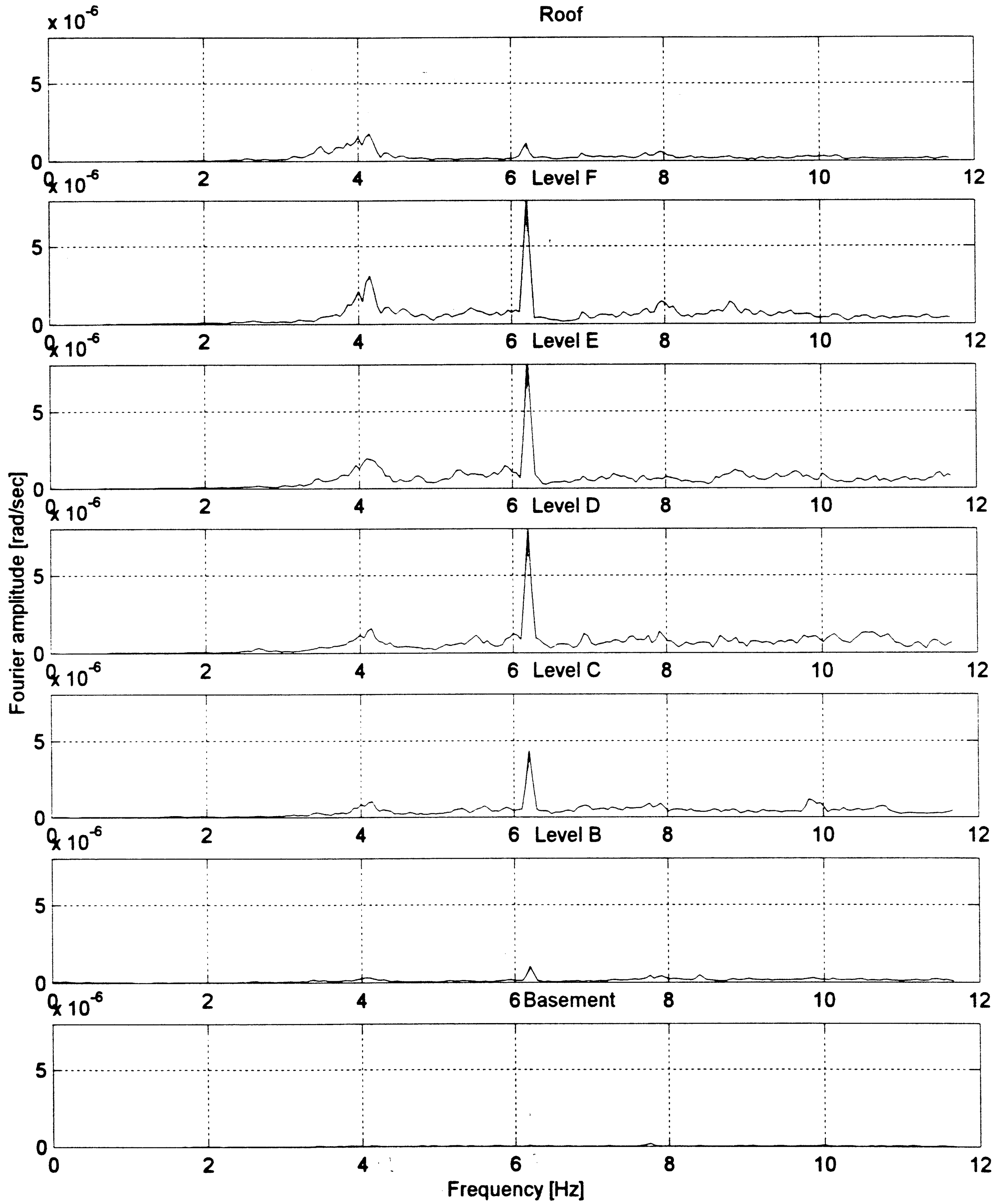

Fig. B.11 Fourier Amplitudes for Stacks Rotations

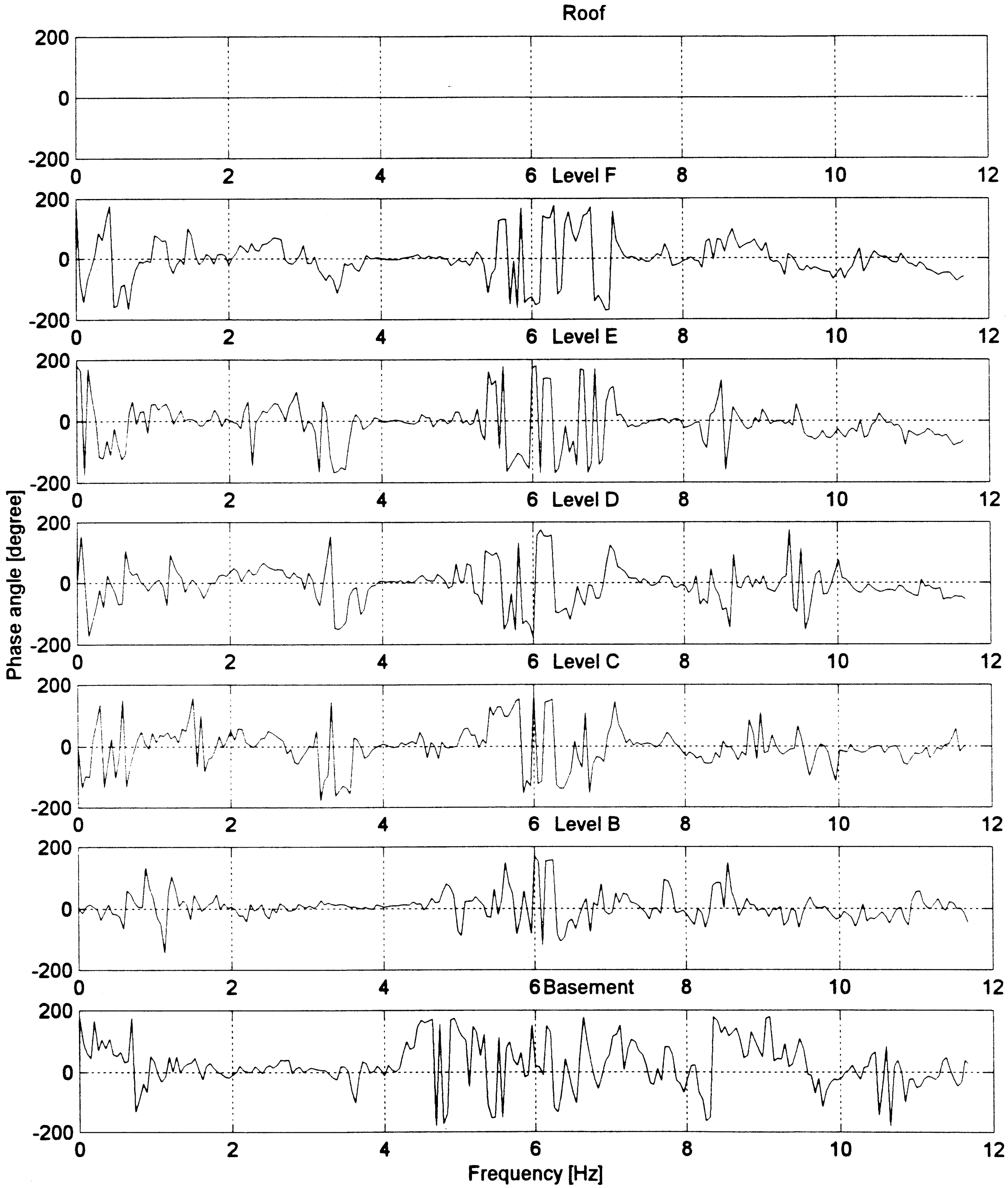

Fig. B.12 Phase Angles for Stacks Rotations