Noise Induced House Vibrations and Human Perception*

Harvey H. Hubbard, member INCE,† summarizes noise induced house responses including frequencies, mode shapes, acceleration levels and outside-to-inside noise reductions. The role of house vibrations in reactions to environmental noise is defined and some human perception criteria are reviewed.

One aspect of community response to noise involves people inside houses. Since house structures have many components which are readily excited by noise and which can be coupled, they respond as complex vibrating systems. These dynamic responses are significant because they affect the environment of the observers inside the house. The nature of this noise induced house excitation problem is illustrated in Fig. 1.

A person inside the house can sense the impingement of noise on the external surfaces of the house by means of the following phenomena: noise transmitted through the structure from outside to inside (see Refs. 1-6); the vibrations of the primary components of the building such as the floors, walls and windows (see Refs. 2,3,7 and 8); the rattling of objects such as dishes, ornaments and shelves which are set in motion by the vibration of the primary components (see Refs. 2, 3 and 9); and in the extreme case damage to the secondary structure such as plaster and tile and/or furnishings (see Ref. 7).

The purpose of this article is to summarize available data on house vibration responses due to airborne noise excitation and to define the role of such vibrations in the problem of human perception of environmental noise. The building response data contained herein, are derived largely from aircraft noise, helicopter noise and sonic boom flyover tests. The associated findings are believed to apply directly to any situations for which the airborne noise component is large compared to the seismic component. The material of this article was developed initially as an appendix of Ref. 10, and has been applied to the community noise evaluation of large wind turbine generators. In situations for which seismic excitation of the house structure can be significant, as for road and rail traffic, the response data of the present article may be inadequate.

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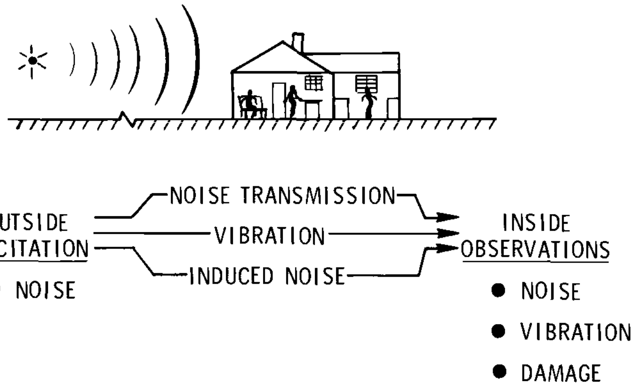

Figure 1—Nature of noise induced house structure responses[3]

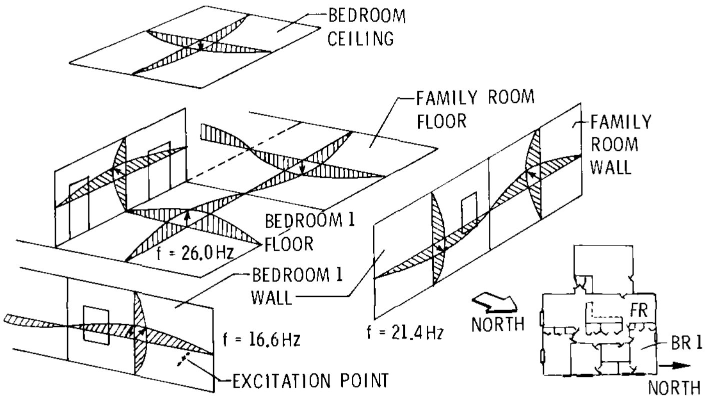

Figure 2—Example frequencies and mode shapes for a one-story house excited by a mechanical shaker, force input-35.6 newtons[2]

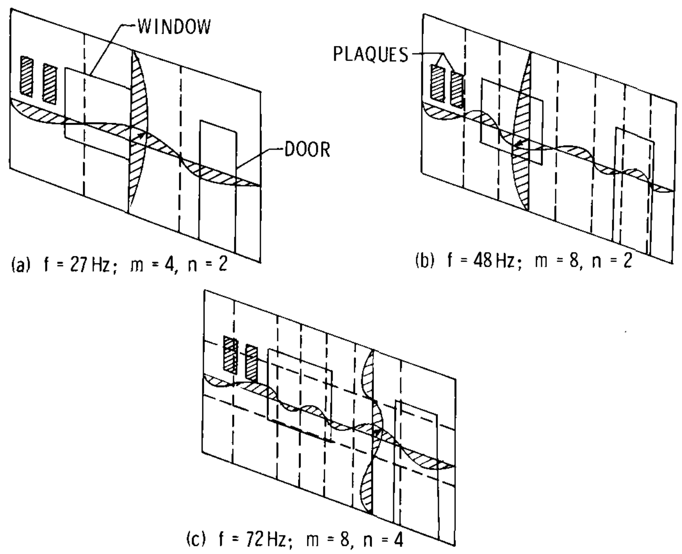

Figure 3—Example higher mode responses of a house wall having door and window openings[2]

Vibrations of House Main Structure Components

Data on the vibration responses of houses is derived from several different sources. Some measurements are available from buildings instrumented with accelerometers, deflection gauges and/or strain gauges on walls, floors, ceilings and windows to record transient responses due to flyovers of subsonic jet and propeller aircraft and helicopters; and the sonic booms of supersonic aircraft.[2,10-15] In addition, a number of experiments have been conducted in which mechanical shakers have been used to excite and measure the responses of houses and house components.[2,8] Results of the flyover and mechanical vibration tests are consistent and tend to characterize the manner in which house structures respond to acoustic loadings.

Frequencies and Mode Shapes. Example mode shapes and frequencies for a one-story test house are given in Figs. 2 and 3. The data of Fig. 2 were obtained by means of a frequency sweep for a constant input vibratory force and at a given point of excitation on the north wall of bedroom number 1 (see insert sketch). The excited wall had a fundamental resonance at 16.6 Hz. The other wall of the room and its floor had resonances at 21.4 and 26 Hz respectively. Data for a number of different house structures indicate frequency values from about 12 to 30 Hz. The above results are representative of typical house structure responses in the first resonance or "oil canning" modes of the type illustrated in Fig. 2. Note that there is evidence of structural and/or air cavity coupling. It can be seen that preferred phase relationships exist as a result of the manner in which the floor and wall structures are arranged.

Higher order modes may, in some cases, be excited for preferred loadings or for more complex structural configurations. Examples of such higher order modes are shown in Fig. 3, which relates to one of the test structures of Ref. 2. Dashed lines are included to indicate experimentally determined node lines. Note that the numbers of node lines and their spacings differ for the three example resonant frequencies. For instance, Fig. 3a shows a modal pattern for which the number of vertical node lines is 4 ($m = 4$, counting the end lines) and the number of horizontal node lines is 2 ($n = 2$, counting top and bottom lines). Uneven spacings of the node lines for the higher resonant frequencies can result from geometric dissymmetry due to window and door cutouts.

Building structures are characterized by nonhomogeneous elements. Walls, floors and ceilings are built-up from an array of evenly spaced beams with sheathing on one or both sides. The sheathing is typically attached to the beams at discrete points by means of nails. The resulting structure of beams and panels tends to respond as dynamically coupled elements but this behavior is much different at low frequencies than at high frequencies.[8] At low frequencies (below 100 Hz) the response is dominated by the behavior of the beams, as suggested by the mode shapes of Fig. 2, and the sheathing panels play only a minor role. On the other hand, higher order modal responses (above 300 Hz) tend to be dominated by the sheathing panels, due to their shorter spans. At intermediate frequencies (100 to 300 Hz) the panels behave as if they were simply supported, while for the higher frequencies the panels behave as though their edges were fixed.[8]

Experience has shown that house structures respond in a linear manner to forced excitation.[2] For cases where the accelerations have been measured for a forced excitation at a given frequency, the acceleration amplitudes are a direct linear function of the input force. Likewise, the measured accelerations increase as a function of frequency for a given input force, and they generally occur about a straight line having a positive slope of 5 dB per octave up to frequencies of about 1000 Hz, the limit of measurements.

Windows vary in size, from the plate glass type which can be several metres in dimension to conventional double hung designs having much smaller sash elements. All windows are similar in that the major element(s) is a relatively thin glass plate simply supported along its edges. A plate glass test specimen of Ref. 8 had natural resonances of 9, 18, 48 and 70 Hz for dimensions of 1.22 m by 1.84 m. Smaller sash windows of conventional houses are noted to have resonant responses in the range of several hundred Hertz. Thus, the range of response frequencies for window components of houses is consistent with those for other structural components. Evidence of window motion may be observed by sight, by feeling, or by the rattling of loose elements.

Acceleration Levels. A large number of measurements are available for the noise induced acceleration levels in house structures (acceleration level $= 20 \log_{10}$ (acceleration, $g/10^{-6}$)). These data have come from a wide range of exposure conditions and rather detailed measurements were obtained for a number of different house structures,[11-15] and from unpublished data by N. D. Kelley and by R. DeLoach, K. P. Shepherd and E. F. Daniels. The above studies relate to the problem of community response to subsonic aircraft, supersonic aircraft and helicopters; and specifically provide data relative to house vibrations and possible damage. Accelerations of the various building components, such as windows, walls and floors, are available and example values are given in Figs. 4, 5 and 6. In each case the measured accelerations are plotted as a function of the peak sound pressure levels measured outside of the house.

Walls. Data for conventional wall (5 cm by 10 cm studs, doubly sheathed) acceleration responses are presented in Fig. 4 for houses exposed to noise from commercial and military jet aircraft, helicopters and propeller aircraft, and sonic booms. The large amount of data for aircraft and helicopter noise are encompassed by the lower hatched area and the available sonic boom related data fit within the upper cross hatched area. These data, which are associated with a wide variety of input spectra, seem to correlate satisfactorily on the basis of peak sound pressure level. It can be seen that the acceleration responses increase generally as the noise levels increase and seem to follow a straight line relationship based on the assumption of linear behavior of the structure.

Floors. Similar results are presented in Fig. 5 for house floor vertical acceleration responses. Note that a limited amount of wind turbine data are also included from Ref. 16. All of the other data shown are for the same test structures as in Fig. 4, and apply directly to the ground floor only. Floor accelerations seem to follow generally a linear response relationship, as did the wall response data. The scatter is, however, considerably greater than for the wall data and the

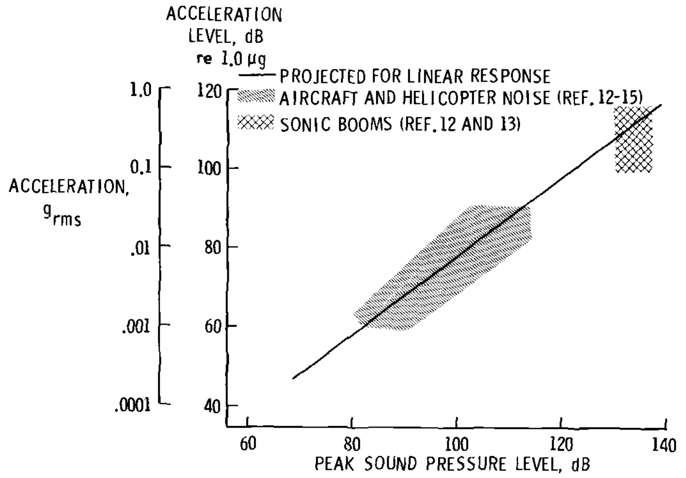

Figure 4—Measured house wall acceleration responses due to noise excitation

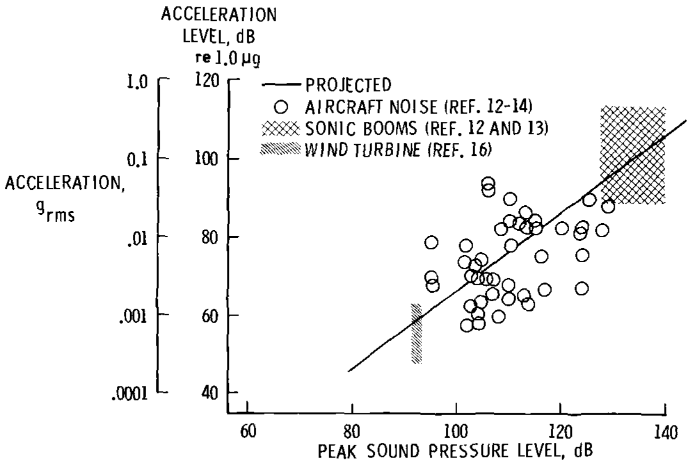

Figure 5—Measured house floor vertical acceleration responses due to noise excitation

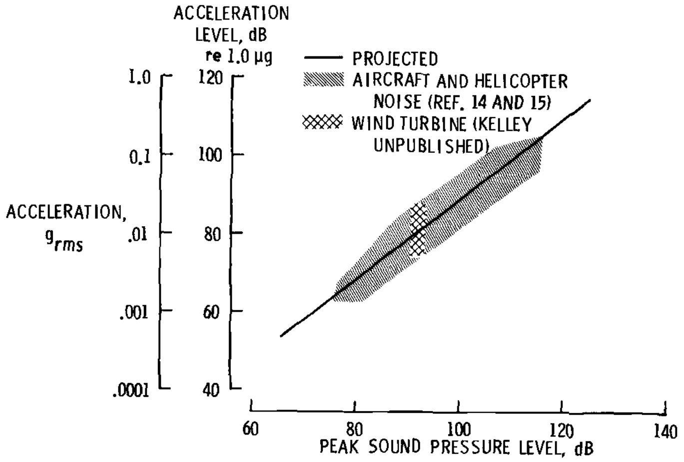

Figure 6—Measured house window acceleration responses due to noise excitation

responses are about 10 dB lower in level for a given noise level input. For comparable inputs, the associated horizontal acceleration values are noted in Refs. 12 through 14 to be about equal to, or are slightly greater than, the vertical values given in the figure.

Windows. Measured acceleration responses for several conventional double hung windows are shown in Fig. 6. Window sash width and height dimensions are about 1 m and glass thickness is about 3 mm. Good correlation is seen for widely different aircraft, helicopter and wind turbine noise inputs, and the trend of the data indicates linear responses;[14-16] and unpublished work by N. D. Kelley, and by R. DeLoach, K. P. Shepherd and E. F. Daniels. For a given input level the window responses are noted to be about 10 dB higher in level than the associated wall responses.

Damage Experience. Very little if any damage to elements of the structure is expected except at extreme values of the input noise level. Experience for blasting, explosions and for sonic booms suggest that damage to houses may occur at peak acceleration values between about 0.3 and 3.0 g in the frequency range of 10 to 100 Hz respectively.[17] It can be seen that the measured levels of wall, floor and window accelerations which are cited for aircraft, helicopter, and wind turbine noise are generally lower than 0.3 g and hence no damage is expected. Sonic boom excitation which is associated with the extreme values of input pressure has been blamed for some incipient damage to light structural elements such as windows, plaster and tile surfaces, etc.[7,10]

Vibrations of Accessories

Wall or floor vibrations of the types described above can give rise to the vibration of wall or floor mounted objects such as pictures, mirrors, plaques, lamps, etc. Such objects are usually in contact with the larger surface at one or more discrete points or along a boundary line, and are put into motion because of the vibratory motions of the surface. Such excitation of objects results in high frequency impact sounds, high frequency vibrations or some associated optical phenomena which serve to identify the event and by so doing cause annoyance of nearby observers. This is an example of nonlinear vibration responses, for which the subaudible frequency excitation of a wall, for instance, can cause audible frequency range responses in a wall mounted object such as a picture.[2,3,9] The rattling of such accessories can be a factor in annoyance.

The data of Fig. 7 are included to indicate the range of acceleration responses expected from vibrating accessories. Two different criteria lines are included from Ref. 9. Both are shown as being horizontal because no significant effects of frequency were identified in any of the experimental data. The top line is drawn at 1.0 g and is the prediction for rattling in the case of normal contact, as for an object resting on a horizontal vibrating surface such as the floor. The hatched area represents the range of comparable experimental data and suggests that in practical cases some rattling might occur at acceleration levels less than the theoretical value of 1.0 g. Such lower acceleration values are usually associated with small contact areas and probably result from local surface imperfections and misalignments from the vertical.

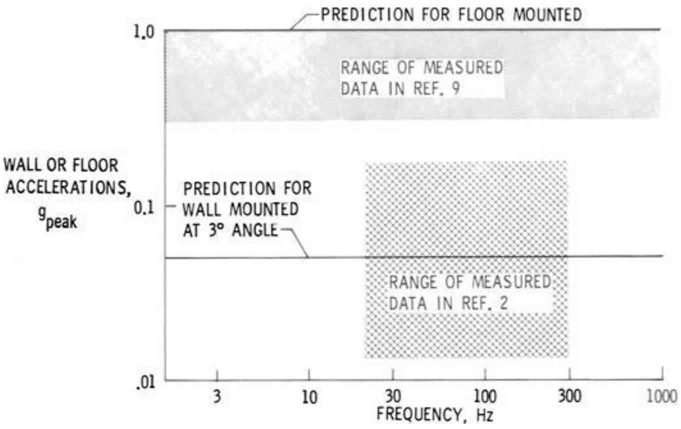

Figure 7—Criteria for the rattling of wall and floor mounted objects due to vibratory excitation

For cases where objects are suspended in pendulum fashion from the wall the lower criteria line might apply. It should apply theoretically to situations where the hang angle (angle between wall and hanging flat object) is about 3 °. The cross hatching represents the range of data available for a number of objects such as plaques, pictures and mirrors, from house situations and for a steel ball in laboratory tests. The scatter of measured results suggests that small variations in the wall geometry or that of the suspended object can be significant. By implication, objects that hang by smaller hang angles are susceptible to rattle at lower acceleration levels.

Vibration Perception Criteria

One of the common ways by which a person may sense the noise induced excitation of a house is through structural vibrations. This mode of observation is particularly significant at frequencies below the threshold of normal hearing, or in the low frequency range where the ear is less sensitive.

Whole Body Perception. There are no standards available for the threshold of perception of vibration by occupants of buildings. Guidelines are available, however, for interim use.[18-20] Together they cover the frequency range 0.063 to 80 Hz. The appropriate perception data from each of the above documents are reproduced in Fig. 8 and are represented by the composite heavy line curve. This curve represents the combined responses of a person in either the up and down, fore and aft, or sideways directions whichever is the most sensitive. This is believed appropriate for the house vibration case because persons may be in various positions when experiencing vibrations. The hatched region of Fig. 8 encompasses the perception threshold data obtained in a number of independent studies.[21-25] Different investigators, using different measurement techniques, subjects and subject orientations, have obtained values which extend over a range of

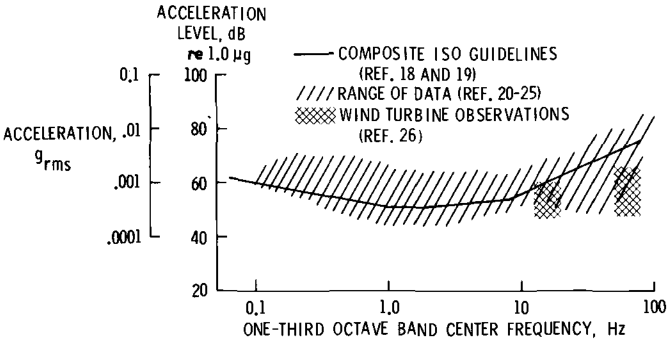

Figure 8—Most sensitive threshold of perception of vibratory motion by humans

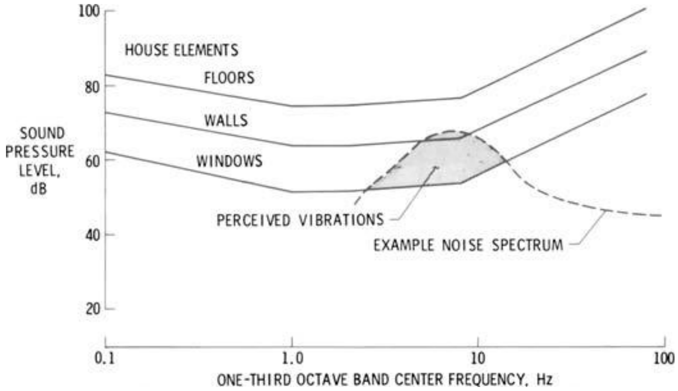

Figure 9—Sound pressure levels sufficient to cause perceptible vibrations of house structure elements over a range of frequencies

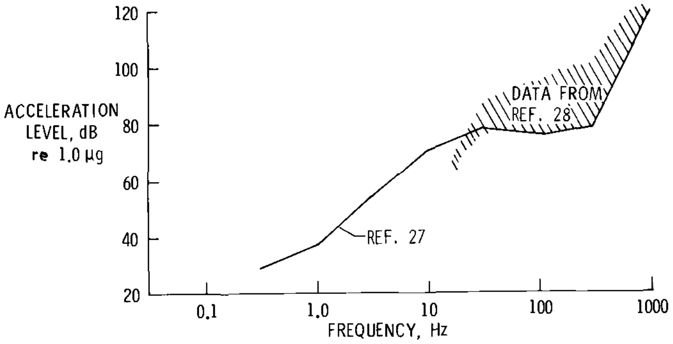

Figure 10—Pure tone thresholds of tactile perception

about a factor of 10 in vibration amplitude. The composite (related) guidelines curve of Fig. 8 is judged to be the best representation of the available whole body (most sensitive axis) vibration perception data.

Note the two cross hatched regions on Fig. 8 from the data of Ref. 26. These are estimated one-third octave band levels of vibrations which were judged perceptible in two different house structures excited by wind turbine noise. Based on the values of the guidelines curve they would be judged marginally perceptible and thus seem to constitute a good confirmation of the other perception threshold data of Fig. 8.

Figure 9 indicates the outside sound pressure levels in given one-third octave bands that will cause perceptible vibration inside a house structure. The top curve was derived directly from the composite perception data curve of Fig. 8 and the floor response data of Fig. 5. It is thus believed that the sound pressure level values indicated are equal to or are near in value of those required to cause perceptible floor vibration for an occupant. The curves labeled "walls" and "windows" are inferred from the data of Fig. 8 and the house element data respectively of Figs. 4 and 6. It is not clear how the concept of whole body perception applies to the wall and window vibrations, but the hierarchy of house element responses suggested in Fig. 9 is consistent with available measurements and with observations. From the figure it is possible to determine the outside sound pressure levels sufficient to cause perceptible vibrations of house structural elements over a range of frequencies. For instance, if a house was exposed to the example noise spectrum of the figure, there would probably be perceived vibrations of the walls and windows and no perceived vibrations of the floors.

Tactile Perception. House building vibrations of walls and windows may also be observed by means of tactile perception (perceived by touch of the finger tips). The available tactile perception data for pure tone excitation in the frequency range of interest is shown in Fig. 10. The most extensive study is reported in Ref. 27 and is represented by the solid curve. Results of a series of more abbreviated studies from Ref. 28 are represented by the hatched area. It can be seen that there is a trend toward lower sensitivity as the frequency increases. The sensitivity to tactile perception is comparable to that for whole body perception (see Fig. 8) in the range of frequences near 100 Hz. Note that window and wall vibrations may be observed by tactile perception at peak noise level excitations of about 90 dB (Fig. 6) and 100 dB (Fig. 4) respectively.

House Noise Attenuations

Another phenomenon observed by the occupants of a house is the noise transmitted to the inside spaces from the outside. The inside noise exposures are different from those on the outside because of the influence of the house structure as the noise is transmitted through it. Under normal circumstances the noise levels are reduced. Data showing example house noise reductions as a function of frequency are given in Fig. 11. The hatched area encompasses results obtained in Refs. 1 through 6. The noise reduction values of the ordinate are the differences between inside and outside readings. The most obvious result is that the noise reductions are larger at the higher frequencies. This implies that the measured spectra inside the house will have relatively less high frequency content than those on the outside.

There are very few data available at the low frequencies (below 50 Hz). In this range the wavelengths are comparable to the dimensions of the rooms and there is no longer a diffuse sound-field on the inside.[29] Other complicating factors are the role of stiffness at these lower frequencies and the existence of air leaks. The inside distribution of pressure can be nonuniform because of structureborne sound, standing wave patterns, organ pipe modes and cavity resonances due to room, closet and hallway configurations.[30] The anticipated

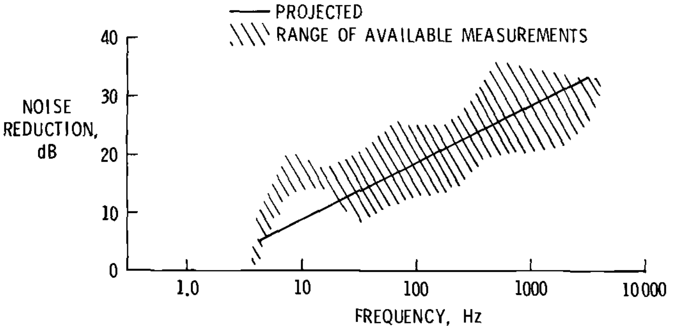

Figure 11—House noise reduction as a function of frequency for the windows closed condition

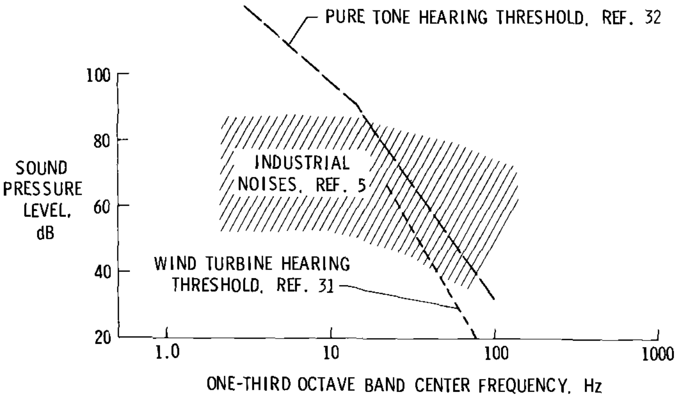

Figure 12—Range of low frequency inside noise levels which caused adverse reactions by occupants

large variation of sound pressure levels from one location to another at very low excitation frequencies has not been documented for houses. Thus, it is difficult to characterize the low frequency noise environment inside of a house structure based on a knowledge of the outside noise environment.

Low Frequency Noise Perception

There are fragmentary reports that indicate some unusual reactions to noise at very low frequencies, particularly when such noises are observed inside a structure or a vehicle.[5] The data of Fig. 12 are representative of some of the documented cases. A number of these are cited where low frequency noise from industrial operations has propagated relatively long distances into residential areas and has resulted in complaints. The hatched area of Fig. 12 encompasses the ranges of frequency and noise level which are believed to have caused the complaints. In all cases the levels of the higher frequency noise portions of the spectra were judged to be well within known tolerable limits. The low frequency components (below 125 Hz) are thus believed to be most significant.

It can be seen that many of the frequency-noise level combinations are below those of the well established hearing thresholds of Refs. 31 and 32. Thus there is an indication that there are significant extra-auditory effects such as noise induced house vibrations, or that there are localized areas in the houses where the inside noise levels are considerably higher than the limited measurements, and may actually exceed the threshold of hearing.

Concluding Remarks

House buildings respond readily to noise excitations and their responses can play an important role in community reactions to noise. Walls, floors, ceilings and large windows respond mainly in the "oil canning" modes at frequencies below 100 Hz and their motions are controlled largely by the beam elements. At higher frequencies the sheathing panels play a greater role and are the dominant elements at frequencies above approximately 300 Hz. Measured accelerations for a number of different types of noise inputs correlate generally on the basis of peak noise level and increase linearly as the input level increases. Wall and floor mounted objects such as lamps, pictures, mirrors, etc., may rattle by excitation of the main structure.

Criteria are included for perception of vibration, the rattling of wall and floor mounted objects, and noise induced damage of secondary structures and furnishings.

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