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MEASURED VIBRATION RESPONSE CHARACTERISTICS OF FOUR RESIDENTIAL STRUCTURES EXCITED BY MECHANICAL AND ACOUSTICAL LOADINGS

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16. Abstract

Modal patterns, acceleration levels, and spectra resulting from mechanical point load excitation and acoustical excitation of four residential structures are described. Also included are examples of noise-induced rattling of hanging decorative objects. Airplane-noise-induced building responses are compared with responses necessary to induce rattling and with forced sinusoidal responses. Measured indoor and outdoor noise spectra induced by airplanes and noise reduction characteristics of two houses are described for overflights of both propeller-driven and turbofan-powered airplanes.

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SUMMARY

Measured vibrational response characteristics of four single-family residential structures for mechanical point load excitation and acoustical excitation are presented. Low-frequency structural responses and modes were associated with the main structural members of the buildings and involved structural interactions between adjacent walls and rooms. Higher frequency responses and modes were associated with individual wall-panel responses, such as those between vertical wall structural members. The low-frequency responses were typical of those induced by sonic-boom excitation and the higher frequency responses were typical of those induced by airplane flyover noise.

Results from the mechanical point loadings also indicated a linear response over the range of loadings generally encountered with normal airplane operations for both the low- and high-frequency structural acceleration responses. The similar acceleration responses and mode shapes indicated for the different types and styles of houses used in the studies are believed to result from the uniformity in spacing, size, and length of structural members.

Examples of a nonlinear response phenomenon are presented which were associated with the onset of rattling of objects in contact with the vibrating structures.

Noise reductions as determined from measurements of airplane noise spectra inside and outside of two test houses were similar for the different styles and types of houses used and were associated with the vibrational response behavior of the intervening structure.

Acceleration responses induced by airplane noise are compared with acceleration levels necessary to effect rattling of wall-mounted objects and rattling was confirmed for typical airplane overflights. A comparison of airplane-noise-induced building responses with forced sinusoidal response data indicated that predominant responses in the airplane-noise-induced vibrations coincided with resonant response peaks in the sinusoidal response curves as would be expected. From results of these studies, it was determined that

mechanical sinusoidal excitation provides a useful tool for predicting both wall acceleration levels for the onset of rattling of hanging objects and predominant building structural responses associated with acoustical excitation from airplane overflights.

INTRODUCTION

The problem of noise has gained national attention as one of the unwanted byproducts of our technological advances. Noise has been ranked with air and water pollution as undesirable pollutants plaguing modern societies. The Langley Research Center of the National Aeronautics and Space Administration has for several years been actively engaged in studies of noise problems associated with aircraft operations and sonic-boom phenomenon (for example, refs. 1 and 2). One area of considerable concern is the accelerated growth and increasing severity of the noise problem which involves residential structures and the comfort of the occupants. Associated with this noise problem are the vibrations of the structure produced by external noise which is subsequently transmitted through the structure to the interior of the dwelling. Since buildings are structures having many components which are readily excited and may be coupled, the entire structure responds as a complex multimodal vibrating system. As a result of these structural vibrations, a person inside the house can sense noise that impinges on the external surfaces of the house structure through three different phenomena: the noise transmitted through the building walls; the vibrations of the primary components of the building such as the floors, walls, and ceilings; and the radiated noise from rattling of secondary decorative objects, such as dishes, ornaments, and shelves, which are set in motion by the vibrations of the primary structure.

Most of the available acoustical literature on house structures or components deals with areas such as transmission loss or noise reduction, partition design, and sound insulation (refs. 3 to 7). Some general information on the structural vibration characteristics of house structures is presented in references 8 and 9; however, more specific data are not as readily available. In view of this relative scarcity of detailed data dealing with the vibration characteristics of house structures, a series of experiments was undertaken as part of the overall studies of references 1 and 2 to define some of the response properties of house components and to evaluate their responses to airplane noise excitation.

The purpose of this report is to compile and present some representative data on the house structures used during the studies of references 1 and 2. These data are believed to be of general significance regarding airplane noise and sonic-boom exposure problems.

APPARATUS AND TEST PROCEDURE

Test Structures

In the experimental studies of the present report, four residential structures were utilized: two at Edwards Air Force Base, California, and two at NASA Wallops Station, Virginia. All four structures were single-family dwellings which were furnished with the usual household items including couches, chairs, tables, carpeting, and decorative items such as drapes, ornamental plaques, mirrors, and pictures. Photographs, floor plans, and construction details of the four houses are presented in figures 1 and 2. The houses at Edwards were constructed of Douglas fir and those at Wallops were constructed of pine.

Edwards Air Force Base structures.- Shown in figure 1(a) are the two structures of standard frame construction used for the sonic-boom and flyover noise studies at Edwards Air Force Base, California. The houses are precut designs which have been mass produced and are considered to be typical of contemporary midwestern construction. These two structures were specifically built at Edwards for the sonic-boom studies of reference 1 and were approximately 2 years old at the time of the present study. Test structure 1 (fig. 1(b)) was a one-story house with three bedrooms, two baths, living room, kitchen, and dining-family room and had a total living area of 112 m^2 (1205 ft^2). Test structure 2 (fig. 1(c)) was a two-story house with four bedrooms, two and one-half baths, living room, dining room, kitchen and family room and had a total living area of 178 m^2 (1915 ft^2).

Wallops Station structures.- In figures 2(a) and 2(b) are shown the two houses used in the airplane flyover noise evaluation studies at Wallops Station. These houses, which were approximately 20 to 25 years old, were part of a housing development. Test structure 3 (fig. 2(c)) was a six-room brick-veneer house with three bedrooms, living room, dining room, kitchen, and one bath and had a total living area of 68.7 m^2 (740 ft^2). Test structure 4 (fig. 2(d)) was a six-room frame house with three bedrooms, living room, dining room, kitchen, and one and one-half baths and had a total living area of 81.2 m^2 (874 ft^2).

Instrumentation and Test Methods

Edwards Air Force Base structures.- A permanent magnet shaker, capable of a maximum vector force of 111 N (25 lbf), was used to excite the test houses. The shaker was attached to hard points (over studs or joists) on either the walls or floors of the structures with a vacuum plate attachment in series with a force gage. A crystal accelerometer was placed at selected locations on the walls of the building to determine the vibratory motion. The accelerometer output, in conjunction with the input signal, was used to obtain a Lissajous figure on an oscilloscope to determine a resonant condition defined as a 90° phase shift between the two signals. A hand-held velocity probe was used to survey the structure to determine relative phase of motion over the structure for locating node lines in defining mode shapes. Approximate response frequencies determined from sonic-boom tests (ref. 1) served as a guide in defining the frequency band of interest in searching for a resonance.

The shaker-induced responses of the buildings were recorded on magnetic tape by using existing instrumentation from the sonic-boom program. Manual frequency sweeps at a constant input force level were made in test structure 1. In both test structures, sinusoidal tests at selected frequencies were made at peak-to-peak force levels of 71.2, 53.4, and 35.6 N (16, 12, and 8 lbf). Reference 1 presents a complete description of the accelerometers, microphones, strain gages, and recording equipment used in the sonic-boom program.

Wallops Station structures.- Vibration equipment and instrumentation used during the Wallops studies were more automated than those used at Edwards. The shaker was controlled by a sweep oscillator operating through a power amplifier. The force output of the shaker measured with the force gage was used as a servo signal to the sweep oscillator to maintain automatically a constant input force with frequency. The output of a crystal accelerometer was automatically recorded against frequency on a calibrated graphic level recorder. The vibration modal patterns of the structures were determined manually as previously described.

During the overflight program at Wallops, vibration levels induced by the airplane noise were in many instances sufficiently large to cause ornamental plaques on the walls to vibrate. Therefore, special vibration tests were performed to study the conditions under which rattling of the plaques and other objects would occur. The wall acceleration levels at which rattling was initiated were determined at selected frequencies by increasing the input force level until rattling was heard. The acceleration level of the wall at a location between the plaques was then recorded. The ornamental plaques and mirror involved in the studies are illustrated in figure 3. Each plaque measured 50.2 by 14.6 cm $\left(19\frac{3}{4}\text{ by }5\frac{3}{4}\text{ in.}\right)$ and had a mass of 0.676 kg (0.0463 slug); the mirror measured 71.1 by 61 cm (28 by 24 in.) and had a mass of 6.5 kg (0.444 slug). Figure 3(a) shows the plaques in position on the north living room wall of test structure 3, and figure 3(b) illustrates the method used to attach the plaques to the wall. A photograph of the mirror is presented in figure 3(c), and the hanger detail is illustrated in figure 3(d). To determine the effect of different mirror hanging angles on the rattling behavior, the mirror was suspended with the hanger flat against the wall (mirror angle of 1.30°, fig. 3(d)) and with the hanger set out from the wall 1.27 cm (1/2 in.) (mirror angle of 3.14°). The positions of the ornaments, mirror, and shaker are indicated in the floor plans in figures 2(c) and 2(d).

RESULTS AND DISCUSSION

Results of the experimental vibration tests performed with the four residential house structures are presented in figures 4 to 25. Included in the results are the forced vibration responses throughout the structures for various vibratory input locations. Also included are measured mode shapes of the structures for several of the resonant response peaks at frequencies determined from the sinusoidal sweep data. Acceleration thresholds are given for rattling of wall-mounted mirror and ornamental plaques in two of the test houses. Typical airplane-induced noise data inside and outside of houses are presented for two overflights and the associated noise-induced wall accelerations are compared with acceleration levels of the plaque rattle boundaries determined by sinusoidal tests and with forced sinusoidal response data.

Vibration Data for Edwards Test Structure 1

Presented in figure 4 are typical wall and floor acceleration responses and the associated sound pressure levels (noise) in bedroom 1 of Edwards test structure 1. The results are for a constant force excitation of the east wall of bedroom 1. The data indicate that at low frequencies the spectrum of floor motions correlate with the sound pressure spectrum environment, whereas the higher frequencies in the spectrum of wall motions correlate with the higher frequency portion of the sound spectrum in the room. The resulting noise spectrum is, of course, vibration induced since there is no noise source other than the forced vibration responses of the structures.

Experimentally determined modes and frequencies of portions of test structure 1 are presented in figure 5. With sinusoidal excitation, the first resonance of the east wall of bedroom 1 occurred at a frequency f of 16.6 Hz. The associated mode was a diaphragm motion with nodes at the edges of the wall. Further velocity-probe surveys of adjacent walls, floors, and ceilings and of adjoining rooms revealed that a major portion of the north end of the test structure was vibrating at the same time, as illustrated by the sketches in figure 5. Although the shaker was relocated and retuned to determine that the north bedroom wall and floor had resonant frequencies of 21.4 Hz and 26.0 Hz, respectively, the mode shapes were readily determined during excitation of the east wall at 16.6 Hz. Conversely, during excitation of the north wall or the floor at their resonant frequencies, one could determine the mode shapes of the other structural surfaces equally as well. Thus, the mode surveys revealed that what appeared to be a fundamental wall mode of a room was actually part of the more complex overall interaction of the building's modal behavior as indicated in figure 5. Such data indicate that the structural elements that comprise the complex framework of the house do not respond as isolated components but respond as part of the complex interconnected system so that the excitation of one part of the house is transmitted to other nearby house components.

As a result of sonic-boom excitation, the bedroom 1 floor and east wall responded predominantly at about 21 Hz and 16 Hz, respectively, which are in good agreement with the resonant frequencies determined by sinusoidal excitation.

Vibration Data for Edwards Test Structure 2

Structural vibration data and associated sound pressure levels (noise) for Edwards test structure 2 (two-story house) are presented in figure 6. In figure 6(a), acceleration levels for various locations in test structure 2 are plotted as a function of the excitation force at a frequency of 21.2 Hz, a resonance of the dining room wall. The data symbols are keyed to the location of the measurement in the building. As shown in the building floor plan, the circles are for a location on the east dining room wall near the input force, the squares are for a location on the north wall of bedroom 1, the triangles are for a location on the kitchen floor, and the diamonds are for a location in the center of the dining room floor. The significance of the data is that the accelerations for all the locations are linear with input force for the range of input forces used in the tests.

Resonant frequencies of other dining room areas in test structure 2 were 21.4 Hz for the north wall, 21.2 Hz for the east wall, and 21 Hz for the floor. For the living room, the frequencies were 22.2 Hz for the east wall and 26.9 Hz for the south wall. The closeness of the resonant frequencies of these structural sections partially explains why the vibration excitation of one area readily induces responses of adjacent areas of the house.

Figure 6(b) presents the sound pressure levels (noise) resulting from the structural vibrations induced during discrete frequency excitation of the east wall of the dining room at 21.2 Hz. As for the acceleration responses, the symbols are keyed to the locations in the test structure. The sound pressure levels range from 90 to 95 dB near the source of excitation to 70 dB at about 5 to 6 m (15 to 20 ft) away in the center of the family room, and the level is proportional to the input force in the range of input forces used. It may also be noted that the levels in bedroom 1 are comparable to those in the dining room.

The building response modes for part of test structure 2 are presented in figure 7. The mode shapes are similar to those for the one-story test structure 1 (fig. 5). As indicated in figure 7, the north bedroom wall, the bedroom floor (dining room ceiling), and the other walls (no mode shape shown) were vibrating in the fundamental motion as a result of the discrete frequency excitation of the dining room wall at 21.2 Hz.

From analyses of the response data from the sonic-boom studies (ref. 1), it was noted that low-amplitude, higher frequency signals were often superimposed on the lower frequency structural responses. During the modal vibration survey tests, the sources of the higher frequency responses were attributed to high-frequency panel modes similar to the panel mode at 405 Hz on the east dining room and bedroom 1 wall as shown in figure 8. This mode, for example, had a full wave length between the wall studs along the width of the rooms and five horizontal nodes in the vertical direction from the floor of the dining room to the ceiling of the upstairs bedroom. In this particular mode the wall studs in both the dining room and bedroom were nodal lines as were the juncture of the wall, floor, and ceiling in both rooms.

Vibration Data for Wallops Test Structure 3

The experimental vibration response measurements of Wallops test structure 3 are presented in figure 9. Included are mode shapes associated with several of the resonances determined from the sinusoidal sweep data.

The acceleration response shown in figure 9(a) is for the west living room wall of test structure 3. The frequency range for the automatic frequency sweep test did not extend below 20 Hz and the first indicated resonance at 27 Hz was not the fundamental response of that wall; however, subsequently the first mode was manually determined to be at 14 Hz. The mode (shown in fig. 9(b)) at 27 Hz has an $m = 6, n = 2$ shape where m and n are the number of node lines in the horizontal and vertical directions, respectively. Mode shapes associated with several of the other resonances below 100 Hz were not obtained for this wall since the response was such a low level at distances from the input force locations and it was difficult to trace the node locations. It should be noted that the trend of the response data in figure 9(a) for a constant-amplitude sinusoidal input force is, in general, to increase with frequency at about 6 db/octave as represented by the dashed reference line in the figure.

Figure 9(c) presents the acceleration response for a location on the large steel casement window in the west living room wall. The major difference between the window response and the wall response is that for the window the higher frequency peaks appear to be much sharper; this response indicates lower damping as might be expected for such a measurement location. The large peak at about 14 Hz is the first mode of the wall mentioned previously.

Response data for excitation of the north living room wall are presented in figure 9(d). The lower frequency range of excitation extends to 10 Hz and a resonant peak occurs at 15 Hz. The lower frequency modes associated with several of the resonant peaks are presented and discussed in connection with the rattle studies given in a subsequent section. It should be pointed out, however, that the modes of the north wall were easier to determine than those of the west wall. The two cutouts (window and door) in the north wall evidently permitted greater wall motion in the lower modes. It should also be indicated that the relatively large response at 55 Hz (no mode shape determined) was associated with strong, audible vibrations of the metal radiant heaters along the baseboard of the walls of the room.

In the response spectra of the north wall, maximum response peaks occurred between 400 and 600 Hz. The mode shape associated with one of these responses is illustrated in figure 9(e). The mode was a panel mode at 540 Hz which was characterized by a vibration pattern having a half-wave between wall studs (studs were node lines) and nine horizontal nodes from floor to ceiling.

Acceleration response spectra for walls in bedrooms 1 and 2 of test structure 3 were similar to those for the living room walls but differed slightly in resonant frequencies and level of response. The higher frequency panel modes in the 500-Hz region were also found in these areas of the house.

The structural interactions found between adjacent walls and rooms in the Edwards test structures 1 and 2 were not evident in the vibration behavior of the Wallops test structure 3. It is believed that the interactions were less pronounced because this house had a concrete slab foundation and more massive brick-veneer walls.

Vibration Data for Wallops Test Structure 4

Vibration response spectra of portions of Wallops test structure 4 are presented in figures 10 and 11. In figure 10, response data are presented for sinusoidal excitation of the middle of the west living-room—dining-room wall. The acceleration response is measured approximately 10 cm (4 in.) above the input force location. The spectrum shows the large number of resonances existing in the frequency range of the test. For this particular wall acceleration spectrum, resonances below 100 Hz occurred at 12, 15, 23, 32, 40, and 65 Hz. As indicated in the previous section, the slope of the response spectra for practically all measurement locations in the house structures was about 6 dB/octave. The 6-dB/octave reference line in figure 10 indicates that this trend is also evident for the response on the west wall and was noted in other areas of test structure 4.

Mode shapes associated with several of the response peaks of figure 10 are presented in figure 11. For instance, the 12-Hz resonance has an $m = 2, n = 2$ mode shape (fig. 11(a)); however, the adjacent and opposite walls, the floor, and the ceiling were also vibrating in a diaphragm manner. The second resonance at 15 Hz has an $m = 4, n = 2$ mode shape (fig. 11(b)), and the 23-Hz resonance has an $m = 6, n = 2$ mode shape (fig. 11(c)). At the 65-Hz resonance an $m = 12, n = 2$ mode shape occurred (fig. 11(d)). No mode shapes were determined for the 32-Hz and 40-Hz resonances.

As was true for test structure 3, response spectra in bedrooms 1 and 2 of test structure 4 were quite similar to the spectrum shown for the living room. In bedroom 1, for instance, the fundamental resonance of the north and east walls and the associated diaphragm motions of the remaining room surfaces occurred at 9 Hz and 9.8 Hz, respectively. Resonant responses at 22 Hz and 42 Hz for the north wall had $m = 4, n = 2$ and $m = 6, n = 2$ mode shapes, respectively. In bedroom 2 the south and east walls had $m = 2, n = 2$ mode shapes at 8.7 Hz and 11 Hz with the structural interactions of the other room surfaces also evident for each of these resonances. The fundamental frequencies generally fall within 2 or 3 Hz (20 to 30 percent) for walls varying in length from 7 m (23 ft) to about $3\frac{1}{2}$ m (12 ft). (See table I.) Such results indicate that the fundamental wall response for walls of the same height is relatively insensitive to changes in the length of the wall. The high-frequency responses of the wall panels in the frequency range from 400 to 600 Hz, which were similar to the responses occurring in the Edwards test structures 1 and 2 and in the Wallops test structure 3, were also measured in test structure 4.

TABLE I.- FREQUENCIES OF VARIOUS WALLS IN TEST STRUCTURE 4

House section	Wall length		Experimental frequency, Hz
	meters	feet	
LR west wall	7	23	12
BR 1 north wall	4.3	14	9
BR 1 east wall	3.6	11.8	9.8
BR 2 south wall	4.0	13	8.7
BR 2 east wall	3.4	11.2	11

General Structural Responses

Structural interactions.- The results from the sinusoidal vibration tests indicated that the fundamental responses of the various wall and floor sections in a given house were in a relatively narrow frequency band. Thus, when a particular section was vibrated at its fundamental response, vibrations of the various other house sections generally occurred as a result of (1) the closeness of their resonant frequencies and (2) the physical structural contact of the sections with each other. These interactions, which may involve both the structure and the volume of air inside the rooms of the house, resulted in preferred vibratory mode shapes.

The vibration interactions found in the house structures are illustrated in figure 12. Illustrated in the left-hand sketch are the interactions for floor vibrations in a one-story house, whereas illustrated in the right-hand sketch are the interactions of the vibrations between stories in a two-story house. In the left-hand sketch, structural interactions between the floor joists under the bedroom and the joists of the adjacent family room are primarily responsible for the vibrations of the family room floor. During the vibrations of the bedroom floor, an alternating moment is transferred through the central floor support which tends to excite the family room floor in opposite phase to the bedroom floor. In the right-hand sketch, the same type of interaction is illustrated for vibrations between stories of a house. The interactions between rooms on the same floor level also take place in a two-story structure, but the second floor also provides interactions in the vertical direction. These interactions in the dynamic response of a house structure when excited at a point are similar to those encountered during sonic-boom excitation for which input loading was transient in nature and impinged on all external surfaces of the house.

Modal responses.- There are several important considerations in relation to the low-frequency vibratory modes of buildings. They are potential damage to the structure, the comfort of people, and the production of noise.

Since the largest portion of the energy of a sonic boom (N-wave) is concentrated at the lower end of the frequency spectrum, the low-frequency structural modes are susceptible to excitation by inputs such as the sonic boom. From the standpoint of potential structural damage, it should be pointed out that the low-frequency modes measured in this study produced larger displacements than the high-frequency modes. However, the assessment of potential structural damage associated with such vibrations is beyond the scope and purpose of this report.

Most of the lower frequency mode shapes ($m = 2, n = 2$ and sometimes even $m = 4, n = 2$ and $m = 6, n = 2$) in all the test structures are generally below the frequency range of hearing for people. However, these modes may still be important subjectively since the motions at these low frequencies can be felt directly or as transmitted motion through chairs, couches, or other household furnishings. It is interesting to note that, although the duration of the vibrations associated with such low frequency modes is relatively short when the structures are excited by either airplane noise or sonic booms, the acceleration amplitudes of these disturbances are all above the threshold of perception and generally above the vibration acceleration levels considered to be unpleasant for steady-state vibrations (ref. 10).

An additional consideration associated with the lower frequency structural modes is that they can be an input to secondary objects, such as mirrors and decorative plaques, in contact with the structure. The response of these secondary objects may, in turn, produce significant noise in the audible frequency range.

In contrast, the higher frequency panel modes are quite audible and are the major mechanism for the re-radiation of external noise to the interior of the house. As previously indicated, the panel modes are associated with the vibrations of the ceiling and interior wall sheathing materials generally between the wall studs (studs are nodes). Although such response modes were noted on the lower frequency structural modes induced by sonic booms, these higher frequency modes are generally more pronounced during airplane flyover noise excitation. Not only may these panel modes be subjectively irritating but they may also induce rattling of objects and thereby worsen the subjective irritation.

From the experimental results several important and common aspects in the trend of the responses of the walls in the test structures were noted. First, the slope of many of the acceleration response spectra in the houses was about 6 dB/octave. This trend of the slope would be expected on the basis of impedance considerations of linear systems (ref. 11). Second, the fundamental frequencies of walls differing in length by about a factor of 2 were within 2 or 3 Hz (20 to 30 percent) of each other. Such a frequency spread is about the same as that predicted for the fundamental mode of a uniform plate (ref. 12) with comparable variations in the plate length. Third, resonant responses having high m number modes occur at relatively low frequencies as compared with the high frequencies associated with the same m number modes for a plate. For example, in Wallops test structure 4, an $m = 12, n = 2$ mode shape of a wall occurred at a frequency of 65 Hz. The ratio of this frequency to the fundamental mode frequency ($m = 2, n = 2$) was 5.4. For a uniform plate with the same dimensions as the wall, the ratio of frequencies for the same m and n number modes is 13.0. Such results indicate that, although the mode shapes of the walls are platelike in appearance and have fundamental frequencies that vary with dimensional changes about the same as a plate, the trend of the frequency of the higher modes does not follow platelike behavior. Fourth, high-frequency wall panel modes in the frequency range between approximately 400 and 600 Hz were found in the different test structures which varied in age from less than a year to about 20 years. Fifth, similar vibration response spectra and mode shapes were found in the different test structures. Although the structures differed in age and style of construction, the general uniformity of spacing, size, and length of structural members and panels in the buildings are believed to contribute to the similarities in vibration behavior.

Rattle Phenomenon

During the study conducted at Wallops Station to evaluate the subjective reactions of people to airplane flyover noise (ref. 2), airplane-noise-induced wall motions of the test residential buildings were sufficiently large to cause ornamental plaques on the walls to rattle. Since these secondary noise sources could have direct bearing on the recorded subjective reactions, vibration tests were also conducted on the two test buildings with special reference to conditions under which rattling of the plaques and mirror would occur.

Plaque vibration data for test structure 3.- Figure 13 presents a typical acceleration response of the north living room wall for a sinusoidal input force level (zero to peak) of 26.7 N (6 lbf). The shaker was located between the door and the window, and the acceleration response of the wall was measured at a point between the plaques (fig. 2(c)). The wall response exhibits a number of resonant conditions throughout the frequency range of interest, three of which were investigated to define their associated mode shapes. These mode shapes as determined from velocity pickup measurements are illustrated in the sketches of figure 14. An $m = 4, n = 2$ mode shape is associated with the 27-Hz resonance, an $m = 8, n = 2$ mode shape with the 48-Hz resonance, and an $m = 8, n = 4$ mode shape with the 72-Hz resonance.

The acceleration levels at which the ornamental plaques on the north living room wall of test structure 3 were first noted to rattle are presented in figure 15. Each level denoted by a data symbol is for a specific input frequency (a resonant frequency), and no information is presented for any intermediate frequencies. The general trend of the data in figure 15 indicates that the acceleration threshold for rattling increases slightly with increasing excitation frequency. However, a relatively higher acceleration level is required for rattling at 72 Hz. In figure 14(c), it is seen that two nodal lines pass through the immediate area of the plaques at this frequency. Thus, an increased wall acceleration at the reference point would be expected to cause the plaques to rattle at that particular frequency.

Plaque vibration data for test structure 4.- Figure 16 presents a typical acceleration response of the north living room wall of test structure 4 for a constant sinusoidal input force level (zero to peak) of 26.7 N (6 lbf). The shaker was located between the door and the window of the north wall and the accelerometer was mounted on the wall between the plaques (fig. 2(d)). As for test structure 3, three strong resonances occur in the frequency range below 100 Hz. These resonant conditions were subsequently investigated to determine their associated mode shapes, and the results are presented in figure 17. As shown in the figure, the wall was vibrating in an $m = 2, n = 2$ mode shape at 22 Hz, in an $m = 6, n = 2$ mode shape at 40 Hz, and in an $m = 6, n = 4$ mode shape at 69 Hz.

In test structure 4, seven different resonant conditions were investigated in determining the vibration levels at which the plaques first begin to rattle. The results are presented in figure 18. As for test structure 3, the acceleration threshold for rattling is seen to increase slightly with increasing input frequency. For the 69-Hz resonance, two nodal lines pass through the immediate area of the plaques (fig. 17(c)). Thus, as for the similar situation in test structure 3, an increase in acceleration level at the reference point is necessary to initiate plaque rattle.

Mirror vibration data for test structure 4.- The responses of the east wall of the living room of test structure 4 and of a mirror mounted on that wall were measured. The acceleration responses of the wall and of the mirror were induced by exciting the center of the west living room wall at a constant frequency of 15 Hz (a resonance of the west wall) over a range of force levels. At this frequency, the induced motions of the east wall (due to structural interaction), although small, were sufficient to cause the mirror to rattle.

Figure 19 presents the acceleration responses of the east wall as a result of excitation of the west wall. The sinusoidal input force level (zero to peak) is normalized to a value of 75.6 N (17 lbf). Data are presented for the wall alone as well as for the wall with mirror hanging at two different angles 1.30° and 3.14° to determine the effect of hanging angle on the rattling of the mirror. Data indicate that the response of the wall alone varies linearly with input force level over the force range studied. However, with the mirror hanging against the wall (mirror angle 1.30°), the wall acceleration response increases abruptly by approximately a factor of 2 at a normalized force level of about 0.62. This is the level at which the mirror begins to rattle, and the increase in wall vibration level is attributed to the mirror impacting against the wall. Above the input level at which impacting first occurred, the response of the wall again varied linearly with force level up to near the maximum value. At that point the response was observed to become erratic. Behavior at higher input force levels was not investigated. Similar behavior was observed for the mirror hanging angle of 3.14° except that the factor-of-2 increase in wall acceleration response occurred at a lower normalized input force level (about 0.40). It is believed that this latter result occurred because the center of gravity of the mirror (due to the particular geometry of the mirror) was more nearly under the mirror attachment point for the larger hanging angle (3.14°) and, thus, less force was exerted against the wall at the contact point at the bottom of the mirror. Consequently, less acceleration of the wall would be required for the onset of rattling of the mirror.

The acceleration responses of the mirror during these tests are presented in figure 20 along with the acceleration response of the wall as a reference. The response of the mirror with the hanger flat against the wall (mirror angle 1.30°) is parallel to the response of the wall alone but at a level approximately 1.6 times higher. At a normalized input force of about 0.7, the response increased abruptly by about a factor of 4 and, then, once again followed a line parallel to that of the wall. At the maximum excitation force level the responses of the mirror also became erratic.

For the 3.14° mirror hanging angle, similar behavior was found. However, for this angle, the acceleration response level of the mirror also increased abruptly by about a factor of 4 at a normalized force level of about 0.45. Once again, at the maximum input force level, erratic response was observed.

The sharp increase in the acceleration response of the mirror occurs at about the same force level as the increase in the wall acceleration response seen in figure 19. This result suggests that the impacts of the mirror against the wall are the sources of rattling. With the hanger flat against the wall, the rattling (impacting) is initiated at a lower force level. However, at a given force level during rattling, the acceleration responses of the mirror are about the same for both mirror angles.

The rattle boundary data of figures 15, 18, 19, and 20 are presented in figure 21 in terms of the displacements associated with the acceleration levels for which rattling is initiated. Although there is some scatter in the data, the displacements of the walls associated with the onset of rattle of wall ornaments appear to decrease with frequency at approximately 12 dB/octave (constant wall acceleration) as denoted by the reference line in the figure. This trend is analogous to the behavior of a forced single-degree-of-freedom system. For frequencies above resonance, the response is mass controlled (that is, inertial forces are predominant) and the response decreases with frequency along a slope of 12 dB/octave. Apparently, the ornaments hanging against the wall behave essentially as a single-degree-of-freedom system with the natural frequency, which produces the higher frequency rattling, being the pendulum frequency of the ornaments. Since the forcing frequencies (wall responses) are well above the experimentally measured pendulum frequency of 0.83 Hz for the plaques, the foregoing trend of displacements as a function of frequency would be expected. The wall displacements in figure 21 are, in effect, the critical pendulum displacements which will produce rattling. Because the measurement point on the walls was near, but not precisely at, the plaque locations, scatter in the data would be expected especially at the higher frequencies.

Airplane-Induced Noise and Vibrations

During the experiments at Wallops Station not only were forced vibration data obtained but a large quantity of airplane-induced noise and vibration data were also recorded for the two test structures. Typical examples of the manner in which the inside noise is related to the outside airplane-induced noise for two of the many different airplanes used in the study are presented in figures 22 and 23 for test structure 3 and test structure 4. Associated noise-induced structural vibrations for the same two flights are compared in figure 24 with the acceleration levels of the rattle boundaries established by sinusoidal tests for the plaques as discussed previously. One-third-octave-band spectra are plotted for measurement locations inside and outside the houses for the noise (figs. 22

and 23) and for acceleration measurement locations on the north wall of the living rooms in the two houses (fig. 24). The acceleration measurement locations for the airplane-induced vibrations and the sinusoidal vibration tests of the rattle boundaries were the same (between the plaques).

The noise spectra in figure 22 are for a large propeller-driven transport in a landing approach at an altitude of 305 m (1000 ft), whereas those in figure 23 are for a large turbofan-powered jet transport at an altitude of 396 m (1300 ft). The spectra in figure 22 for the propeller-driven airplane obviously differ from the spectra for the turbofan airplane in figure 23. Aside from the level differences due in part to the differences in altitude of the airplanes, the spectra for the propeller-driven airplane exhibits more distinct peaks throughout the frequency range than the turbofan airplane. These peaks are associated with the discrete frequency noise from the reciprocating engines and the propellers. There are less distinct peaks in the turbofan noise in figure 23; however, a dominant feature of the spectra is the presence of a strong peak at about 2000 Hz. This peak is associated with the discrete frequency noise from the fan sections of the jet engines.

The noise reductions supplied by the structures at various frequencies are indicated by the hatched regions in figures 22 and 23. These noise reductions vary considerably with frequency and are associated with the vibrational behavior of the intervening structure. Although the two houses differ somewhat in the type of construction, the noise reductions for the structures are generally comparable. This result should be expected since the vibrational responses and modal behavior were similar due to the uniformity in spacing, size, and length of structural members in the buildings.

The airplane-noise-induced wall vibration levels for test structures 3 and 4 and those associated with rattling of the ornamental plaques on the north living room walls are given in figure 24. The dashed curves with data symbols represent the rattle boundary established by sinusoidal excitation tests (see also figs. 15 and 18). For wall accelerations exceeding those of the boundary, the plaques will rattle and may be annoying. Also shown in figure 24 are the acceleration spectra measured at the same transducer location for the two airplane flyovers. For test structure 3, the accelerations induced by the two different airplanes did not exceed those of the rattle boundary and the plaques, in fact, did not rattle. However, the induced accelerations at approximately 100 Hz (fig. 24(b)) associated with the propeller-driven airplane did exceed those of the rattle boundary in test structure 4 and the plaques were indeed observed to rattle. The rattle phenomenon, which may be important subjectively, is an example of a nonlinear dynamic response situation where the excitation at one frequency results in responses at different frequencies.

Presented in figure 25 are the wall accelerations induced by the two airplane overflights of figure 24 and the sinusoidal response data for the same transducer location on the west living-room—dining-room wall of test structure 4. The wall accelerations for the two overflights were obtained from a 1/3-octave-band analysis of the peak in the acceleration time history induced by the airplane flyover. The data indicate that the wall acceleration levels induced by the propeller-driven airplane at an altitude of 305 m (1000 ft) are higher than the levels induced by the turbofan airplane at an altitude of 396 m (1300 ft). Both levels of response are below that for the particular sinusoidal response for a constant input force level (zero to peak) of 13.3 N (3.0 lbf). However, most of the resonances in the airplane-induced responses coincide with corresponding peaks in the sinusoidal response curve. For example, three of the four low-frequency resonances labeled A, B, C, and D (see fig. 11 for mode shapes) occurred in the data of the propeller-driven airplane and two of the four occurred in the data of the turbofan airplane. However, the highest acceleration levels are generally for the higher frequency modes around 400 to 600 Hz. The exception is the turbofan airplane for which acceleration responses decrease above 200 Hz (fig. 25).

CONCLUDING REMARKS

An experimental study was conducted to determine vibration response characteristics of four residential-type structures. Data were obtained from mechanical excitation and from acoustical excitation by airplane overflights.

The vibration response characteristics and the noise reduction of the houses used in the study were found to be generally similar despite differences among them in appearance, construction materials, and age (from less than a year to about 20 years). The general similarity in response characteristics was attributed to similar basic construction such as common ceiling heights, stud-type walls with standard stud spacing (40.64 cm (16 in.) on center), and other structural details.

Responses below 100 Hz were generally associated with main structural members of the building and with the interactions of adjacent walls and floors. Responses above 100 Hz were generally associated with individual panels such as surfaces between studs. The low-frequency responses were typical of those induced by sonic booms and the high-frequency responses were typical of those induced by airplane noise. The low-frequency responses in the subaudible or near subaudible frequency range, like those in the audible range, may be subjectively important.

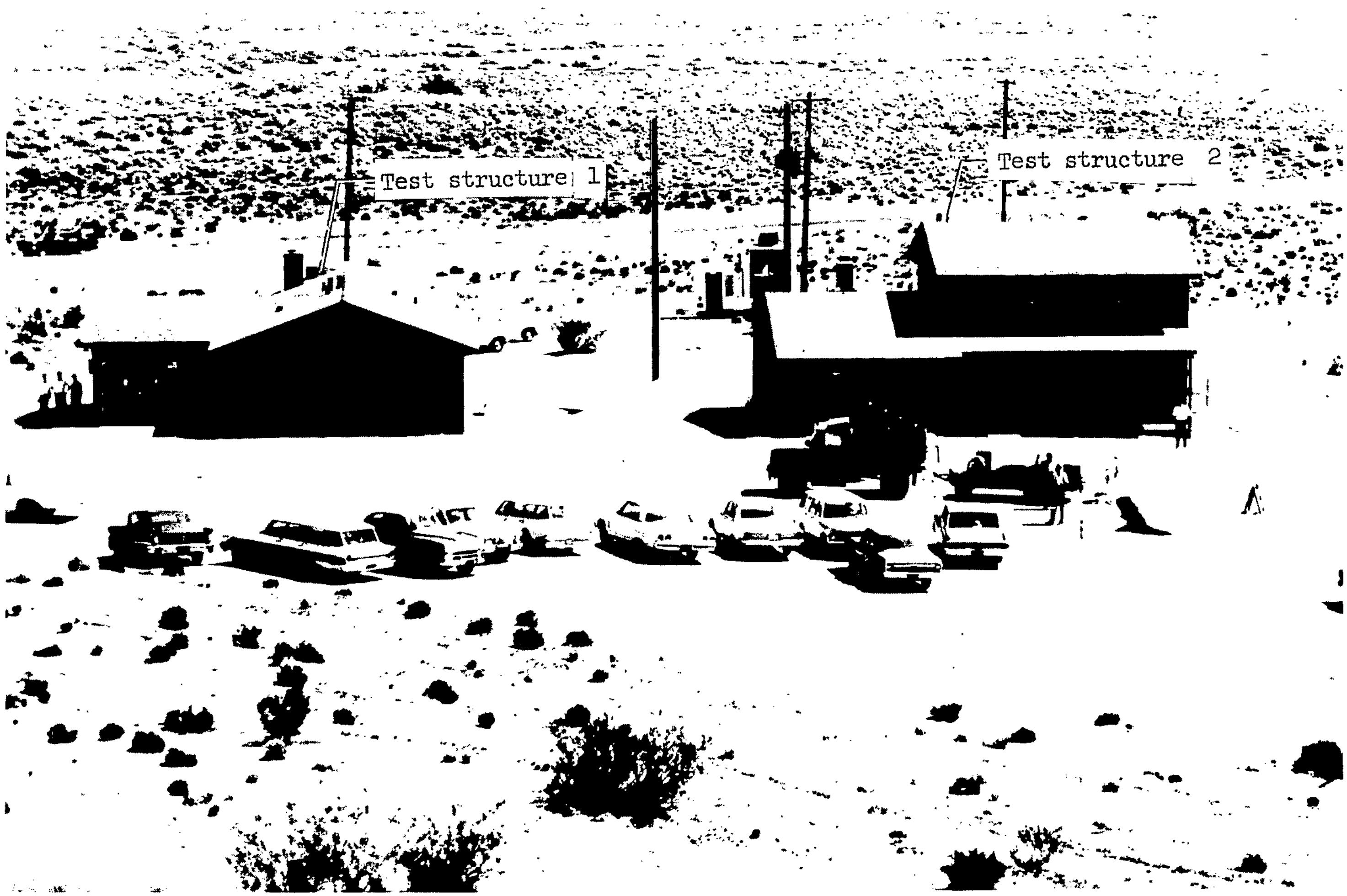
Studies of the rattle phenomenon of wall-mounted decorative objects indicated that as the frequency of excitation increases, rattling was associated with smaller amplitude vibrations. The rattle phenomenon was found to be a nonlinear type of response, whereas response of the building structure was linear in the range of loadings associated with normal airplane operations.

In the studies of the rattle phenomenon associated with wall-mounted objects, mechanical sinusoidal excitation was used to establish acceleration threshold levels above which rattling occurs. These sinusoidally established threshold levels agreed with the levels associated with rattling that was experienced during noise excitation from airplane overflights. Similarly, mechanical sinusoidal excitation was also used to obtain resonant response frequencies which were in agreement with the predominant airplane-induced responses of the structure. From these studies of rattling and structural responses, it was determined that mechanical sinusoidal excitation provides a useful tool for predicting both wall acceleration levels for the onset of rattling and building structural responses associated with acoustical excitation from airplane overflights.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., February 25, 1970.

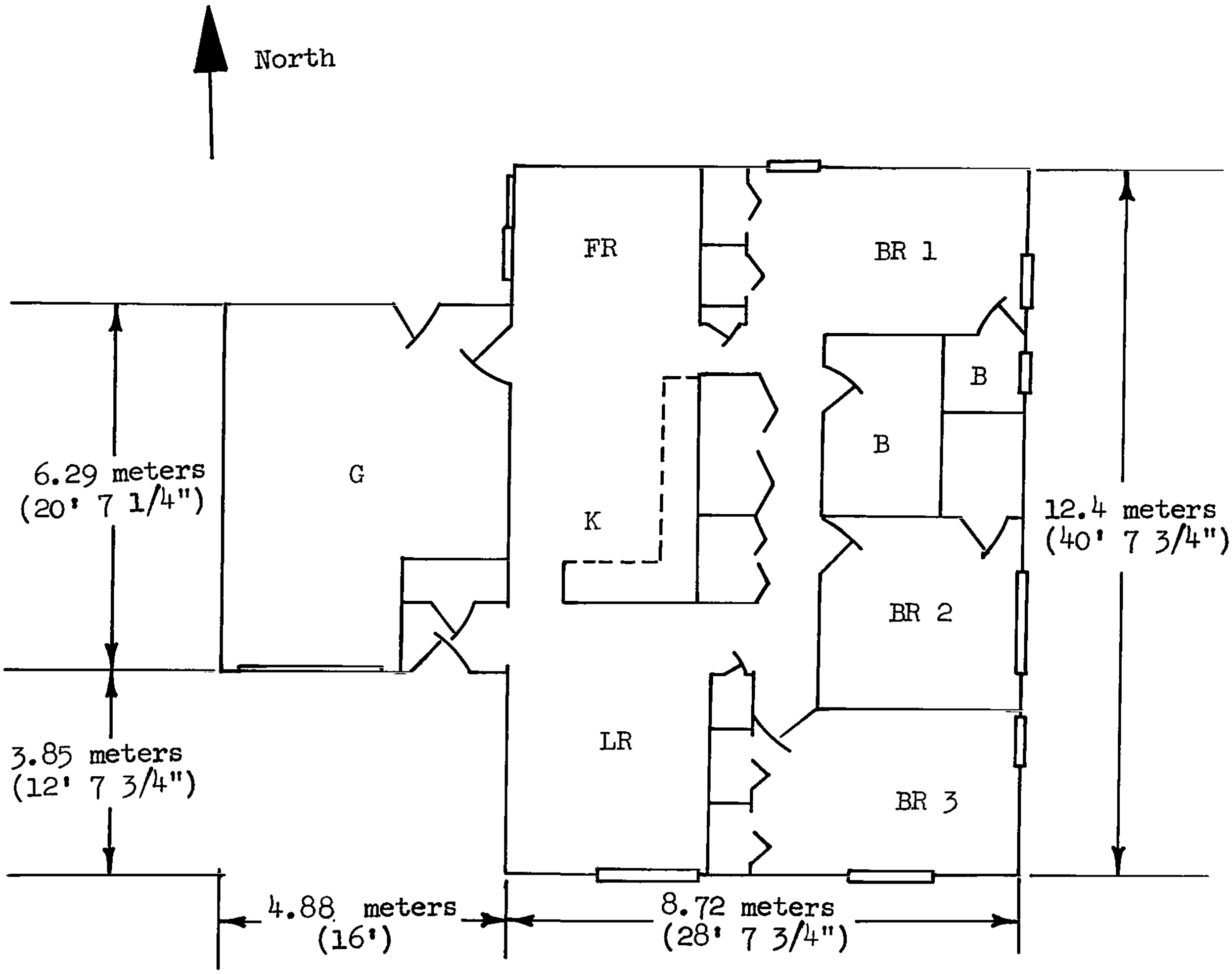
REFERENCES

1. Anon.: Sonic Boom Experiments at Edwards Air Force Base. NSBEO-1-67 (Contract AF 49(638)-1758), CFSTI, U.S. Dep. Com., July 28, 1967.
2. Anon.: Progress of NASA Research Relating to Noise Alleviation of Large Subsonic Jet Aircraft. NASA SP-189, 1968.
3. Mulholland, K. A.: Parbrook, H. D.; and Cummings, A.: The Transmission Loss of Double Panels. J. Sound Vib., vol. 6, no. 3, Nov. 1967, pp. 324-334.
4. White, Pritchard H.; and Powell, Alan: Transmission of Random Sound and Vibration Through a Rectangular Double Wall. J. Acoust. Soc. Amer., vol. 40, no. 4, Oct. 1966, pp. 821-832.
5. Bishop, Dwight E.: Reduction of Aircraft Noise Measured in Several School, Motel, and Residential Rooms. J. Acoust. Soc. Amer., vol. 39, no. 5, May 1966, pp. 907-913.
6. Ford, R. D.; and Lord, P.: Practical Problems of Partition Design. J. Acoust. Soc. Amer., vol. 43, no. 5, May 1968, pp. 1062-1068.
7. Schiller, K. K.: Physical Aspects of Sound Insulation Through Walls. J. Sound Vib., vol. 6, no. 3, Nov. 1967, pp. 283-295.
8. Anon.: Effects of Sonic Boom on Buildings. Mater. Res. Stand., vol. 4, no. 11, Nov. 1964, pp. 581-623.
9. ARDE Associates: Response of Structure to Aircraft Generated Shock Waves. WADC Tech. Rep. 58-169, U.S. Air Force, Apr. 1959. (Available from DDC as AD 229 463L.)
10. Goldman, David E.; and Von Gierke, Henning E.: Effects of Shock and Vibration on Man. Engineering Design and Environmental Conditions. Vol. 3 of Shock and Vibration Handbook, Cyril M. Harris and Charles E. Crede, eds., McGraw-Hill Book Co., c.1961, pp. 44-1 – 44-51.
11. Hixson, Elmer L.: Mechanical Impedance and Mobility. Basic Theory and Measurements. Vol. 1 of Shock and Vibration Handbook, Cyril M. Harris and Charles E. Crede, eds., McGraw-Hill Book Co., c.1961, pp. 10-1 – 10-59.
12. Warburton, G. B.: The Vibration of Rectangular Plates. Proc. Inst. Mech. Eng. (London), vol. 168, no. 12, 1953, pp. 371-384.



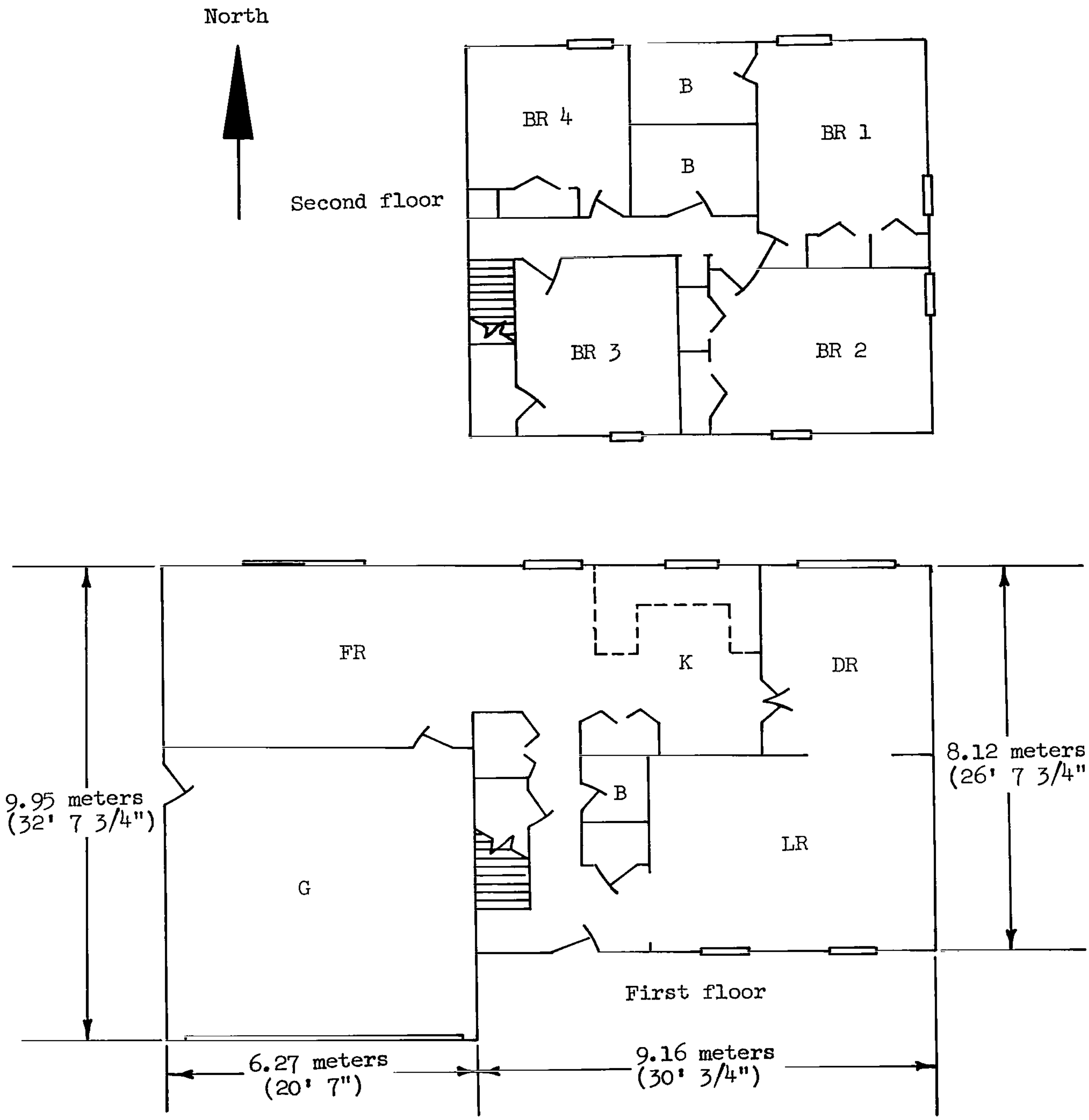
(a) Test structures 1 and 2.

Figure 1.- Edwards Air Force Base test structures and floor plans. L-70-1537



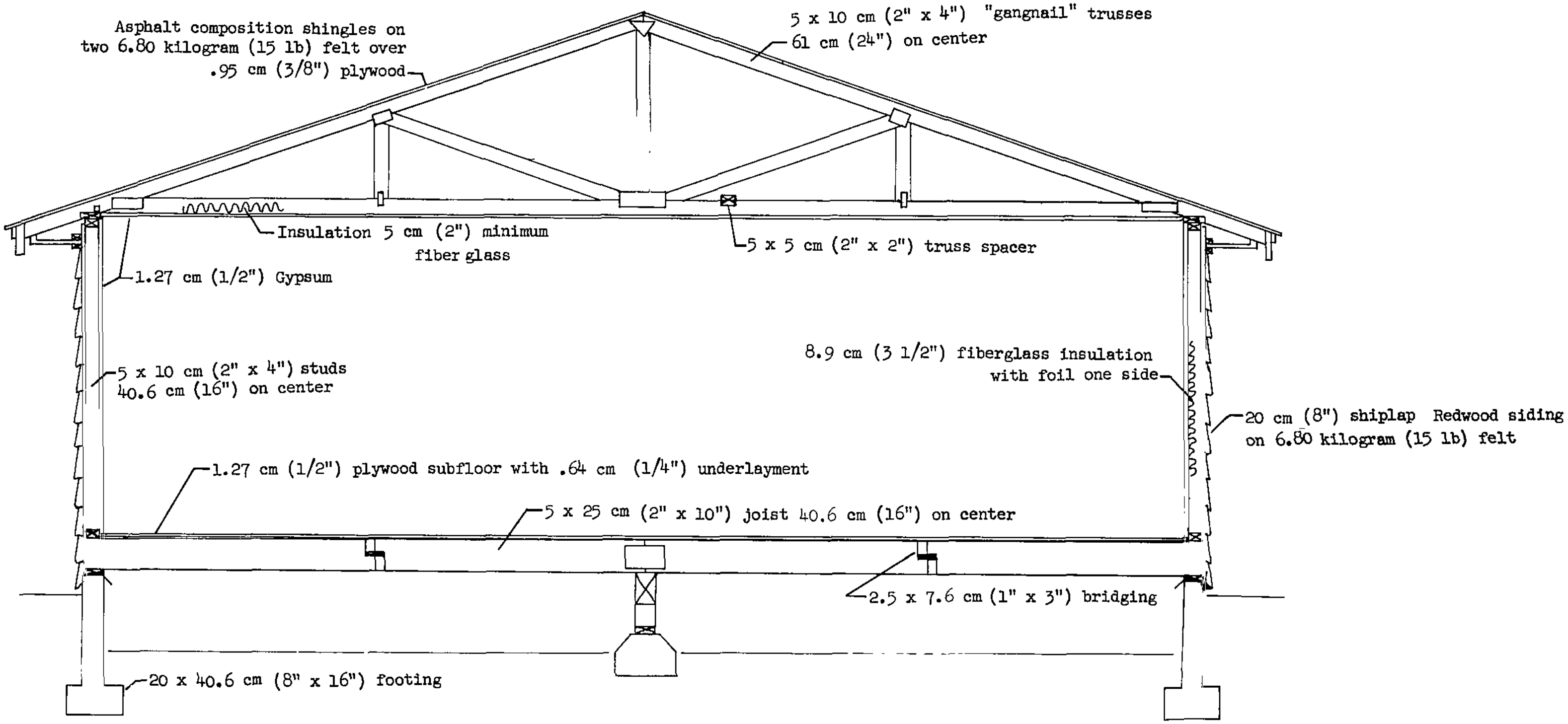
(b) Floor plan of test structure 1.

Figure 1.- Continued.



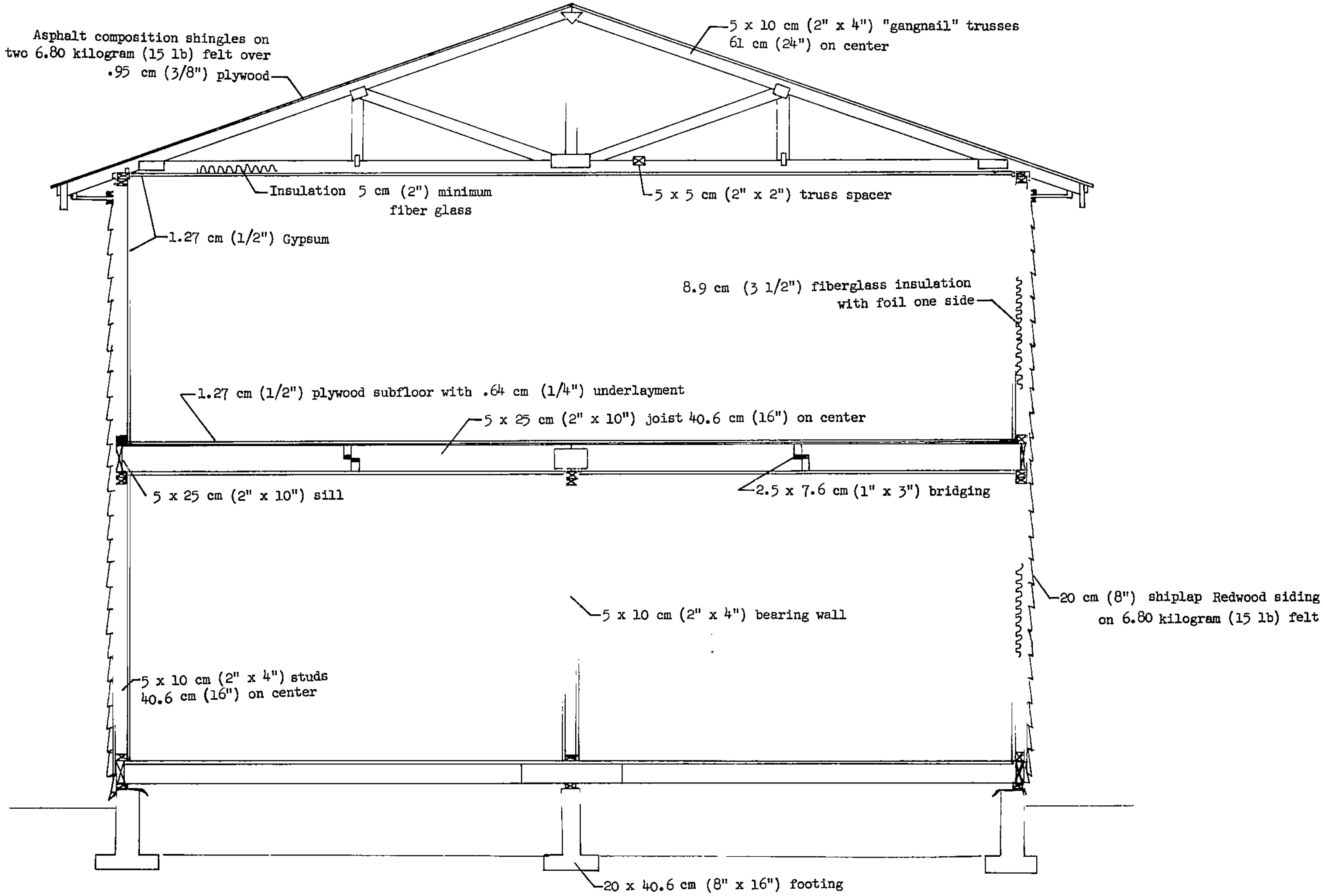
(c) Floor plan of test structure 2.

Figure 1.- Continued.



(d) Section view of test structure 1.

Figure 1.- Continued.



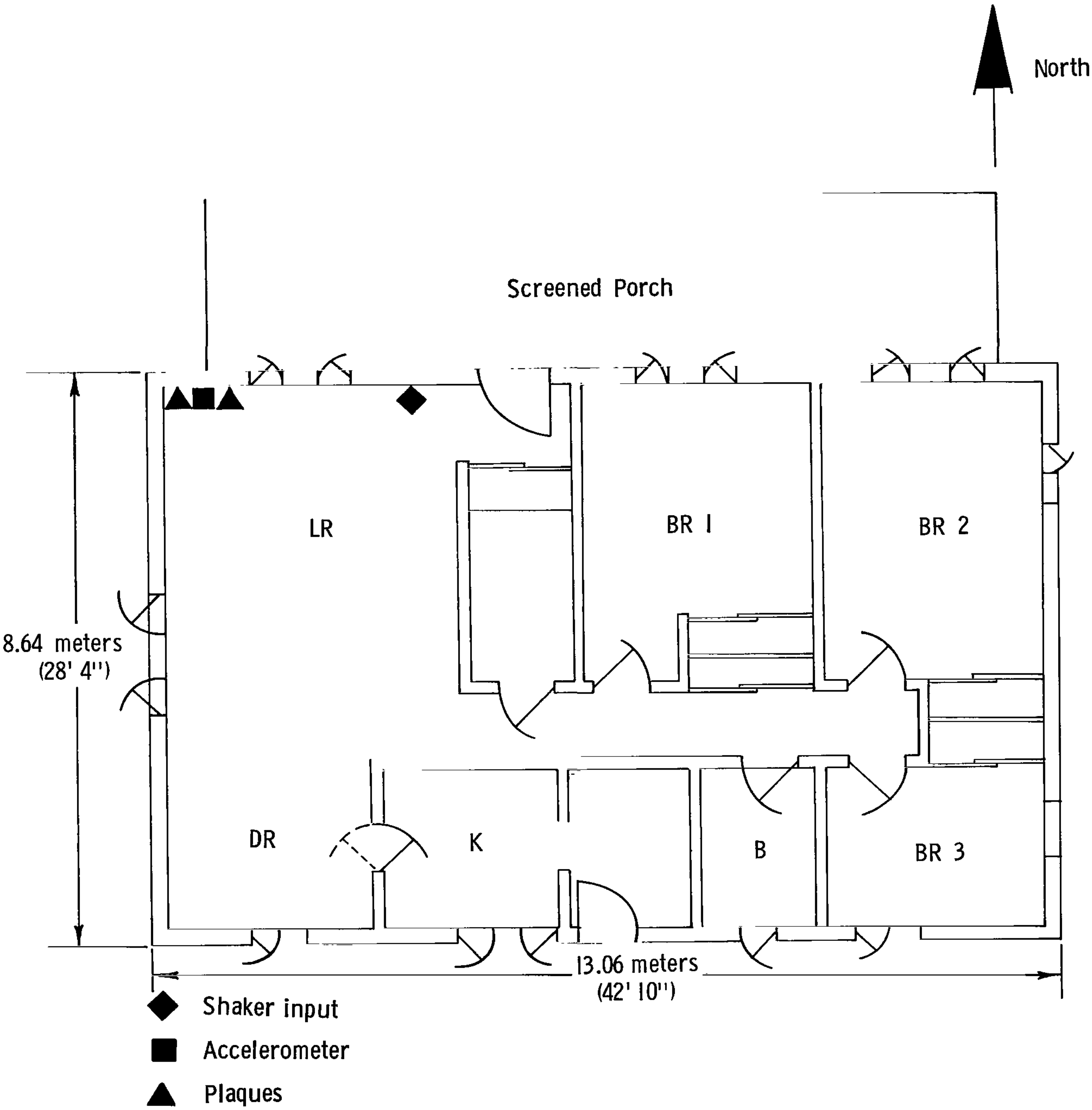
(e) Section view of test structure 2.

Figure 1.- Concluded.

(a) Test structure 3.

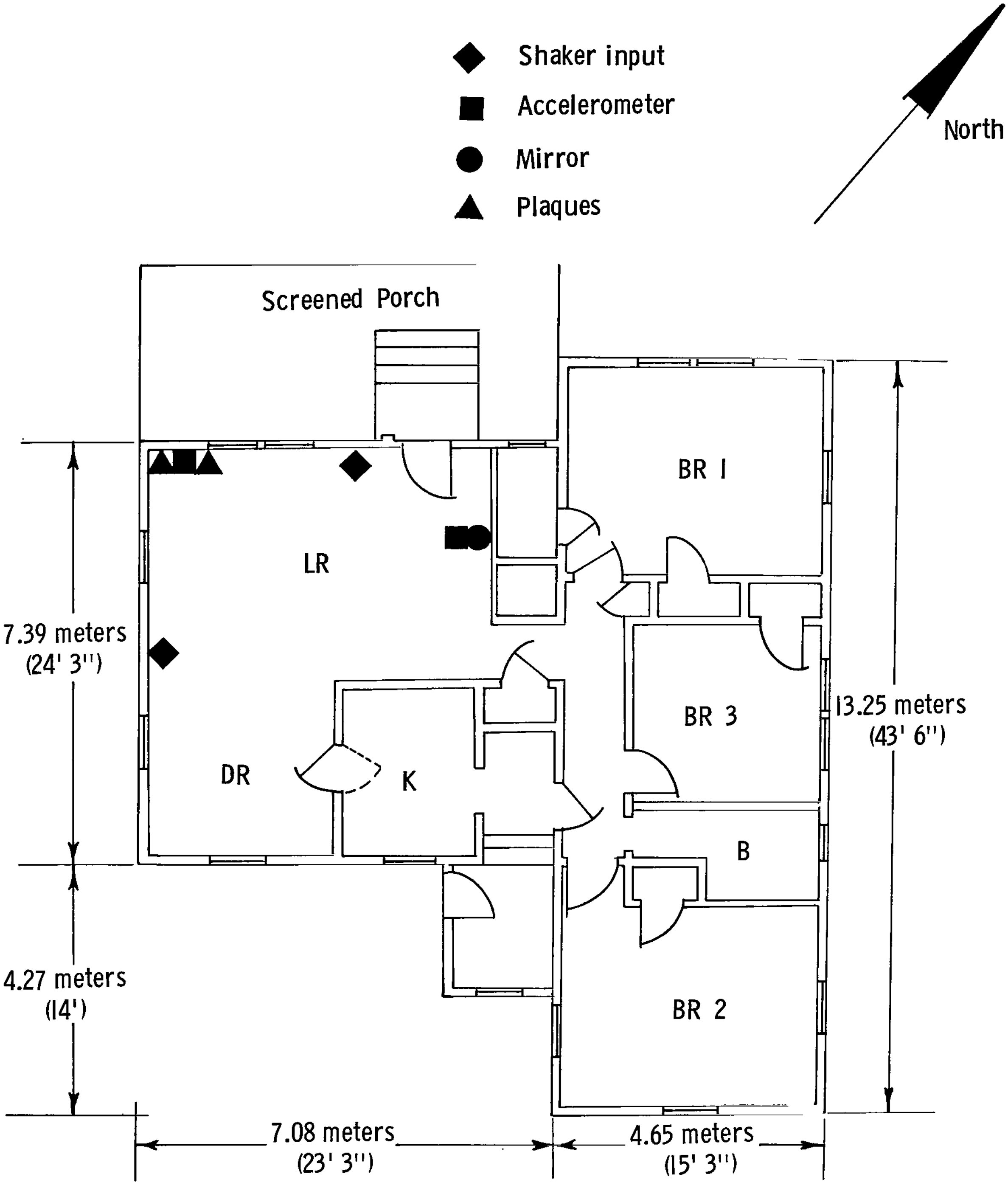
(b) Test structure 4.

Figure 2.- Wallops Station test structures and floor plans. L-70-1538



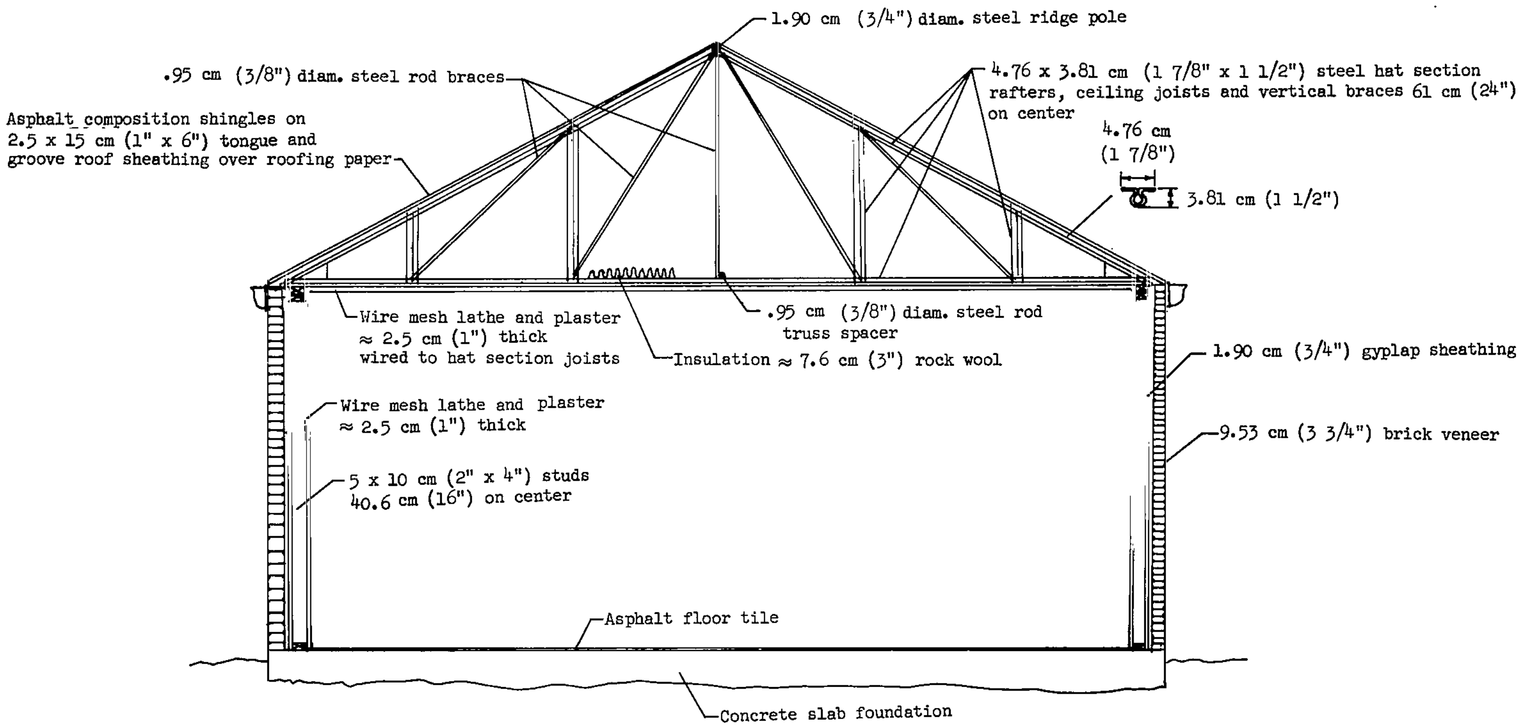
(c) Floor plan of test structure 3.

Figure 2.- Continued.



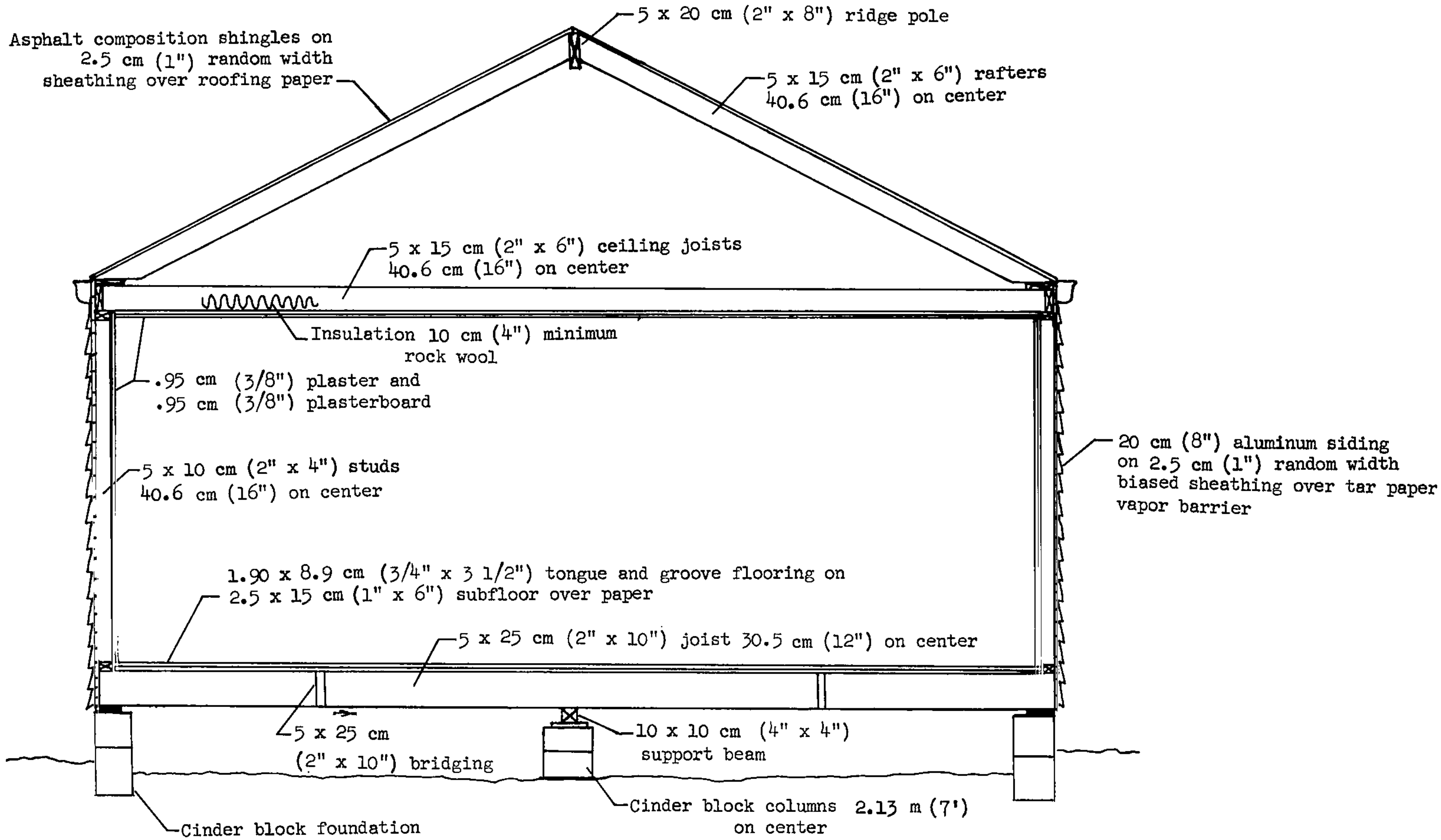
(d) Floor plan of test structure 4.

Figure 2.- Continued.



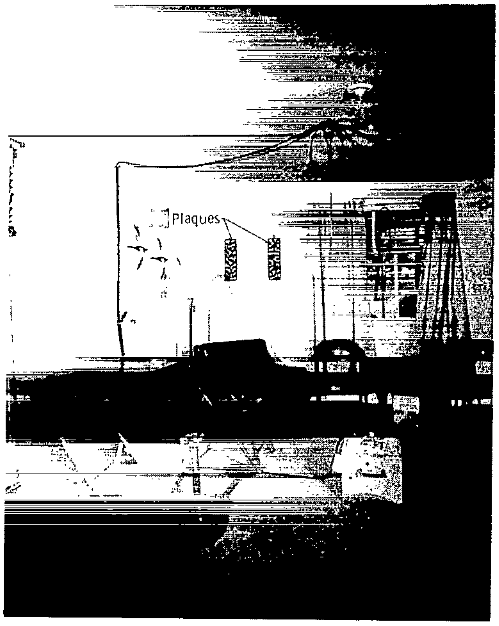
(e) Section view of test structure 3.

Figure 2.- Continued.

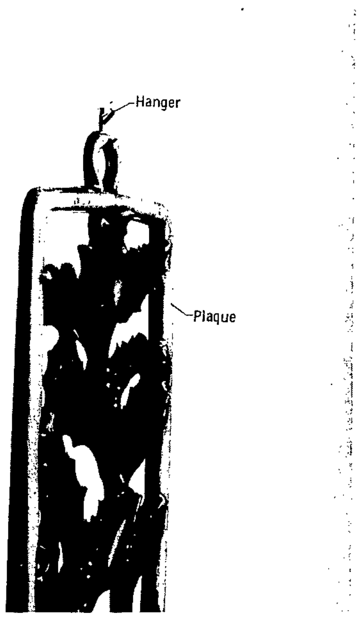


(f) Section view of test structure 4.

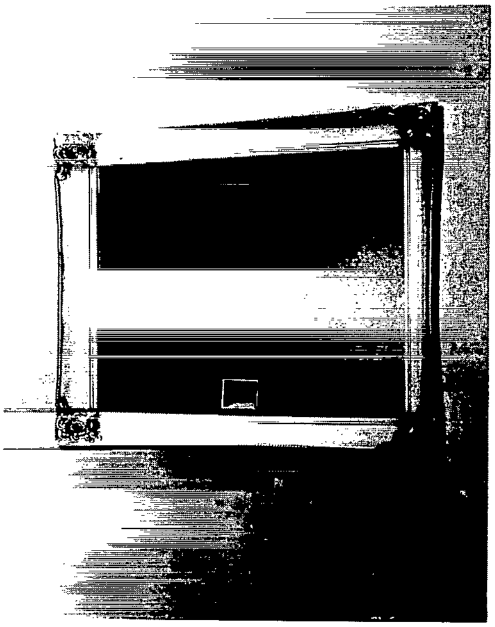
Figure 2.- Concluded.



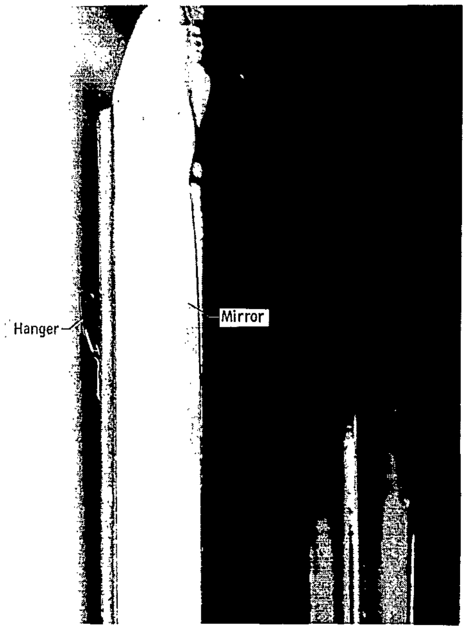
(a) Ornamental plaques in test structure 3.



(b) Plaque hanger detail.



(c) Decorative mirror.



(d) Mirror hanger detail.

Figure 3.- Plaques and mirror associated with study of rattle phenomenon. L-70-1539

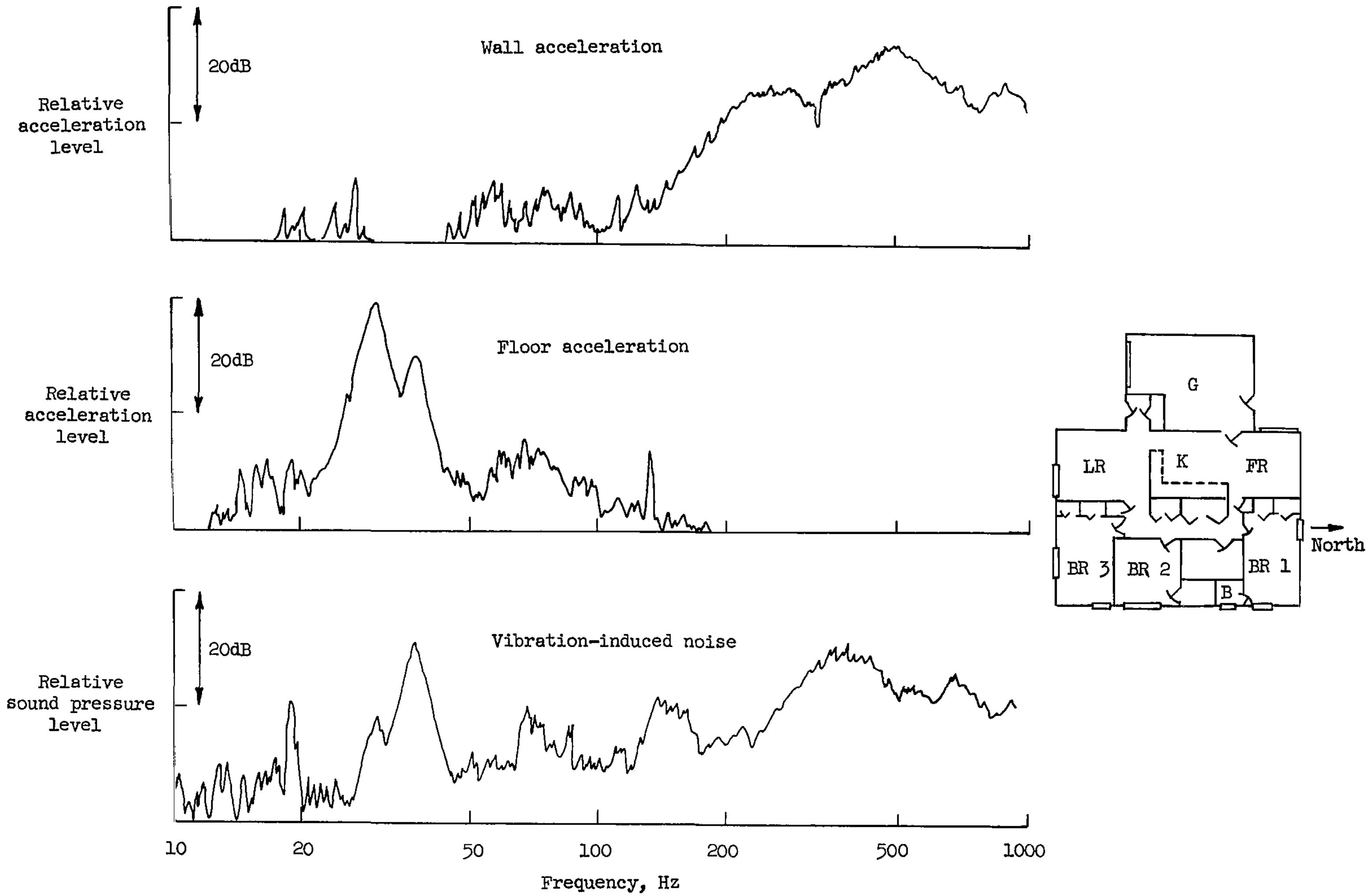


Figure 4.- Response of bedroom 1 of Edwards test structure 1 to constant input force.

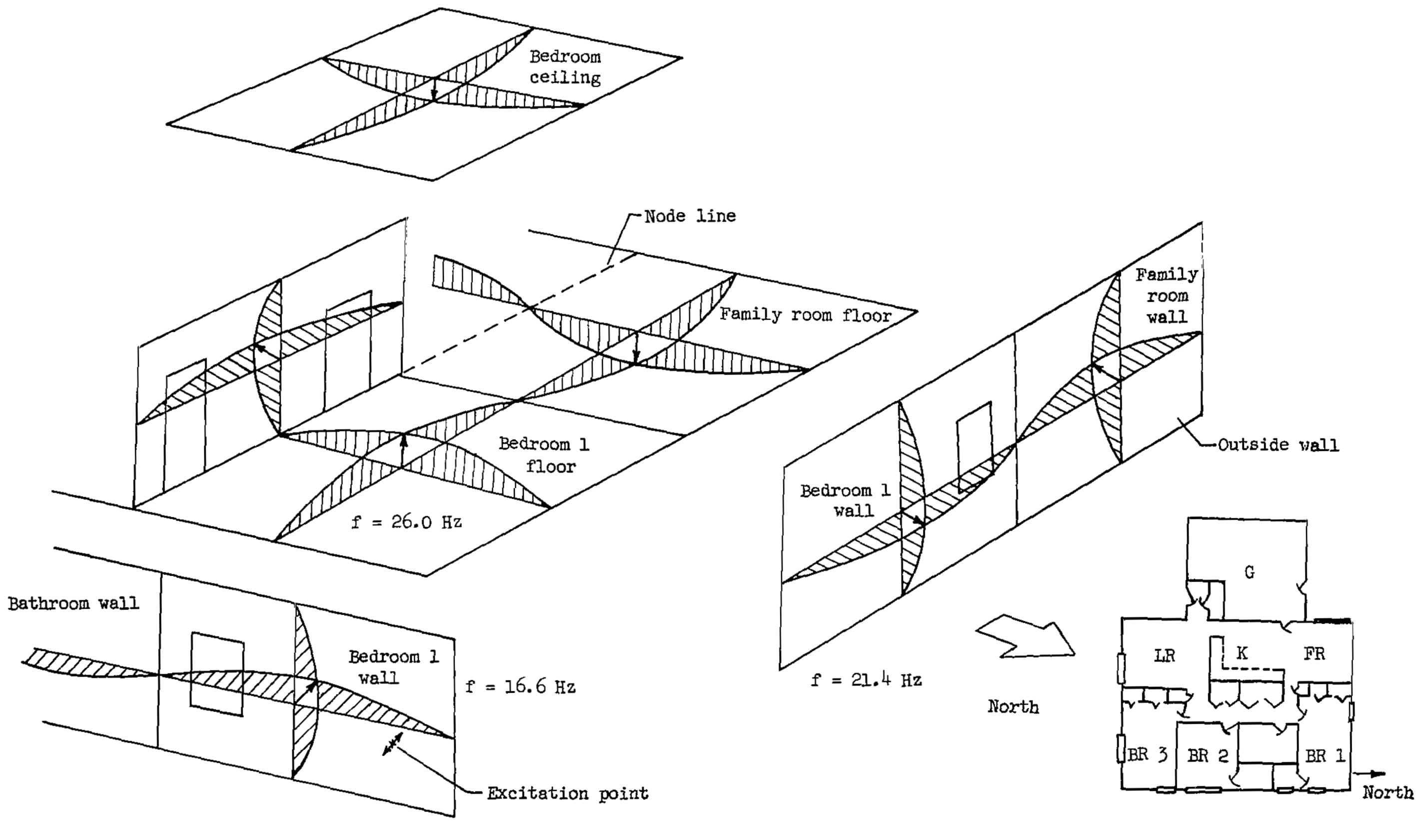
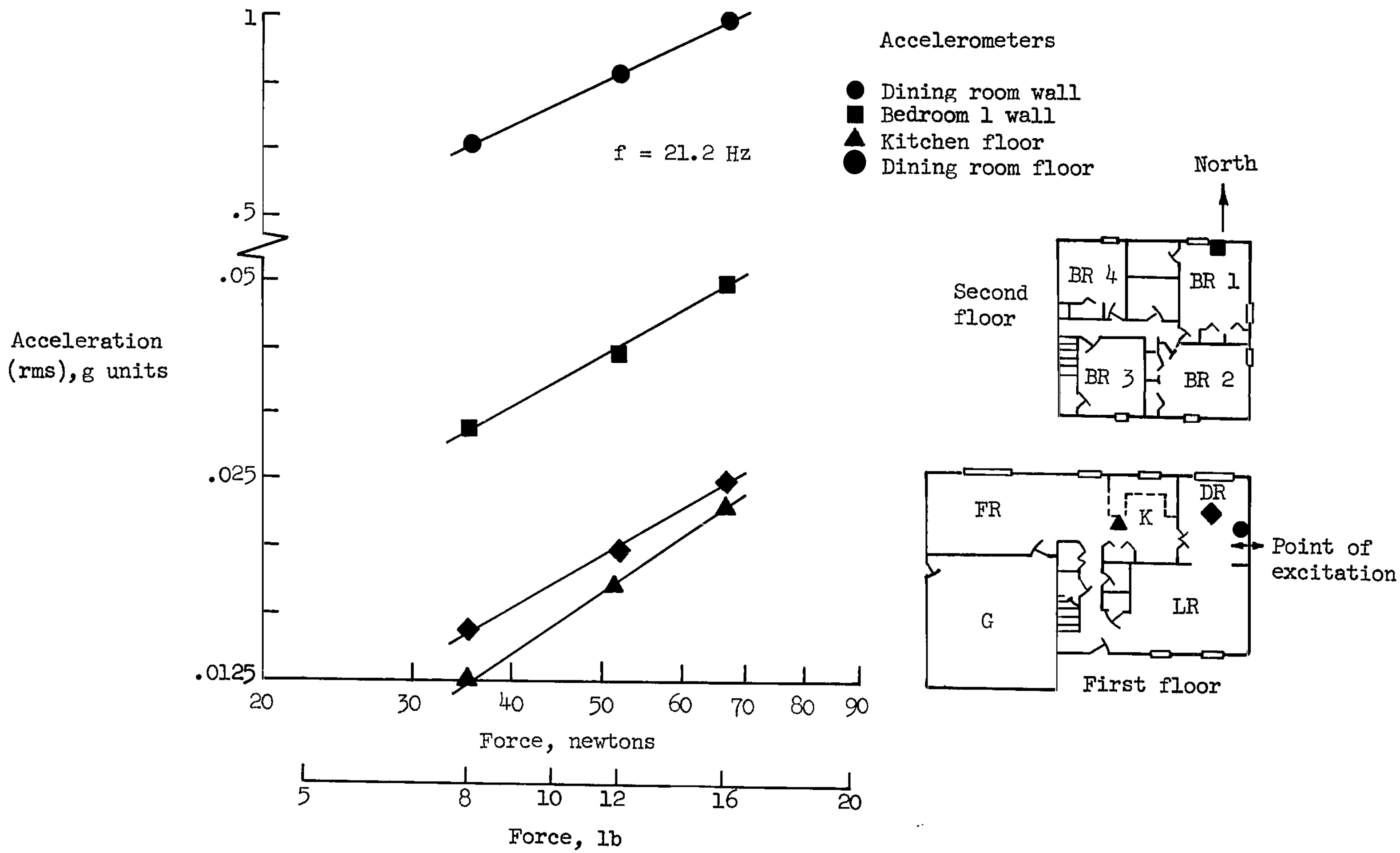
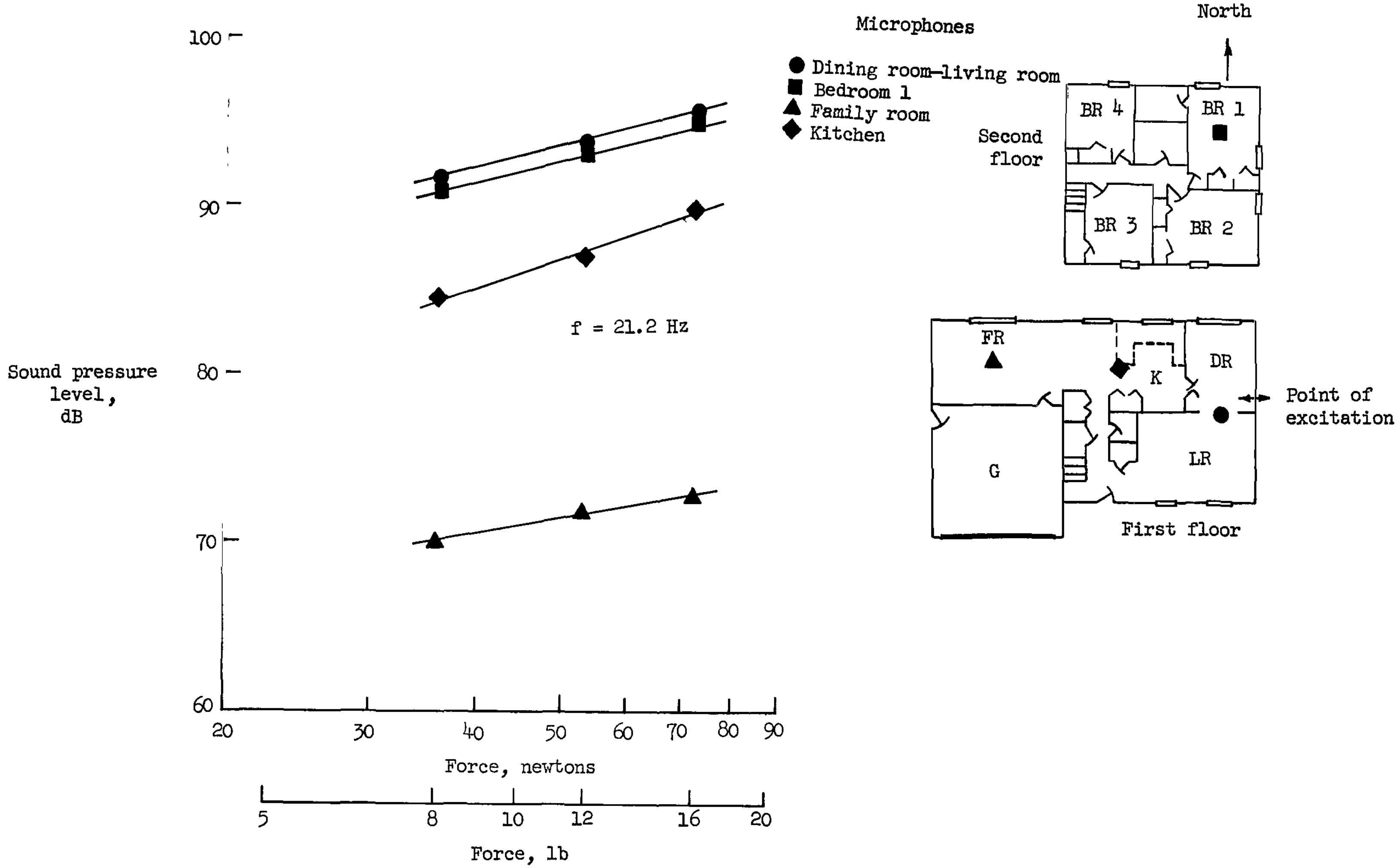


Figure 5.- Mode shapes and frequencies of Edwards test structure 1. Force input, 35.6 newtons (8 lbf).



(a) Accelerations.

Figure 6.- Accelerations and sound pressure levels as a function of point input force for Edwards test structure 2.



(b) Sound pressures.

Figure 6.- Concluded.

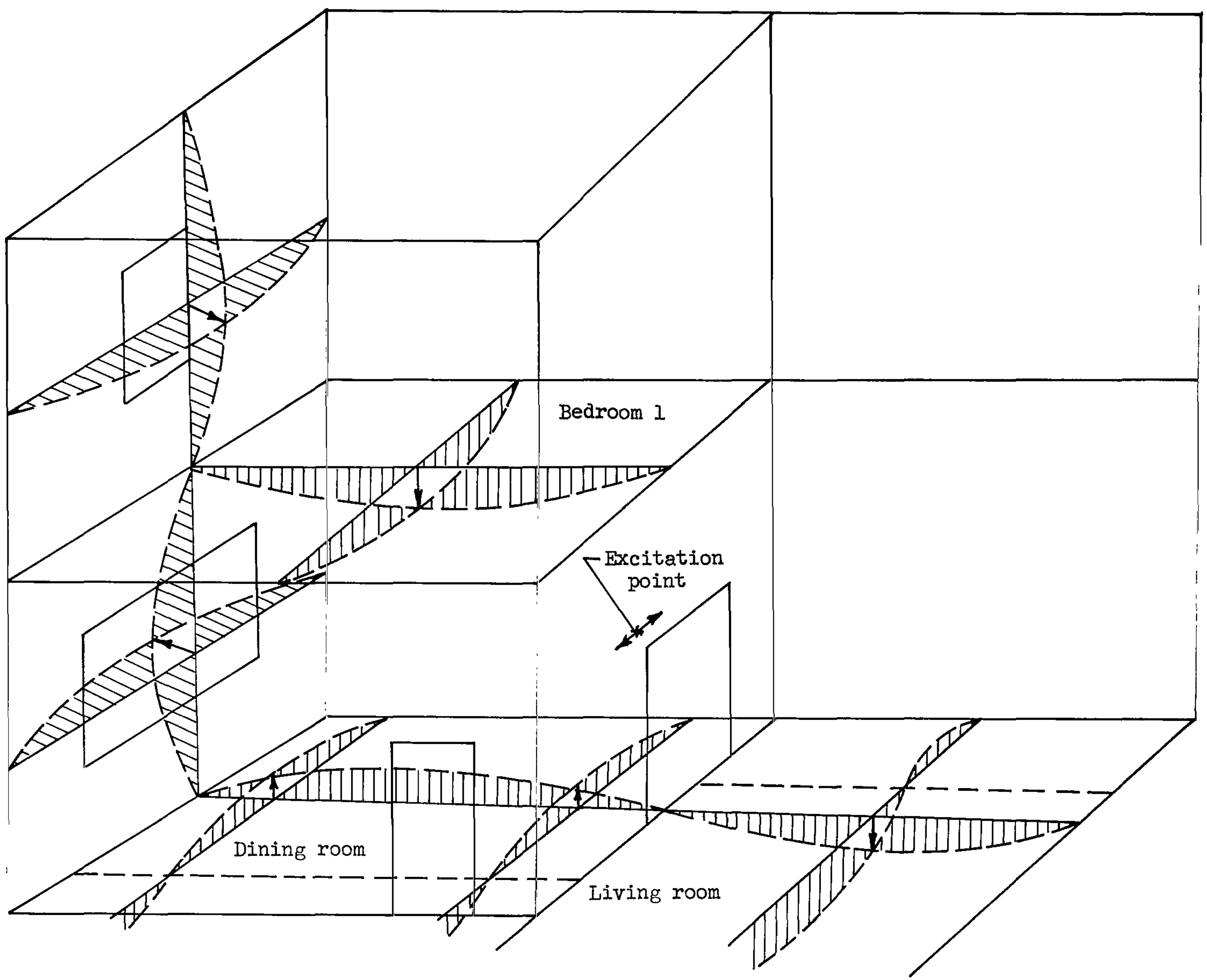


Figure 7.- Low-frequency vibration mode shapes of Edwards test structure 2.

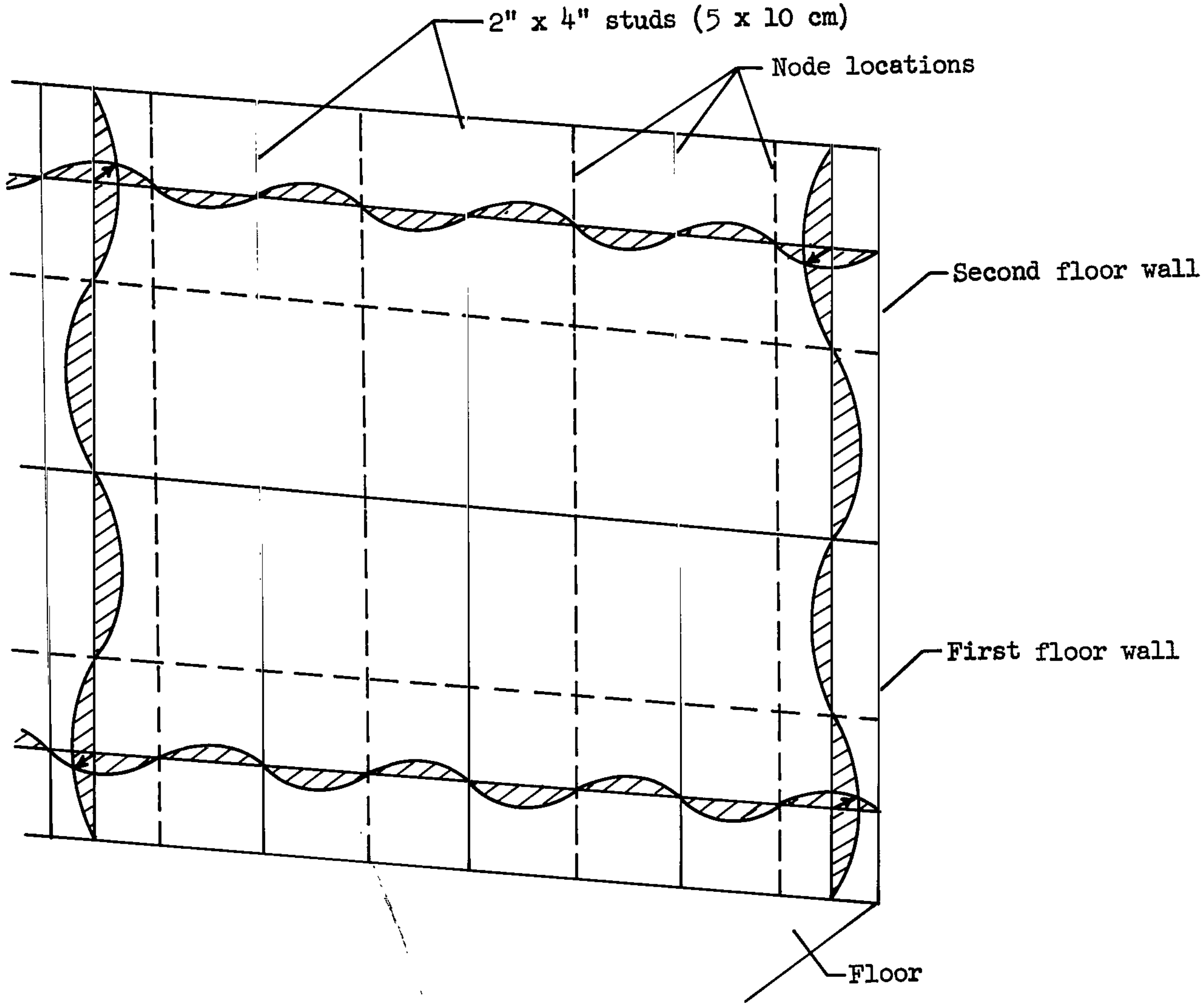
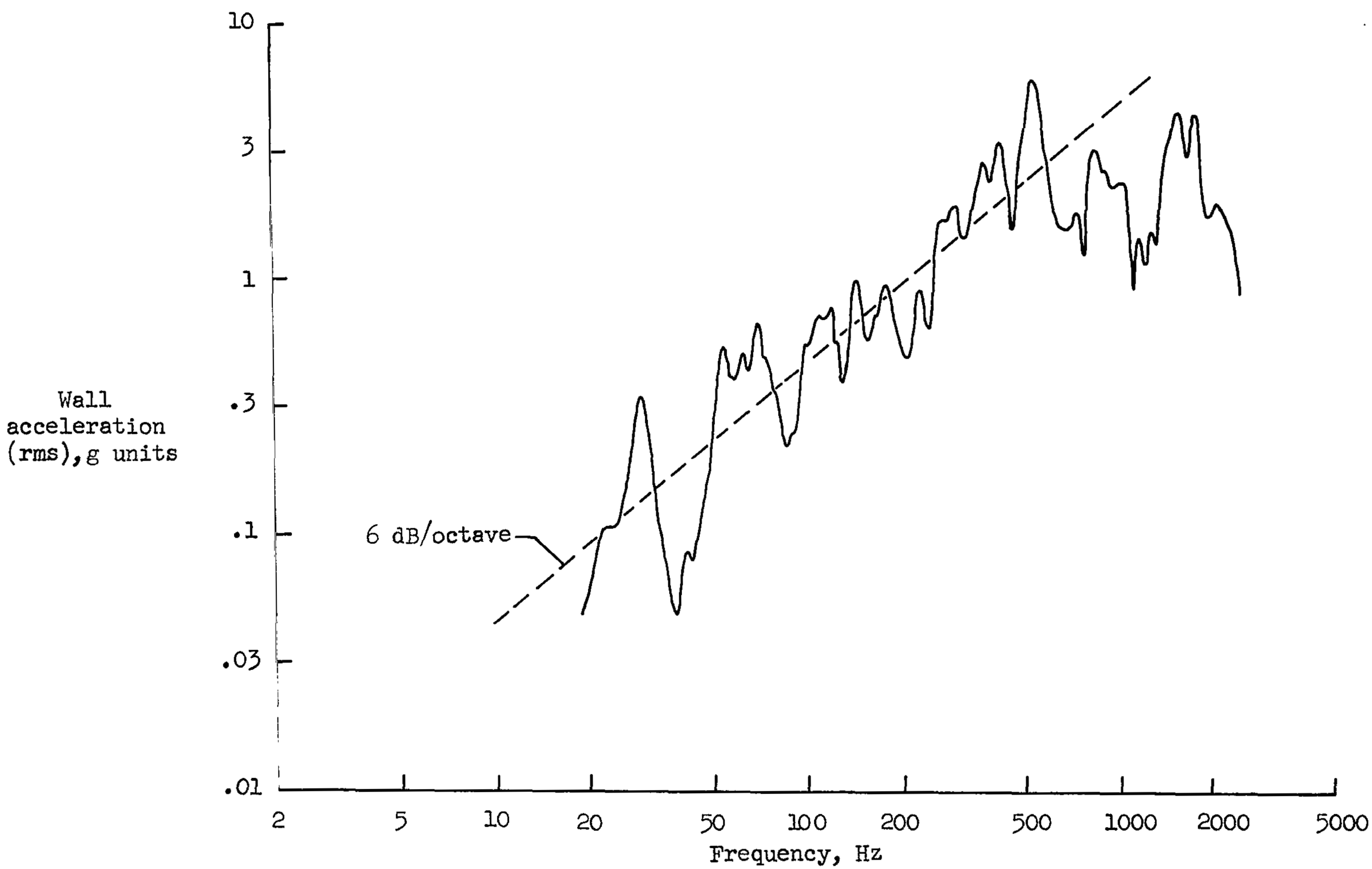
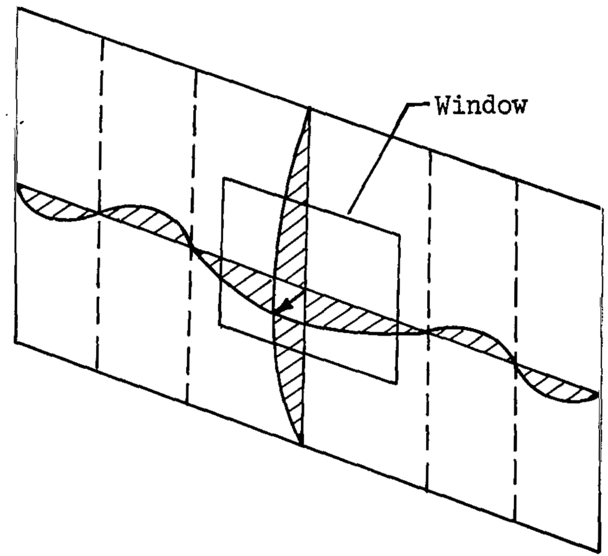


Figure 8.- High-frequency panel mode shapes in Edwards test structure 2. f = 405 Hz.



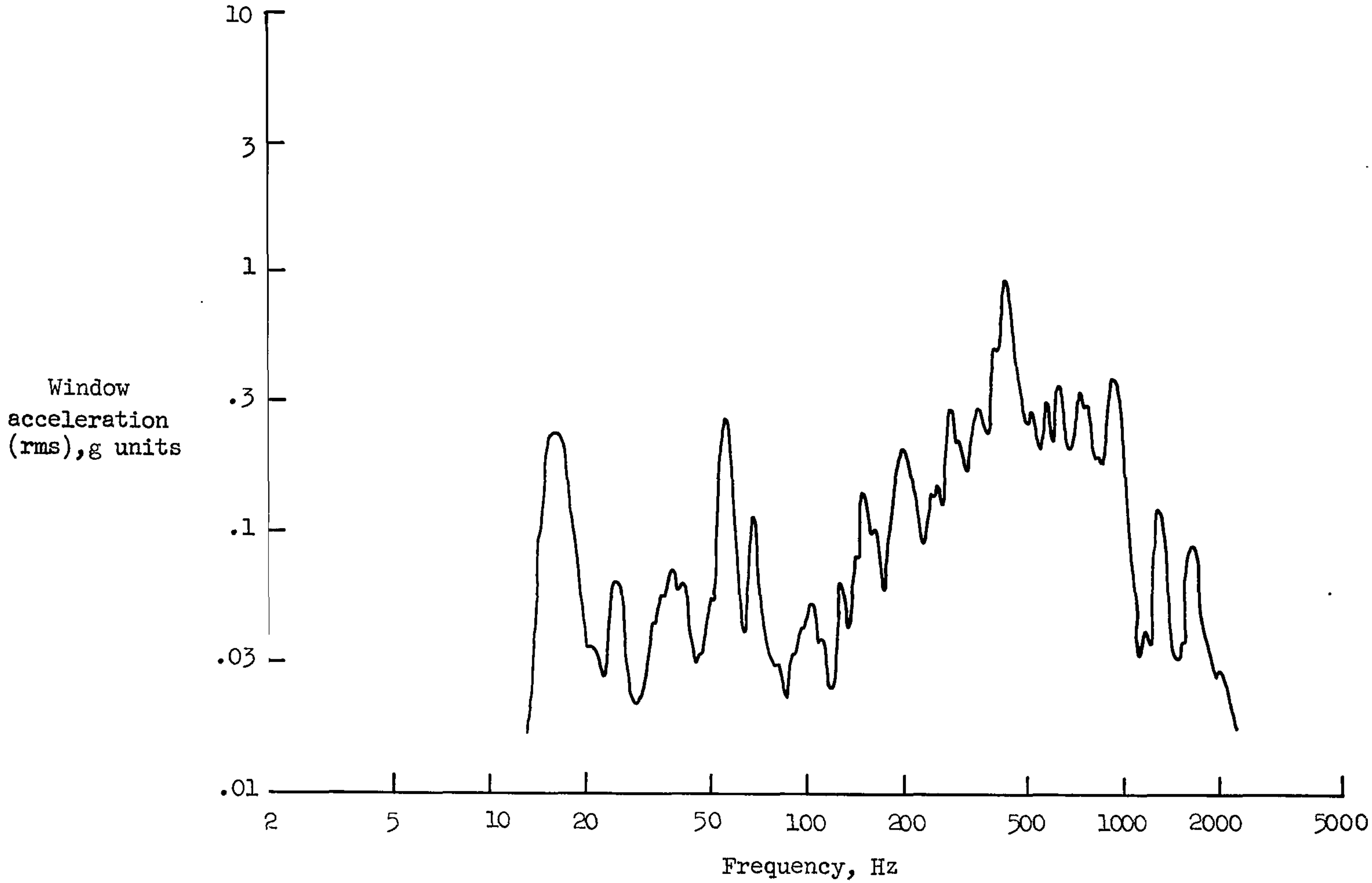
(a) Acceleration spectrum of west living room wall.

Figure 9.- Acceleration spectra and vibration mode shapes of Wallops test structure 3.



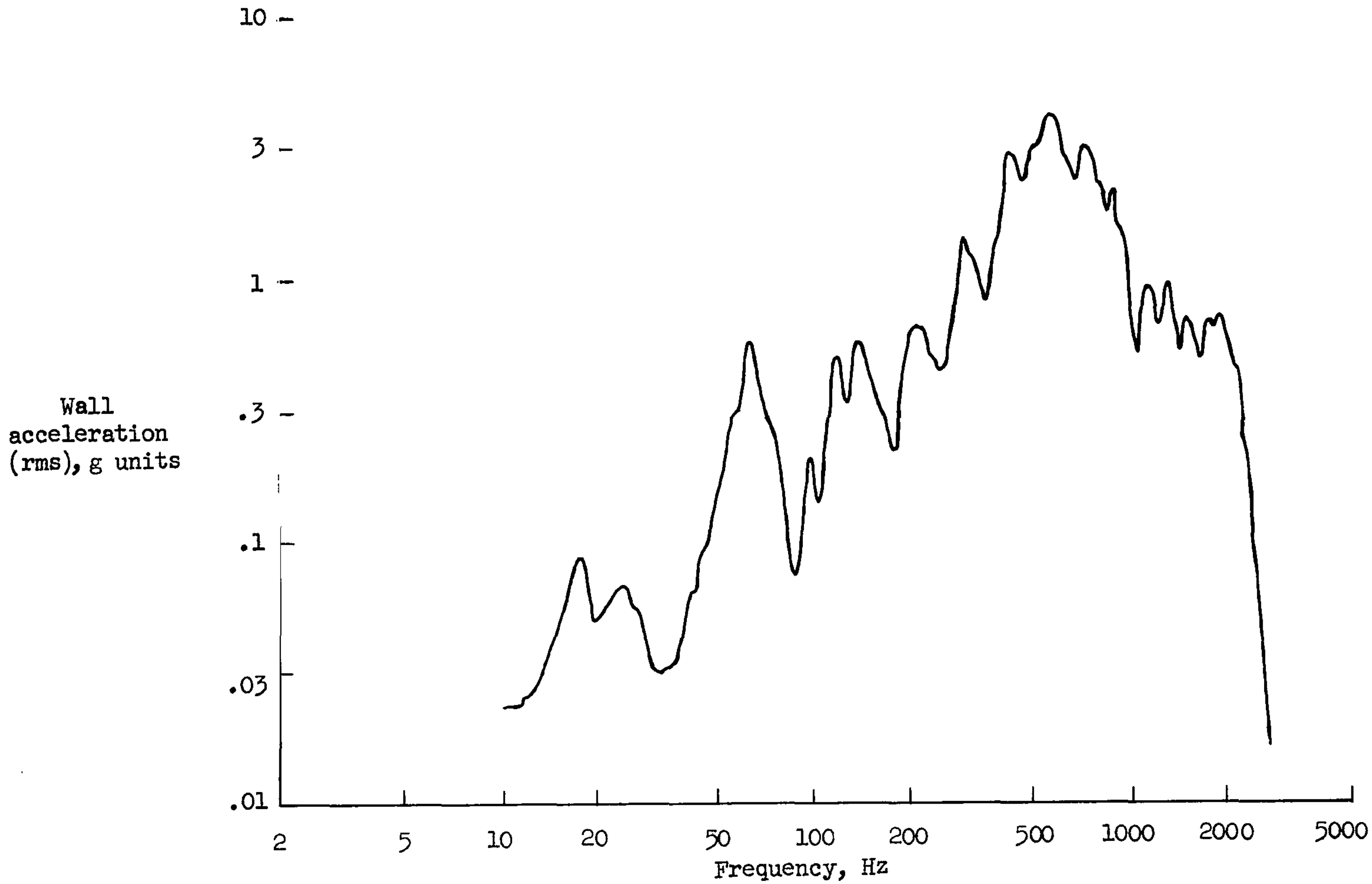
(b) Mode shape of west living room wall. f = 27 Hz.

Figure 9.- Continued.



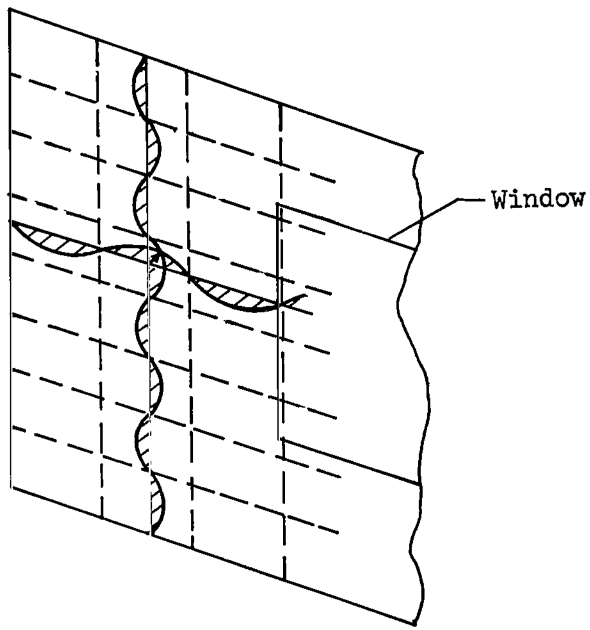
(c) Acceleration spectrum of window in west living room wall.

Figure 9.- Continued.



(d) Acceleration spectrum of north living room wall.

Figure 9.- Continued.



(e) High-frequency mode shape of north living room wall. f = 540 Hz.

Figure 9.- Concluded.

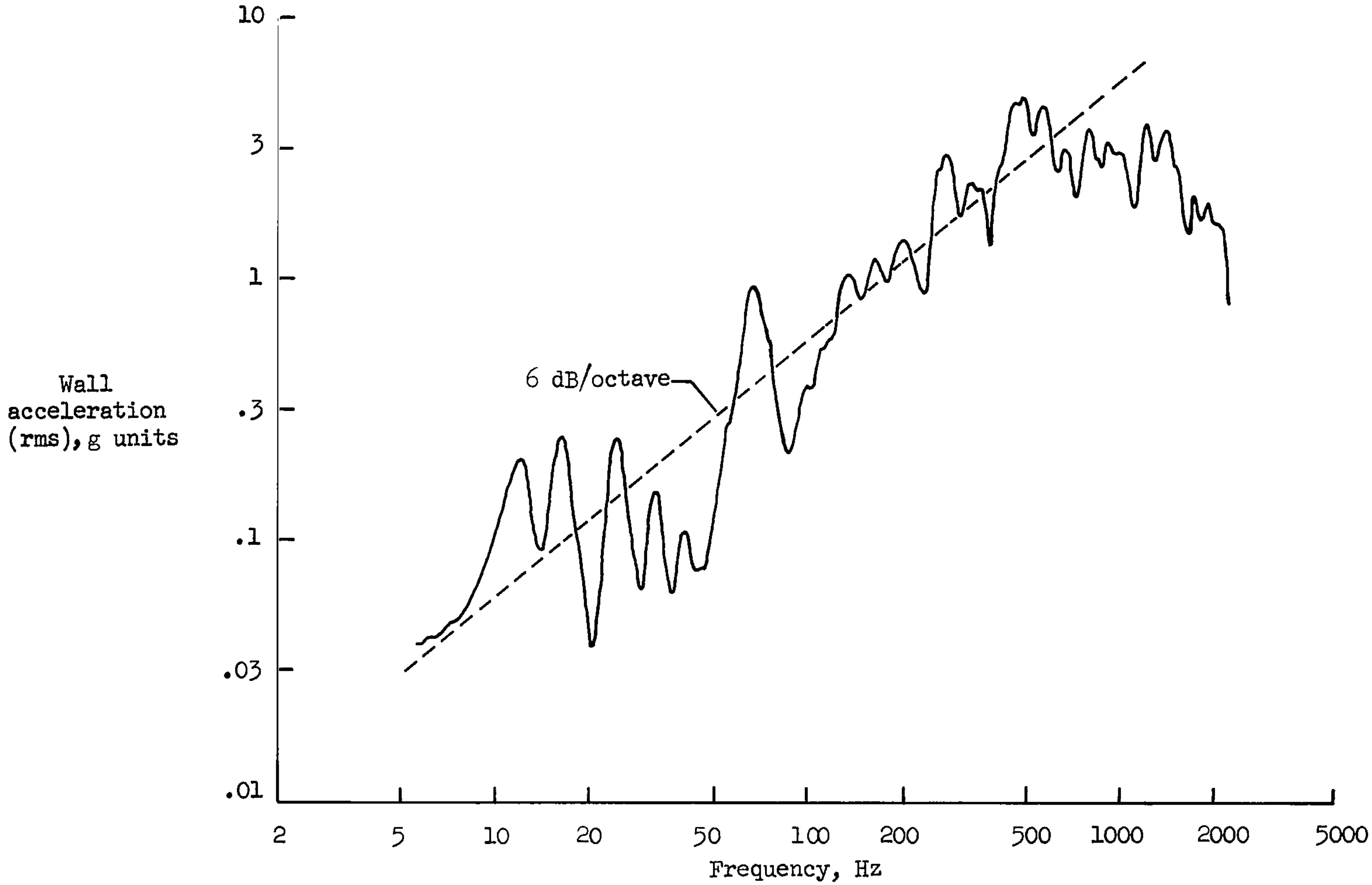
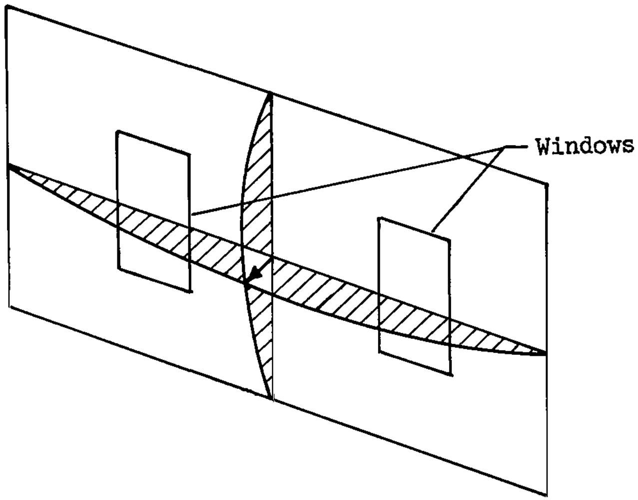
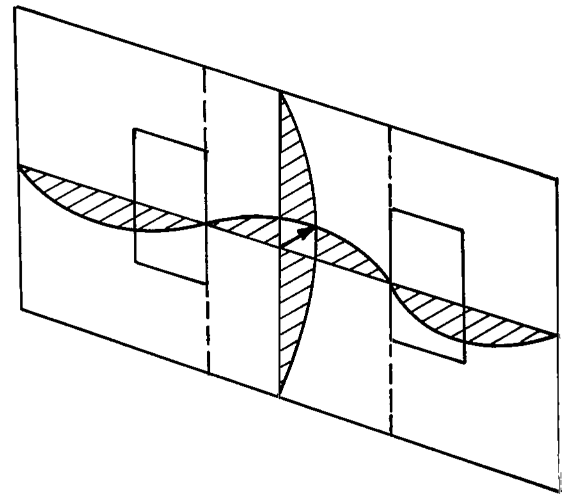


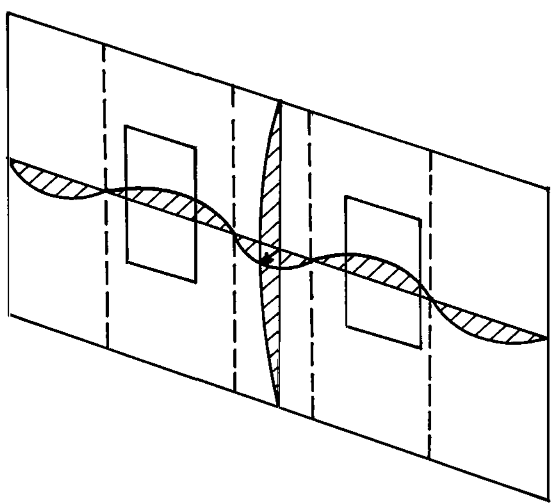
Figure 10.- Acceleration spectrum of the west living-room—dining-room wall of Wallops test structure 4.



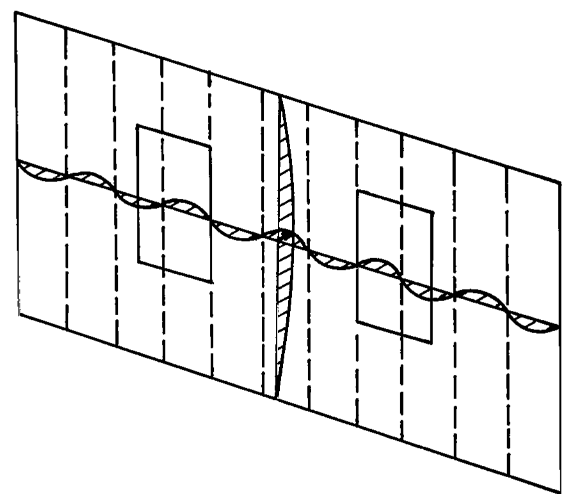
(a) f = 12 Hz; m = 2, n = 2.



(b) f = 15 Hz; m = 4, n = 2.



(c) f = 23 Hz; m = 6, n = 2.



(d) f = 65 Hz; m = 12, n = 2.

Figure 11.- Vibration mode shapes of the west living-room—dining-room wall of Wallops test structure 4.

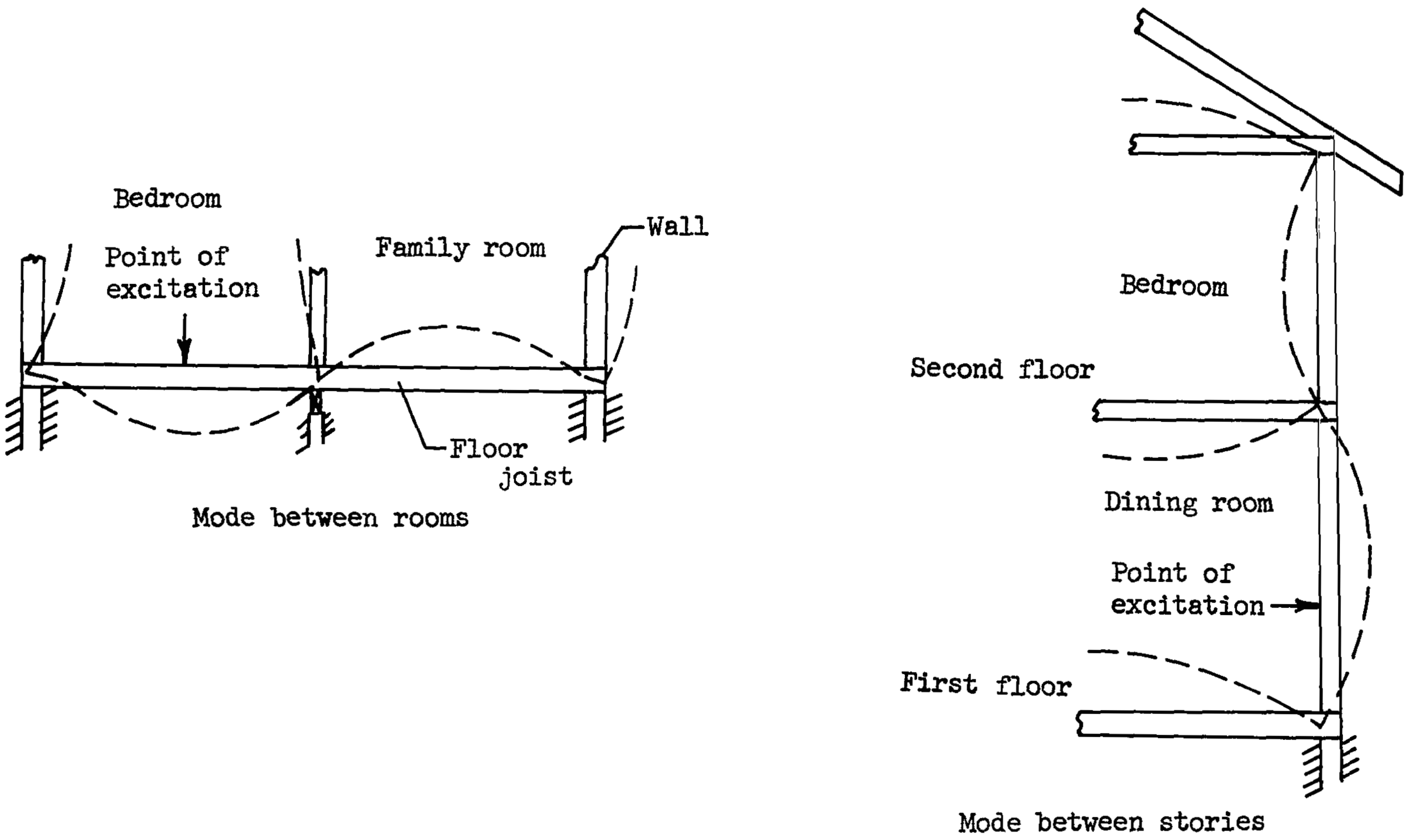


Figure 12.- Vibration modes illustrating structural interactions.

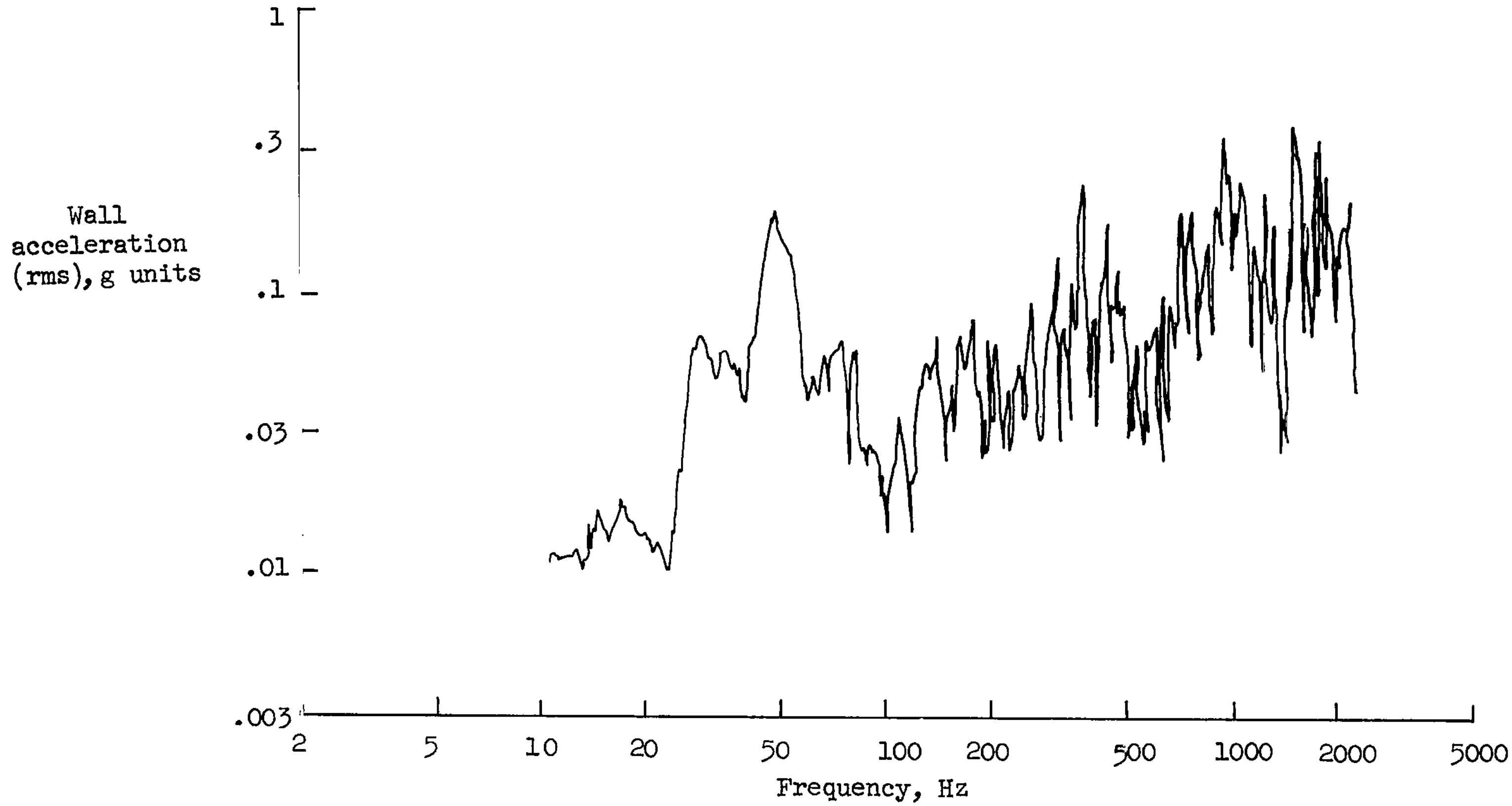
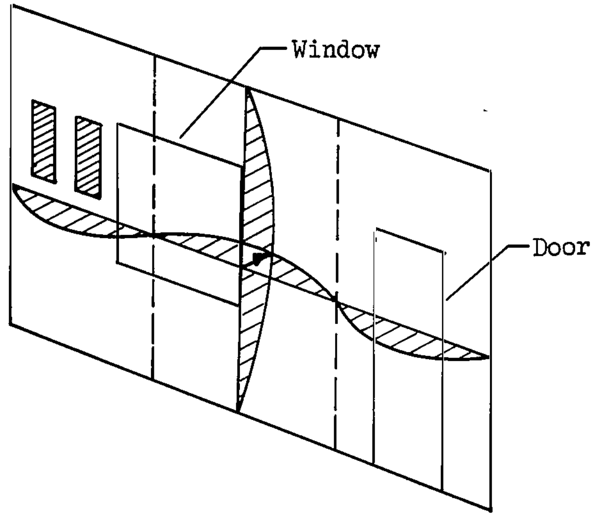
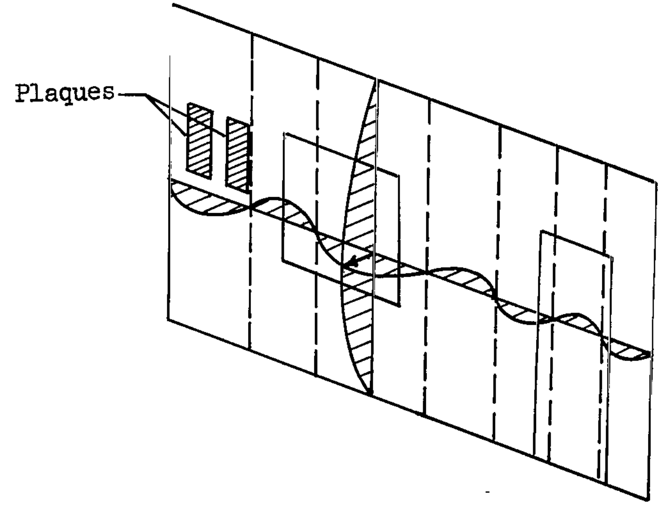


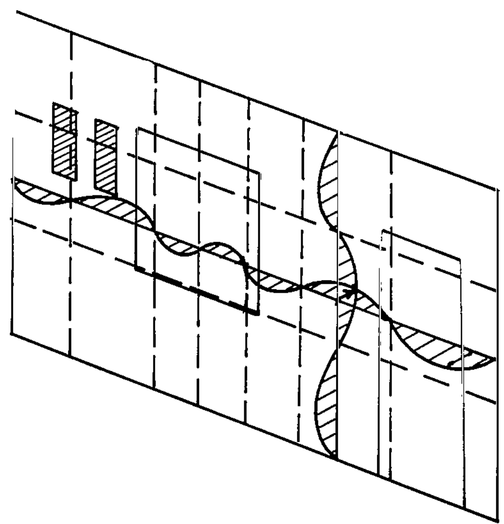
Figure 13.- Acceleration spectrum, associated with study of rattle phenomenon, of the north living room wall of Wallops test structure 3.



(a) f = 27 Hz; m = 4, n = 2.



(b) f = 48 Hz; m = 8, n = 2.



(c) f = 72 Hz; m = 8, n = 4.

Figure 14.- Vibration mode shapes, associated with study of rattle phenomenon, of the north living room wall of Wallops test structure 3.

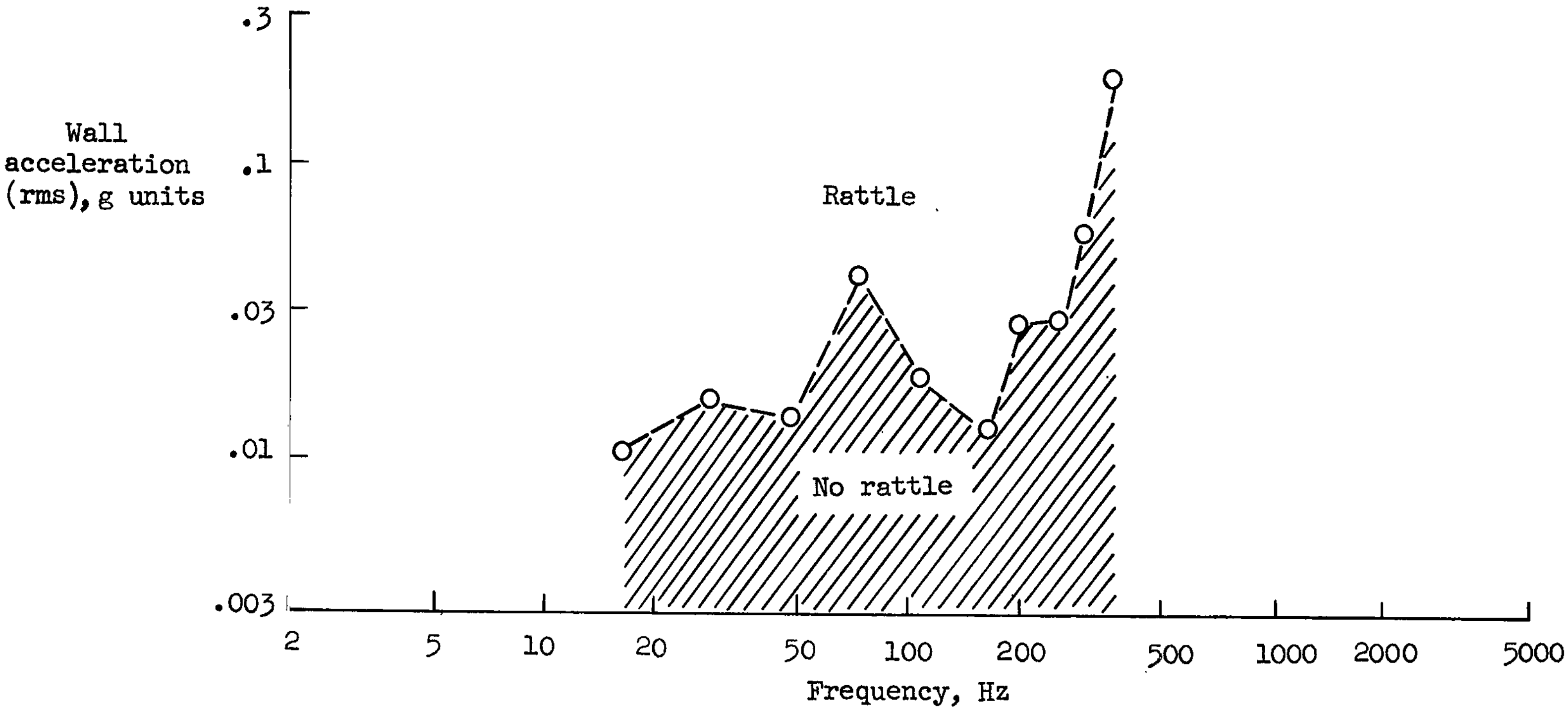


Figure 15.- Plaque rattle boundary on north living room wall of Wallops test structure 3.

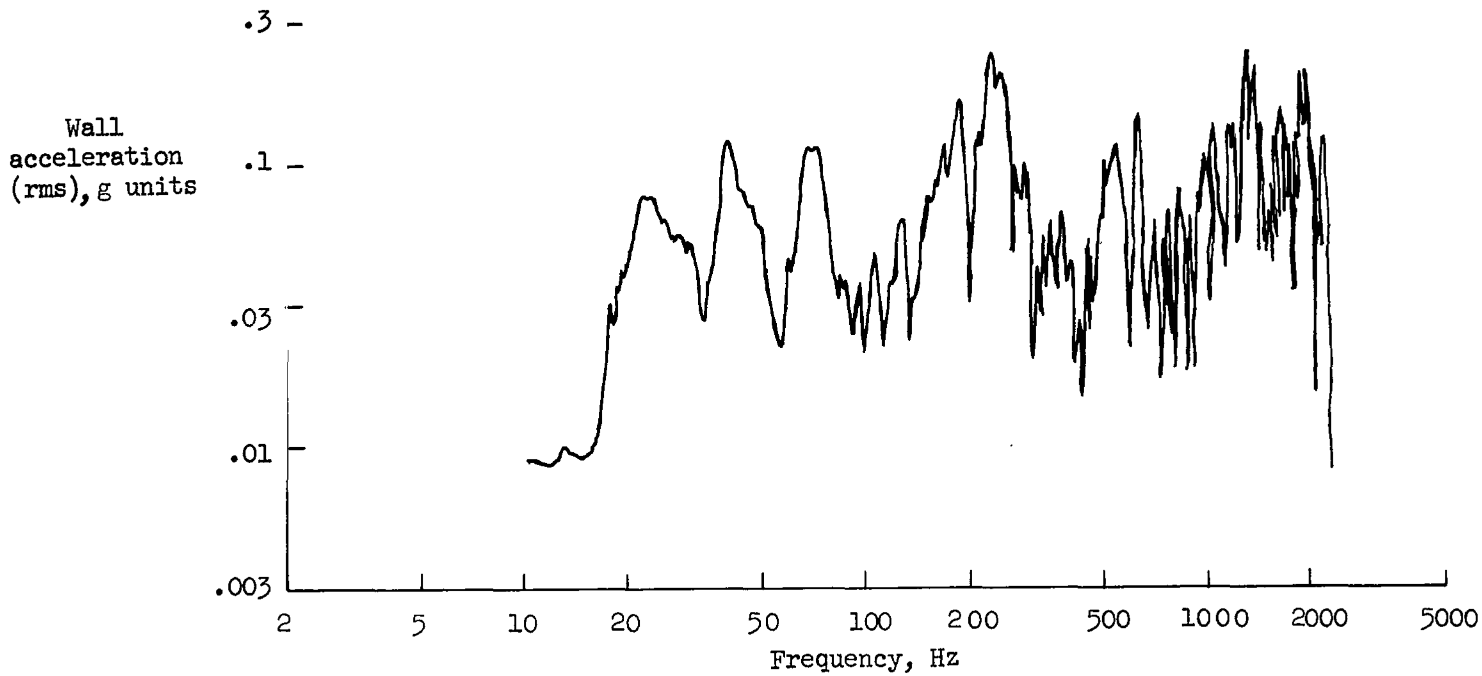
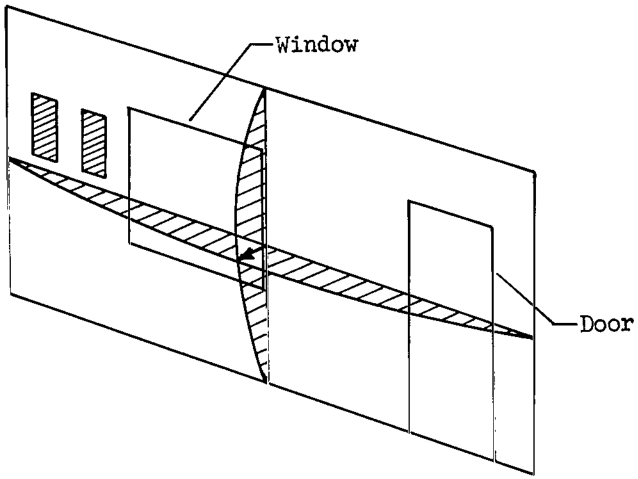
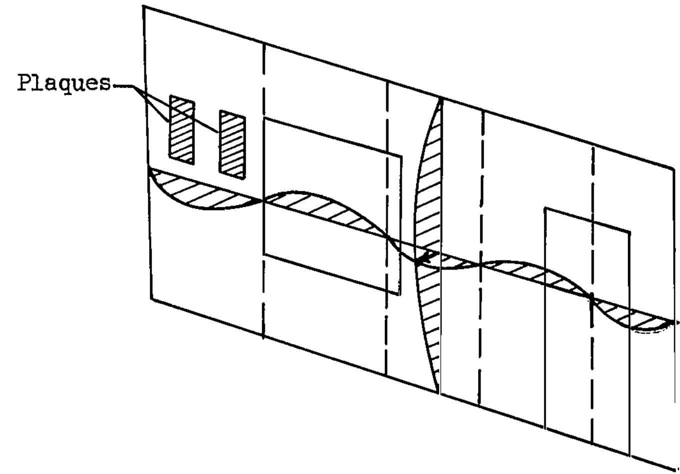


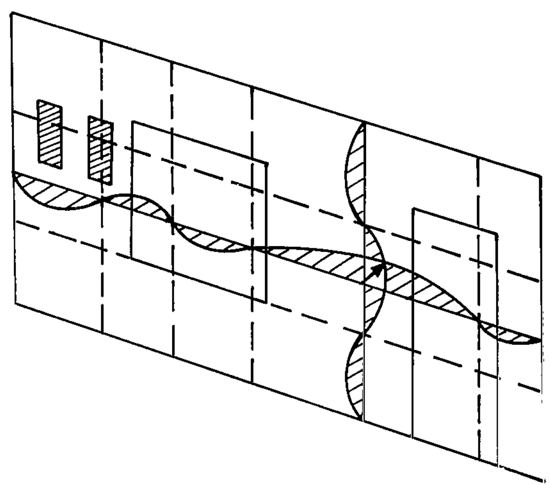
Figure 16.- Acceleration spectrum, associated with study of rattle phenomenon, of the north living room wall of Wallops test structure 4.



(a) f = 22 Hz; m = 2, n = 2.



(b) f = 40 Hz; m = 6, n = 2.



(c) f = 69 Hz; m = 6, n = 4.

Figure 17.- Vibration mode shapes, associated with study of rattle phenomenon, of the north living room wall of Wallops test structure 4.

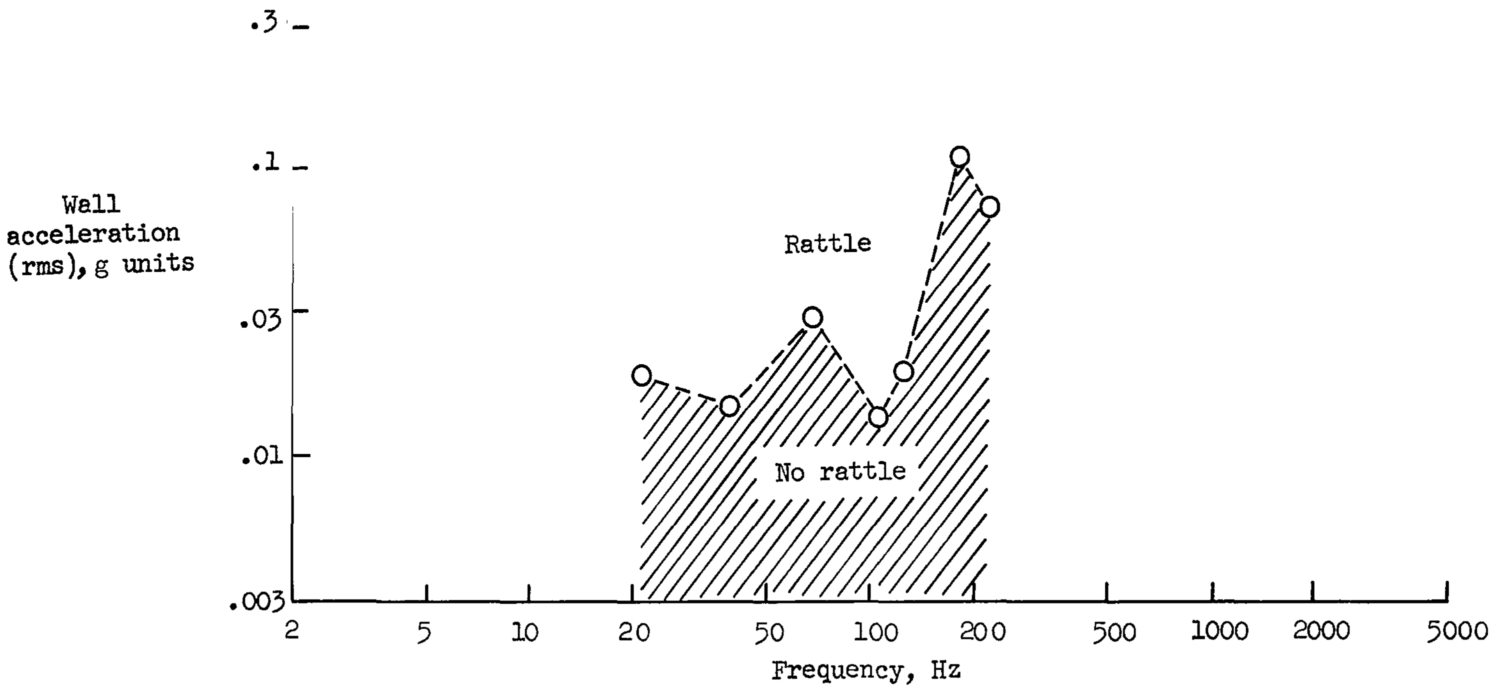


Figure 18.- Plaque rattle boundary on north living room wall of Wallops test structure 4.

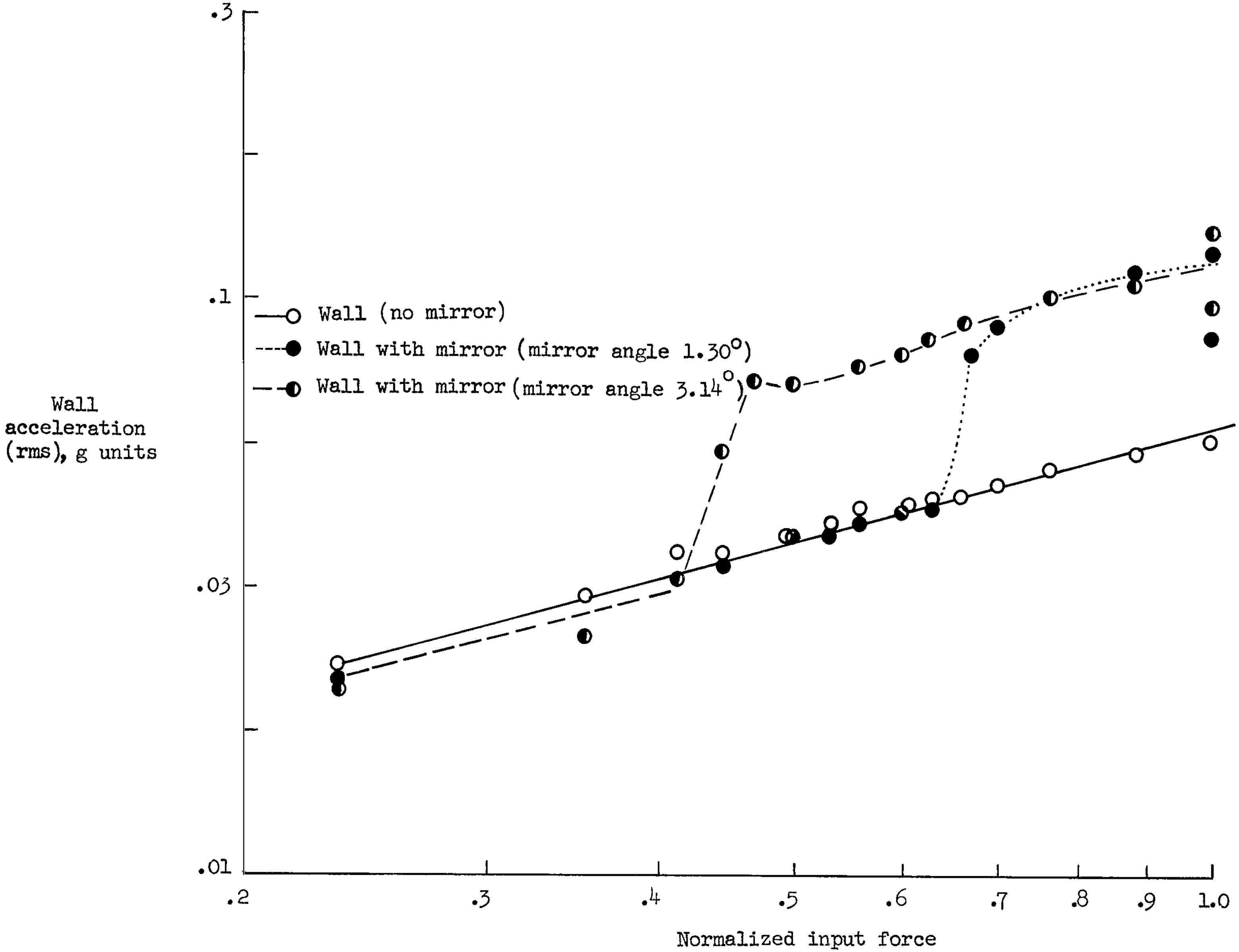


Figure 19.- Wall accelerations with and without mirror for various normalized sinusoidal input force levels. Wallops test structure 4; f = 15 Hz.

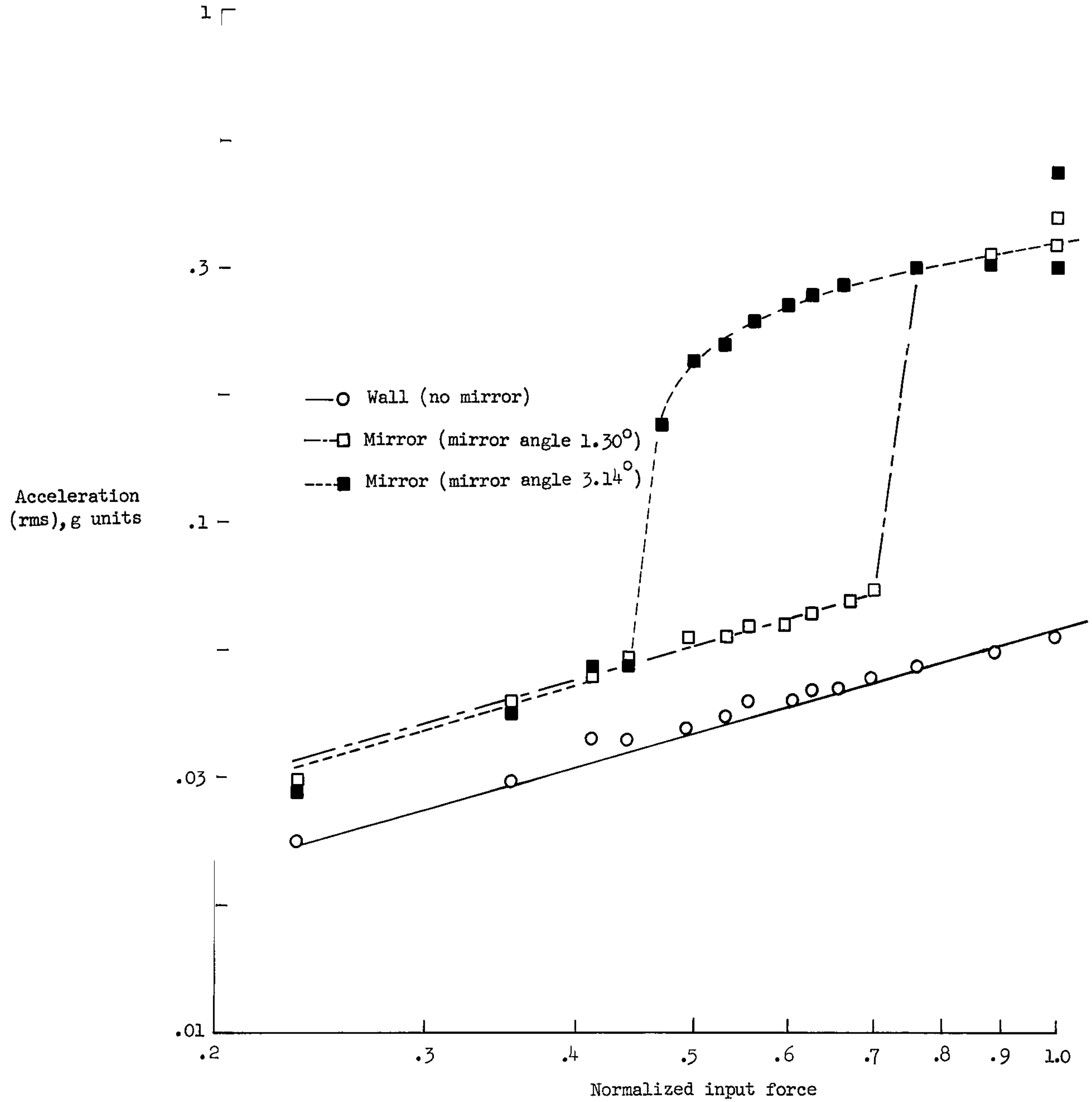


Figure 20.- Mirror accelerations for two different hanging methods for various normalized sinusoidal input force levels. Wallops test structure 4; f = 15 Hz.

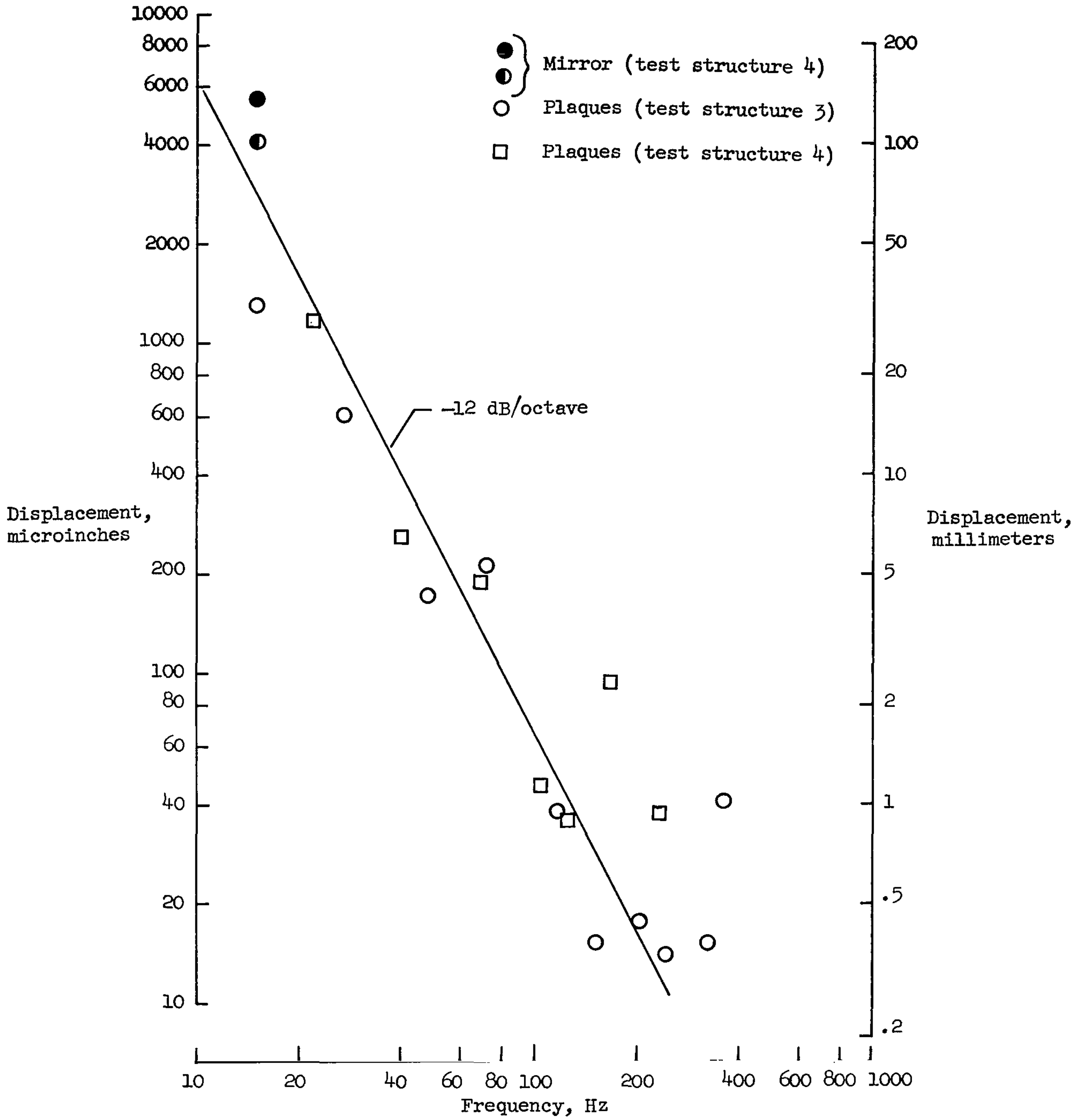
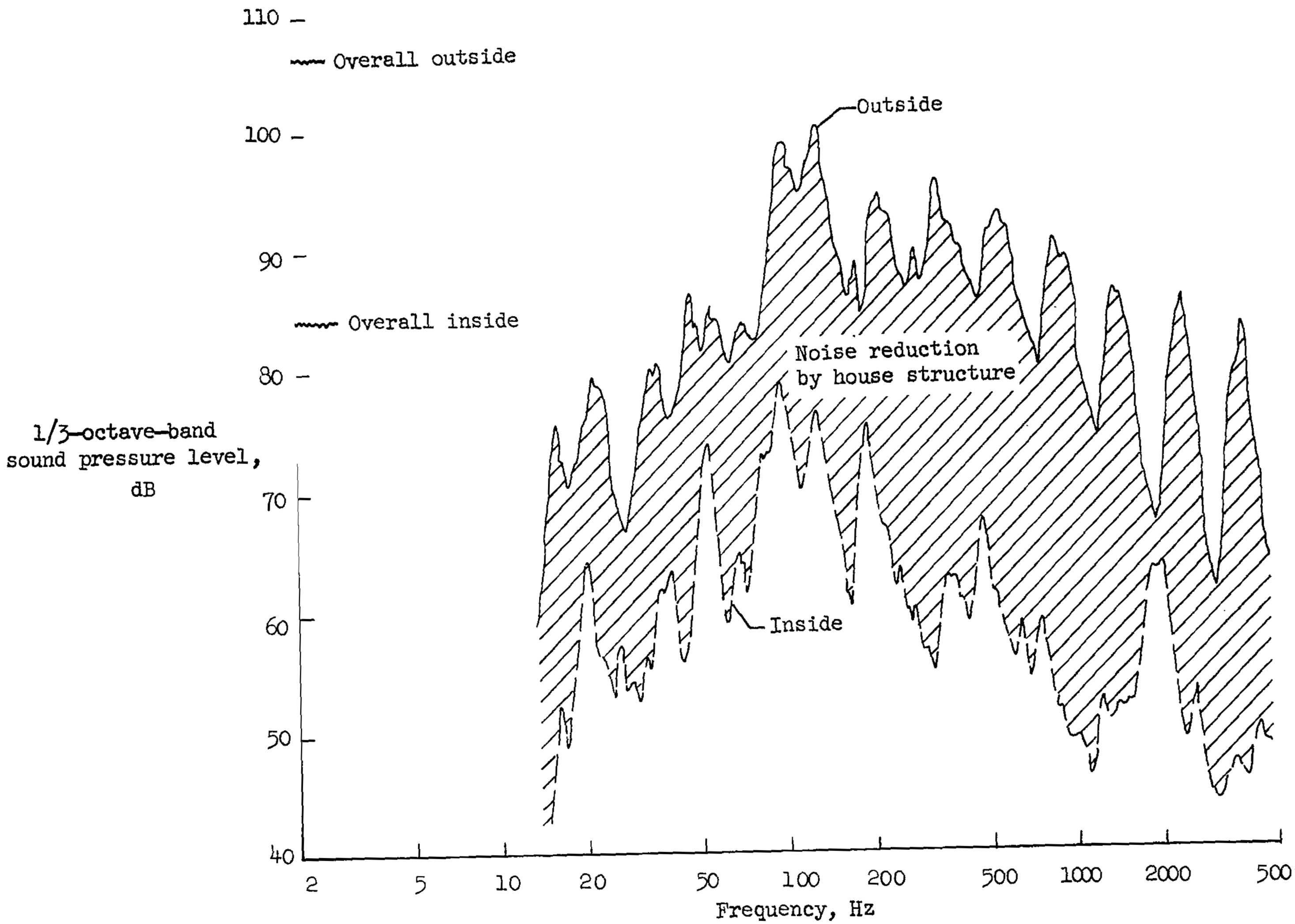
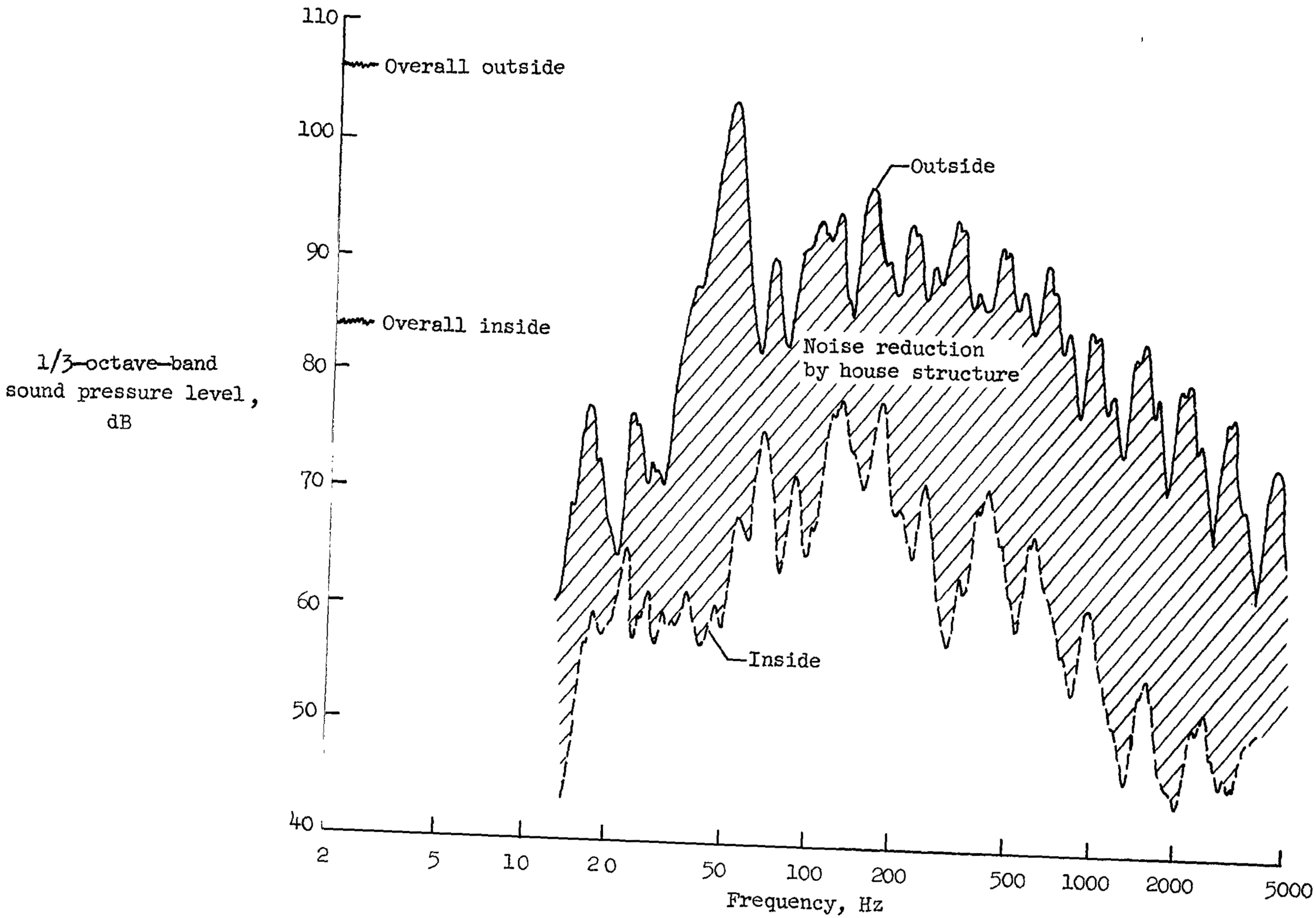


Figure 21.- Wall displacement as a function of frequency associated with acceleration levels for which rattling of plaques and mirror is initiated.



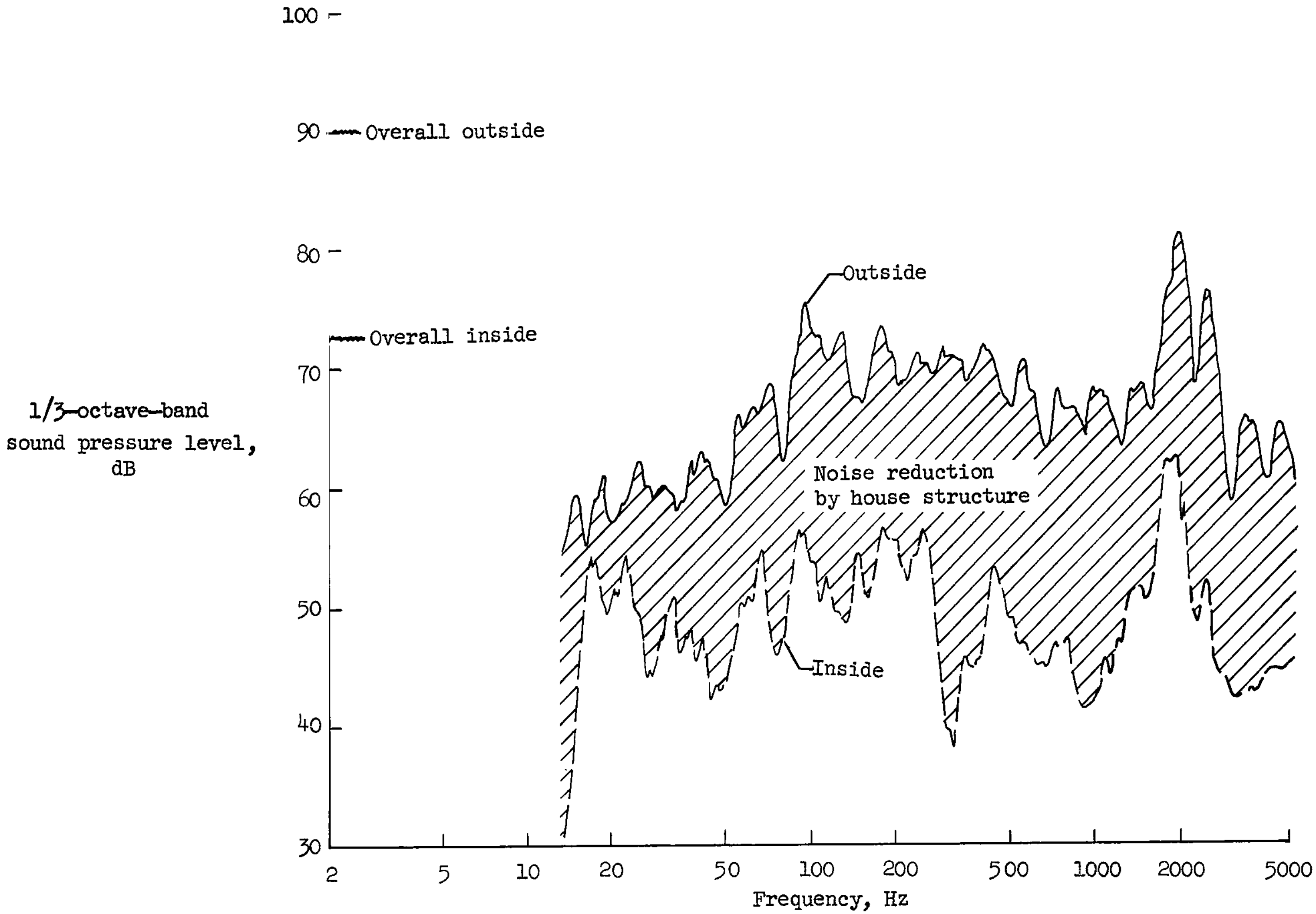
(a) Test structure 3.

Figure 22.- Outside and inside 1/3-octave-band sound pressure spectra induced by Lockheed 1049G airplane flyover.



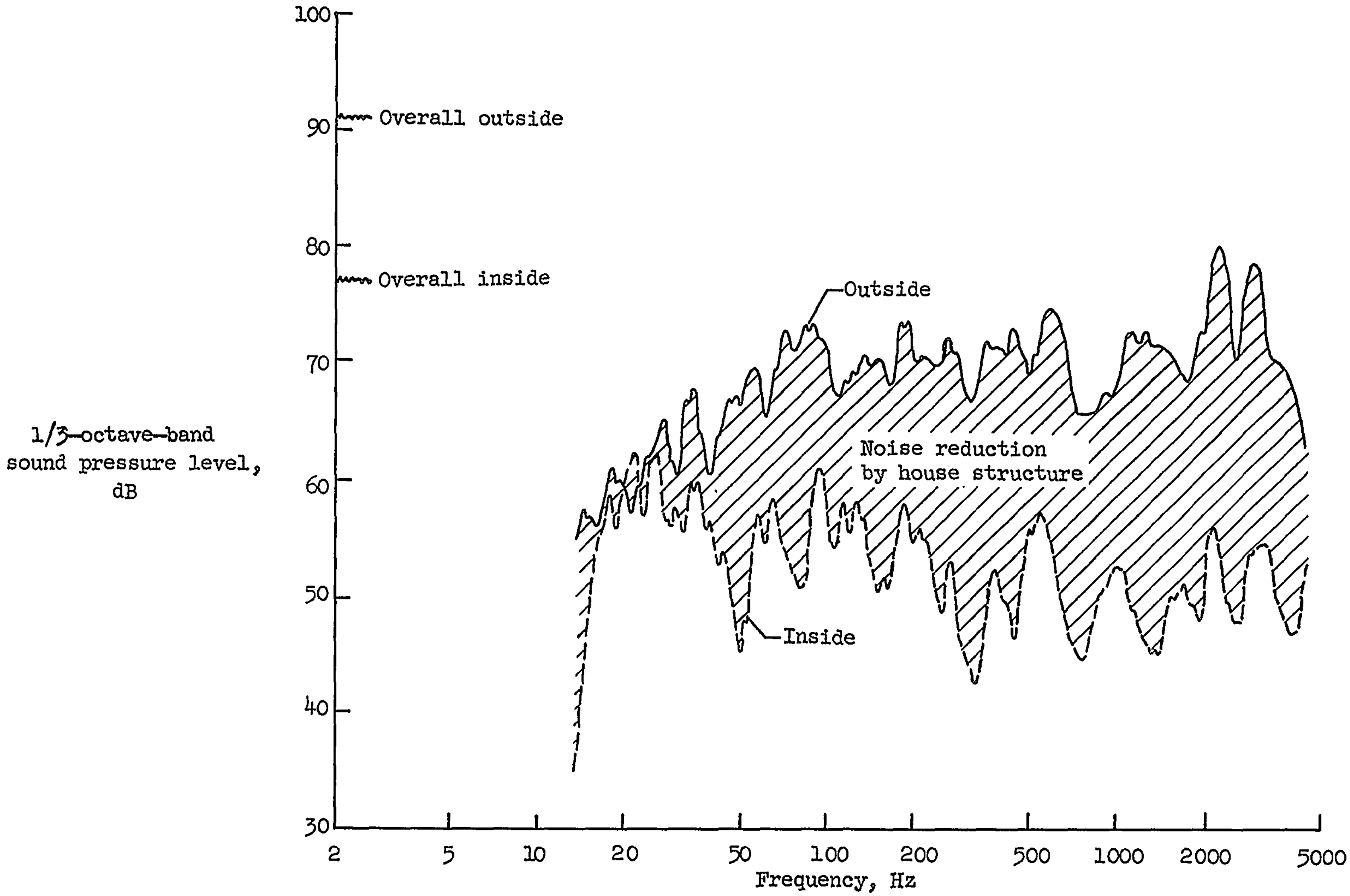
(b) Test structure 4.

Figure 22.- Concluded.



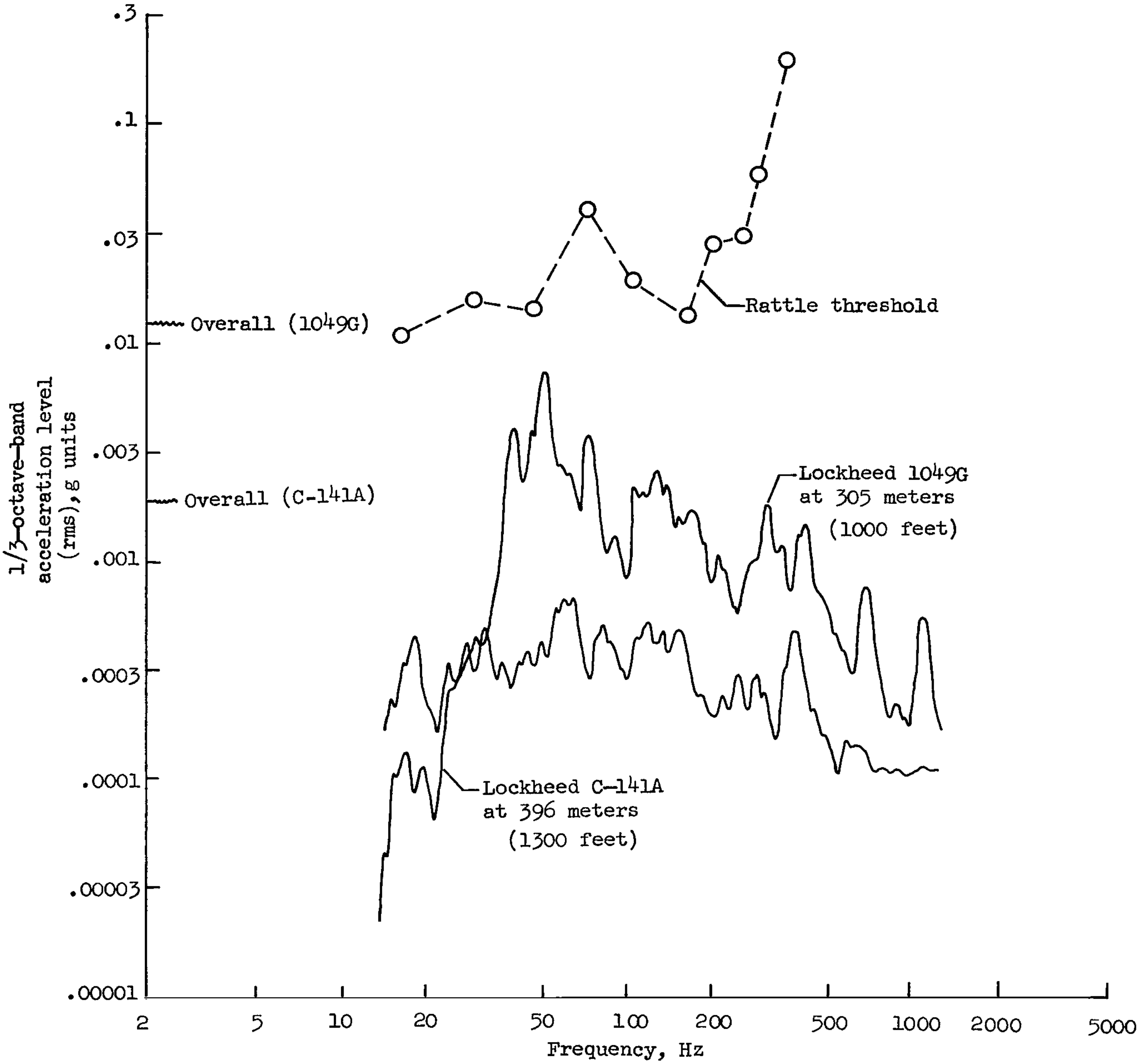
(a) Test structure 3.

Figure 23.- Outside and inside 1/3-octave-band sound pressure spectra induced by Lockheed C-141A airplane flyover.



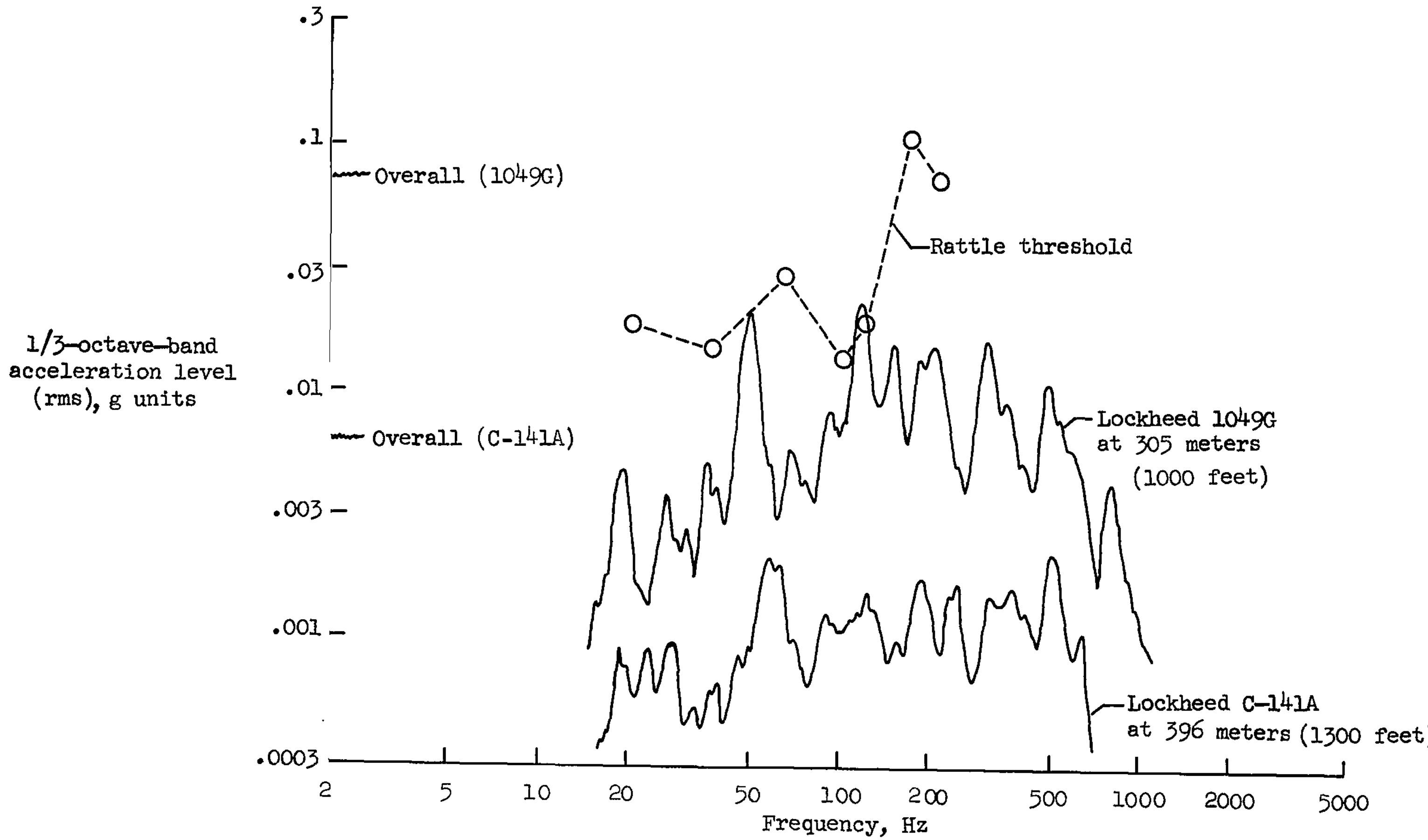
(b) Test structure 4.

Figure 23.- Concluded.



(a) Test structure 3.

Figure 24.- Airplane-induced wall accelerations with plaque rattle threshold accelerations.



(b) Test structure 4.

Figure 24.- Concluded.

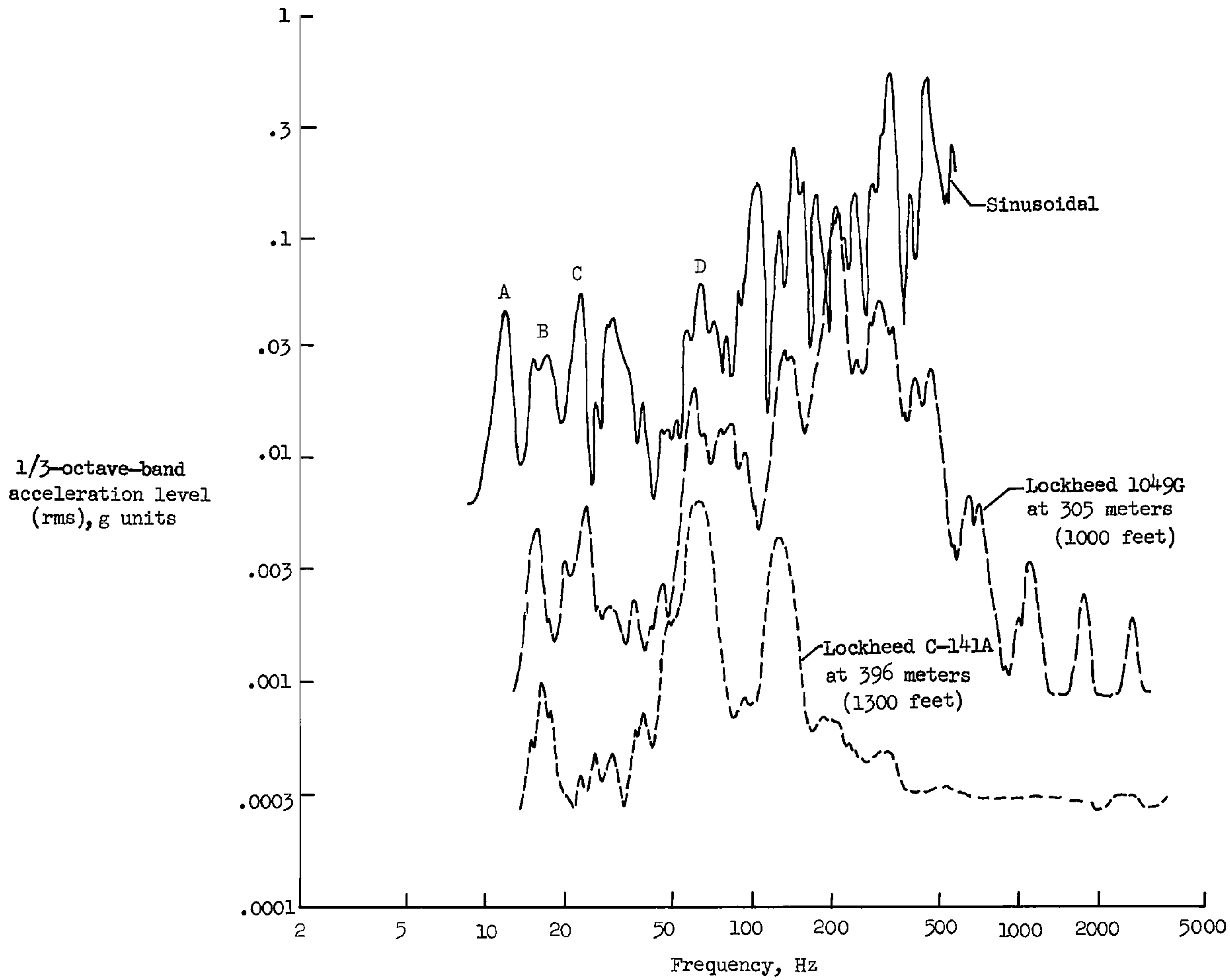


Figure 25.- Airplane-induced wall accelerations and sinusoidal response data for the same transducer location on the west living room wall of Wallops test structure 4.

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