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Structureborne Sound in Buildings: Needed Practical Research in Light of the Current State of the Art

Eric E. Ungar

June 1980

Report No. 4309

Prepared for:
Center for Building Technology
National Engineering Laboratory
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PREFACE

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1. INTRODUCTION

The designation "structureborne sound" has found general acceptance in the past decade for referring to processes that involve solid bodies (structures or structural components) as generators, transmitters or radiators of audible sound. Structureborne sound thus is concerned primarily with the audio frequency range — that is, with frequencies between roughly 16 Hz and 16 kHz. However, structural vibrations in the 4 Hz to 100 Hz range generally are also considered in the domain of structureborne sound, even though in this frequency region people usually can feel the structural vibrations more readily than they can hear the associated airborne sound.

Structureborne sound clearly plays a major role in determining the noise and vibration environments in buildings. Of the exterior noise that reaches the interior of a building, only that which is transmitted via openings — e.g., open windows, doors, or ducts — does not involve a structureborne aspect. The same statement applies also to noise transmitted from one space (room) in a building to another. Where sound results from structural vibrations, such as may be caused by passing traffic, by people walking, or by machinery motions, the structureborne sound aspect obviously is the primary one.

Several classical problems of building acoustics fall within the domain of structureborne sound, including that of sound transmission through walls connecting two rooms, particularly in the presence of flanking, and that of impact noise. Sound transmission through a wall, after all, involves the wall being set into motion by airborne sound incident on it, and then radiating sound due to this motion; flanking occurs as the direct result of the transmission of structureborne sound along floors, ceilings and sidewalls. Impact noise, as the name implies, involves the generation of structural vibrations by impacts on the structure's surfaces; these vibrations produce noise due to radiation from the directly impacted structural components, as well as from those to which vibrations are imparted indirectly.

The fundamental aspects of the applied science pertinent to structureborne sound, as well as much of the total body of the relevant information, were summarized by L. Cremer and M. Heckl in a German book that appeared in 1967. This book was subsequently updated, revised, translated into English, and published in 1973 under the title of *Structure-borne Sound* [Cremer, 73]*. It is still the only available extensive collection of basic and engineering information on measurement and excitation, propagation and attenuation of structureborne sound and on the associated radiation of airborne sound.

Recent economic, sociological and technological trends have led toward increased construction of multi-family dwellings and larger office and industrial buildings, many of which are designed and built by modern methods that permit the economically efficient use of lighter structural components and larger unsupported spans. These trends have resulted in buildings that transmit structureborne sound relatively well. At the same time, people have in recent years become more concerned with the noise

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*Brackets indicate references appearing in the bibliography at the end of this report. References are identified by the last name of the first-listed author and the year of publication.

and vibration environments to which they are subjected [Berendt 67, Sadowski 75]. It is therefore appropriate to examine the field of structureborne sound for the purpose of identifying potential building improvements, with particular emphasis on those improvements that involve minimal economic penalties or that may result in associated benefits, such as in terms of energy conservation. It accordingly is the intent of the present report to present an overview of the current state of the art, in order to identify fruitful areas of investigation.

The first of the following sections presents a general introduction to the field of structureborne sound and discusses the most important phenomena. The section thereafter summarizes some of the recent results described in the technical literature, and the final section suggests some areas for future research. An annotated bibliography is appended.

2. THE IMPORTANT PHENOMENA

2.1 Excitation and Local Response

Structureborne sound may be produced by airborne sound incident on structural surfaces, by vibrations of mechanical systems in contact with structures, by impacts of solid objects, or by unsteady fluid forces acting on surfaces of the structures of concern. The excitation of structureborne sound by incident airborne sound is the primary phenomemon associated with sound transmission through walls, much of the audible noise due to rotating equipment in buildings is due to excitation of the supporting structures by the equipment's vibrations, the noise and vibrations due to footfalls are common manifestations of structureborne sound generated by impacts, and noise radiated from the side of a duct often results largely due to the unsteady pressures associated with the flow of air in the duct.

The responses of uniform panels (such as window panes or the walls of a room) to incident airborne sound have been studied extensively, in part because much the same phenomena that are involved in establishing these responses also play a role in determining the airborne sound radiation due to vibrations of such panels. Airborne sound incident on a panel produces a distribution of fluctuating pressures on the panel's surface, and these pressures cause the panel to vibrate. These panel vibrations produce changes in the pressures that act on the surface (and also lead to the radiation of airborne sound), but these changes and their effects on the panel vibrations generally are of second order.

A panel responds best to pressures whose temporal and spatial characteristics match those associated with natural modes of the panel vibrations or those corresponding to waves freely propagating along the panel. Thus, a panel responds well to pressures that vary in time at a natural frequency of the panel and that have a spatial distribution that corresponds to the related mode shape, and a panel also responds well to airborne waves that have a "trace" wavelength and speed (i.e., wavelength and speed as measured along the structural surface) that match those of flexural waves in the panel. (See Fig. 1.) The two foregoing matching conditions are closely interrelated, of course, because any mode can be considered as a standing wave obtained by superposition of oppositely traveling waves.

Although a panel's boundary conditions affect the characteristics of its lowest few modes significantly, the effects of the boundary conditions diminish with increasing frequency and for typical building components tend to be unimportant above a few hundred hertz. Thus, the audio-frequency responses of finite panels (where boundary conditions play a role) generally may be understood in terms of those of infinite plates (where boundaries do not affect the local responses).

Reference has already been made to the "coincidence" or "trace-matching" phenomenon, where the pressure distribution traveling along a panel due to an obliquely incident airborne sound wave matches the displacement distribution associated with a flexural wave propagating in the panel. Although this phenomenon in the strictest sense can occur only for infinite panels, its essential features also control the responses of finite panels. For any isotropic panel there exists a so-called "coincidence frequency" (sometimes also called its "critical frequency"), at which frequency the wavelength of sound in air is equal to the wavelength of flexural waves in the panel. At frequencies below the coincidence frequency, the wavelength of airborne sound waves is greater than that of the structureborne flexural wave, and thus the trace-wavelength of the airborne wave along the panel exceeds the structureborne wavelength for all angles of incidence of the airborne sound, so that trace matching cannot occur. At frequencies above the coincidence frequency, on the other hand, the airborne sound's wavelength is less than that of the panel flexural wave, so that trace matching can occur for some particular angles of incidence. (Again, see Fig. 1.) Thus, for randomly incident sound, a panel tends to respond relatively well at frequencies above its coincidence frequency and relatively poorly at frequencies below that frequency.

The responses of structural components, such as beams and plates, to mechanical excitations — both of steady and transient (e.g., impact) nature — have been the subject of engineering study for well over a century and have been discussed in scores of textbooks and summarized in several handbooks; e.g., [Harris, 76]. However, most of this information deals with the lowest few modes of well-defined structural systems, and thus generally is of limited value in relation to structureborne sound. Although it is clear that structural components respond best to excitation that acts at a natural frequency of the structure and is applied at an antinode associated with the resonant mode, at audio frequencies the modes and natural frequencies of typical building structural components can rarely be determined. Calculations cannot be carried out meaningfully because boundary conditions and structural geometries usually cannot be defined adequately, and measurements become difficult because excitation at a single frequency generally produces significant responses of several modes.

At high enough frequencies – typically at frequencies that are more than a decade above the fundamental natural frequency of a structural component of concern – the local response of the structural component (i.e., the response at and near the driving point) is very nearly the same as that of a similar component of infinite extent. For example, the high-frequency driving-point impedance of a concrete floor slab is equal to the driving-point impedance of a concrete slab of the same thickness but of infinite extent. The reason for this phenomenon is that the wavelengths become short at high frequencies, so that the propagation path from the driving point to the nearest edge and back to the driving point encompasses many wavelengths. Because there occurs a certain amount of attenuation per wavelength (and in general this attenuation also increases with increasing frequency), a signal returning to the driving point is so highly attenuated that the effect at that point is essentially the same as if there were no signal returning at all – as is the case if the edges that reflect the wave are infinitely far from the driving point.

The behavior of structural panels in response to unsteady pressures associated with fluid flows is much like that in response to airborne sound. The primary difference is that for airborne sound there exists a definite relation between frequency and wavelength, leading to the previously discussed well-defined coincidence phenomenon, whereas for fluid flows the relation between frequency and the pressure "correlation length" depends on flow speed and geometry, as well as the physical properties of the flowing fluid. In fluid flows the pressure fluctuations on bounding structures are random (that is why the spatial distribution of these pressures are described in terms of correlation lengths, and not in terms of wavelengths), but it is still the case that generally the most significant response occurs at frequencies at which the convection velocity of a fluctuating pressure field along a panel matches the propagation speed of flexural waves in the panel.

2.2 Propagation

The vibrations resulting from excitation applied locally to a structural component are not confined to the immediate vicinity of the excitation point. Rather, they spread along the structural component – and from it, to adjacent components.

For structural components that are essentially of the form of plates or beams, flexural motions generally are of primary importance. These bending motions are almost always responsible for the dominant excursions perpendicular to the structural surfaces, which excursions are the ones that lead to the radiation of airborne sound, and which also are the ones that are often most readily felt.

However, flexural motions are not the only ones that occur. Longitudinal (tension-compression) and shear oscillations accompany flexural oscillations in all practical cases; torsional oscillations also occur, particularly where structural assymetries exist. Although longitudinal, shear and torsional oscillations generally play a much less significant role in the direct radiation of airborne sound than do flexural oscillations, they are important factors in the propagation of vibratory energy along structures. Wherever there exists a structural discontinuity – e.g., at edge joints of walls, where a thinner section plate joins a thicker section, where a plate is reinforced by a beam, or where a massive block rests on a plate or beam –

some flexural oscillatory energy is converted into longitudinal and shear energy, and vice versa. Thus, structural joints that impede the transmission of flexural vibrations often do not attenuate structureborne sound as much as one would expect; the longitudinal, shear and torsional components that are transmitted may give rise to flexural vibrations due to another discontinuity, and these vibrations can then radiate airborne sound efficiently.

The interconversions among the various types of structureborne sound waves that result at several important types of discontinuities (e.g., corners, crossings, T-junctions, and changes in thickness, stiffness and mass) have been subjected to considerable study. However, because of the considerable analytical and experimental complexities, only the most idealized cases are fully understood [Cremer, 73]. See Figs. 2 and 3 for an illustration of the effects at a corner.

It should be noted that other types of waves or vibrations may exist in addition to the previously mentioned elementary flexural, longitudinal, shear, and torsional wave motions. The best known of the more complex types of motions are associated with the so-called Rayleigh waves, which occur at free surfaces of solids that are many wavelengths thick. Such waves are of interest in relation to the propagation of vibrations along the surface of the ground, but otherwise are of little importance as far as structureborne noise in buildings is concered.

In addition to the structural parameters that are of primary concern in the design of a building structure — namely, stiffness and mass — another parameter plays a major role in determining its dynamic and structureborne sound characteristics.

That parameter is the structural damping — that is, the structure's capability for dissipating vibratory energy. Structural damping has three important effects: (1) it increases the (spatial) rate of decay of vibrations with distance from the driving point, (2) it increases the (temporal) rate of decay of vibrations after an excitation has ceased to act, and (3) it reduces the magnitude of responses to resonant or broadband excitation.

One can easily visualize how increased energy dissipation capability leads to greater decreases in the amplitude of vibrations with increasing distance from the driving point, in excess of the decrease that occurs as a result of the spatial spreading out of the vibratory energy. Similarly, one can readily understand how greater capability for the dissipation of vibratory energy produces faster decay of vibrations. However, it may be somewhat less obvious that structural damping is the primary mechanism that limits the vibratory responses to long-duration (multi-cycle) excitation at temporal resonance or at coincidence (spatial resonance). Under these conditions vibratory energy is fed into the structure continuously by the excitation while some of it is dissipated by the damping mechanisms; the amplitudes built up until the energy supplied per cycle matches the energy dissipated per cycle. The energy input typically is independent of the amplitude of the vibration, but the energy dissipation increases with increasing amplitude and is proportional to a parameter (such as the "loss factor") that quantifies the damping. Thus, greater structural damping here leads to reduced response amplitudes.

2.3 Radiation

Any vibrating structure sets the ambient air into motion and thus tends to radiate sound much as does a loudspeaker membrane. Indeed, such a membrane is just a special case of a structureborne sound carrier and radiator.

The radiation of sound from vibrating structures has been studied quite extensively, and there exist conceptually relatively simple techniques for calculating the sound field radiated into free space by any structure vibrating with a given pattern of surface motions [Morse, 68 and Junger, 72]. A panel radiates best if its pattern of surface vibrations is compatible with a pattern of sound waves propagating from it. For example, a one-dimensional (straight-crested) flexural wave propagating along a panel can readily produce in the surrounding air a sound wave that has a trace wavelength (along the panel) which matches the wavelength of the flexural wave. Thus, good radiation occurs above the panel's coincidence frequency (see the foregoing discussion of excitation), and it is associated with sound waves propagating at angles from the panel for which the aforementioned trace matching condition is satisfied.*

The surface of a panel vibrating at one of its resonances may be visualized as divided into a series of contiguous cells separated by nodal lines, so that the surface in adjacent cells move in opposite directions in a checkerboard-like configuration (see Fig. 4). Thus, as one cell pushes air outward from the equilibrium surface of the panel, all cells that share an edge

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*This trace-matching condition may be visualized with the aid of Fig. 1 with the propagation direction of the sound wave reversed to represent a radiated (rather than an incident) wave.

with the first cell pull air inward. If adjacent nodal lines are separated by less than half an acoustic wavelength in air (at the panel resonance frequency under consideration), then this push-pull arrangement produces only local air flows along the panel surface, with very little attendant radiation of sound away from the panel. If, on the other hand, adjacent nodal lines are more than an acoustic half-wavelength apart, then this surface flow is negligible and each cell radiates sound much like an acoustic monopole. Of course, adjacent cells are of opposite phase, so that at some points in the airspace around the panels the acoustic pressures cancel, whereas at other points, these pressures may add. (See Fig. 5.) Above the coincidence frequency, there occur preferred directions in which the pressures due to all cells add in phase [Cremer, 73].

This cell visualization approach also permits one to obtain some insight into what happens at baffled and unbaffled panel edges. At free (unbaffled) edges, flow around the edge tends to reduce the acoustic radiation associated with the edge cells. At edges adjacent to rigid baffles, flow cancellation is incomplete, resulting in sound radiation essentially from a small strip of the panel near the edge.

3. RECENT INVESTIGATIONS; THE STATE OF THE ART

3.1 Excitation and Local Response

3.1.1 Footfalls

Floor vibrations due to footfall have been analyzed and studied experimentally in terms of "heel drop" impacts, which are obtained by a man lifting his weight onto the balls of his feet and then relaxing, allowing his heels to strike the floor [Allen 74 and 75, Murray 77]. Experimentally observed pulse shapes associated with actual footfall impacts have been taken into account in a recently suggested method for estimating the peak responses of floors to footfalls [Ungar 79]. The fundamental mode of the floor generally is of primary interest in relation to footfall-induced vibrations, so that estimation and measurement of the frequency, damping and dynamic stiffness (or mobility, admittance, or impedance) associated with that mode become important considerations. Estimation techniques range from simple methods that merely involve multiplying a calculated static deflection by a dynamic load factor [Murray 77] to employing the results of finite-element computations [Petyt 72]. Relatively simple methods often give results that are quite good [Melzig-Thiel 71].

Measurements made on several modern buildings have shown that the peak low-frequency driving point mobilities of floors fall within a limited range of magnitudes and that the damping of occupied buildings is greater than that of incomplete and unoccupied ones [Fahy 78]. Such measurements may be made most reliably with the aid of massive shakers that can produce variable sinusoidal forces. However, the results of transient measurements may also be processed to develop the desired modal data [Gaukroger 74]. Some success has been reported in measuring the driving point impedances of floors using for excitation a steel ball dropped from a given height [Tukker 72]. A relatively simple method using the product of force and velocity signals to determine the steady-state input power has proven useful for field evaluation of structural damping [Otteson 79]. The damping of building materials has been investigated extensively, both at the frequencies of interest for structureborne noise [Kuhl 52, Brooks 77, Gilford 71, Yeh 71] and at the low frequencies corresponding to vibrations of entire buildings [Rusnak 78].

The criteria for the acceptability of footfall vibrations to occupants of buildings still are the subject of some controversy, even though a related international draft standard ("Guide for the Evaluation of Human Exposure to Whole-Body Vibration" ISO Standard 2631, 1974) has gained considerable acceptance. It appears that structural damping plays an appreciable role in establishing vibration acceptability, contrary to implications of this standard [Murray 79, Atherton 76, Steffens 74].

3.1.2 Machinery

Data on the structureborne sound (vibration) levels produced by a variety of mechanical equipment items in use in European buildings have recently been collected [Kuhl 79]. No equivalent collection of data pertaining to U.S. equipment appears to be available. Related prediction methods for shipboard machinery have been developed, however [Plunt 78].

In predicting the vibrations induced by a given machine in a given building installation, the effect of the admittance (or impedance) of the machine's foundation must be taken into account. Thus, one must correct for this foundation effect if one wants to relate data obtained on one installation to the conditions expected in another installation. The use of standard foundations for determining the vibration source-characteristics has been advocated and evaluated [Melzig - Thiel 79, Steffen 71].

High-speed elevators have been mentioned as potentially significant sources of building vibrations [Kravontka 75], but little information is available. In buildings that accommodate vehicles, such as where automobile parking facilities constitute part of the building, vibrations have been ascribed primarily to the sudden loading or unloading of structural slabs that occurs as vehicles traverse structural joints, as well as to the abrupt vertical accelerations that vehicles experience as they enter or leave ramps [Gutowski 76].

3.1.3 Plumbing

Plumbing fixtures and pipes have long been considered to be a significant structureborne noise problem in buildings. The turbulent flow of water produces vibrations which are transmitted to the floors and walls that support plumbing. Turbulence generators, such as taps and valves, are believed to be the primary noise sources [Girard 73], and a standard plumbing noise source has been developed for the purpose of testing installations in buildings [Girard 78, Lekkas 78]. Studies have been carried out of the airborne noise radiated into rooms from building partition walls and flanking structures due to structureborne sound produced by flow in water pipes attached to the partition walls [Gösele 76]. Various means for impeding the propagation of vibrations along pipes and from pipes to walls have also been investigated [Kuhl and Wallherr 79].

3.2 Propagation

Because the complexity of building structures generally prohibits the practical use of classical analytical methods, much effort has been expended on empirical studies of structure-borne sound propagation. Typical experiments have involved driving a structure at a particular location by means of a controllable vibrator and measuring the resulting vibrations at a number of points. Although the results obtained in this way are applicable only to the specific structures studied, some broader qualitative conclusions may be drawn for the general types of structures investigated [Cunliffe 78, Kath 78, Mahig 72 and 74, Sewell 74, Westphal 57]. Some recent measurements made on modern high-rise buildings in Japan have led to data that appears to be broadly useful for estimating the vibration attenuation in such buildings as a function of frequency and distance from the excitation [Ishii 77 and 78].

Some analytical studies have been carried out that shed light on the transmission behavior of building structures. In particular, investigations of spatially periodic configurations have indicated the occurrence of frequency bands in which transmission is relatively unimpeded, as well as others in which transmission is effectively blocked [Mead 75]. Many of the analytical predictions have been verified experimentally, including some by measurements made on ships [Kihlman 74, Nilsson

77], which – after all – have much the same multi-cell configuration as buildings.

For the general prediction and understanding of structure-borne sound propagation, however, the statistical energy analysis (SEA) approach has proven to be most useful, and much recent work has focused on verifying and improving SEA and on evaluating the parameters that make SEA applicable to buildings [CIB 78, Craik 79, Gibbs 76, Elmallawany 78, Wöhle 75, Heckl 75, Nelson 74]. In SEA, a complex structure is considered in terms of its interconnected parts; the average vibratory energy in each part is determined from energy balance considerations. Evaluation of this energy balance requires a knowledge of the energy coupling coefficients for all connected structural component pairs and of the energy loss coefficients (loss factors) for all individual components. Again, much recent and current work is aimed at evaluation of energy coupling coefficients for structural junctions in buildings [Chaumette 79, Davies 78, Girard 77, Hendrieckx 78, Lesueur 78] and in aircraft and ships [Hwang 73, Kihlman 67]. Some of the related measurements involve great difficulty, particularly for field studies, so that special approaches have been studied and developed [Brooks 77, Pavić 76].

3.3 Radiation

Prediction of the sound resulting in a room due to vibrations of its surfaces appears to be a relatively straightforward problem. Although the calculation of the sound in a non-absorbtive room due to vibration of a single wall turns out to be rather complex [Bhattacharya 69], the approximate estimation of noise in a realistic dwelling room due to vibrations of all its surfaces leads to acceptable results [Fukushini 75]. Methods have been developed for measuring the acoustic power radiated from any room surface and thus the surface's radiation efficiency [Macadam 76]. Use of these measured radiation efficiencies, together with absorption data, should enable one generally to make good estimates of the airborne noise produced in rooms due to structureborne sound.

3.4 Control

The usual vibration reduction concepts also apply to structureborne sound, of course. These include the selection of quieter (i.e., more vibration-free) components and the provision of vibration isolation at the source. For structureborne sound, however, the introduction of discontinuities and of damping also tends to be useful for reducing the propagation of vibratory energy [Heckl and Nutsch 75]. Practical means have been developed for increasing the damping of building structures [Spång 75] and of ship structures [Asztely 77], with significant reported noise reduction effects.

One may also expect to obtain some practical noise isolation benefit by locating sensitive areas as far as possible from sources of structureborne noise, by placing sensitive activities or equipment in places that vibrate relatively little or where relatively little airborne sound is radiated by the vibrating structures, or by confining sources of structureborne sound to regions in a building that accept or conduct structureborne sound poorly. A method, based on reciprocity, has been devised [Buhlert 79] for evaluating the sensitivity of selected areas in a building to excitation by structureborne sound and for determining the transmission of structureborne sound between selected locations; this method should be extremely useful for evaluating where in an existing building one should locate sensitive activities or sources of structureborne sound.

4. SOME AREAS FOR FUTURE RESEARCH

4.1 Characterization of Common Sources of Structureborne Sound

Although every modern building contains several items of heating, ventilating and air-conditioning equipment that constitute sources of structureborne noise, no means are available that permit the building designer to select quieter alternative equipment types or models, or to define how much attention is needed for a given piece of equipment. A compilation of structureborne sound spectra generated by commonly encountered equipment items under various operating conditions would be extremely useful, both for selecting quieter equipment items and for choosing favorable operating conditions.

Because the structureborne sound output produced by a given piece of equipment in general depends on the mobility (or impedance) of the supports on which it is mounted, characterization measurements must be made with the equipment mounted on a support having a known mobility. Perhaps a standard support would need to be developed for each class and size of system, but it may turn out that a simple framework resting on soft, highly damped isolators may suffice in many cases.

Prediction of the structureborne sound output of an equipment item in a field installation also requires information about the mobility of the equipment base used in that installation. Thus, the mobilities of often-used equipment bases should also be studied and catalogued.

4.2 Plumbing

Because plumbing fixtures and piping constitute widely prevalent sources of significant levels of structureborne sound, these items merit consideration somewhat along the lines indicated above for HVAC equipment. The structureborne sound spectra produced by widely used items should be catalogued, in order to provide guidance for the selection of favorable alternative items and models. Again, these characterization measurements would need to be made with the items mounted to supports with well-defined known mobilities, and the mobilities of corresponding supports commonly used in actual installations would need to be evaluated.

The practical isolation of plumbing items also merits some study. Representative questions to be addressed include: How can faucets, drains and toilets be mounted to reduce the structureborne sound they transmit to the structures to which they are attached? What sort of resilient pipe-hangers should be used for various commonly employed pipes? How should pipe penetrations through walls be detailed so as to minimize excitation of the walls? What sort of thermal isolation pipe wrappings are also useful for the isolation of structureborne sound? What can be done practically to reduce the propagation of structureborne sound along pipes — e.g., by use of bellows, pipe loops, resilient sections, damping wrappings or by attached "blocking masses"?

4.3 Transmission of Vibrations Along Floors

No reliable means are available for predicting the responses of practical floor structures to local excitation, such as footfalls. Relatively rough estimates of the modal responses of the excited floor or bay* sometimes suffice, but general

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*"Bay" refers to a (generally rectangular) unsupported area bounded by support beams or column points.

guidelines are needed to deal with the relatively complicated systems represented by anisotropic floor slabs (e.g., "ribbed" concrete poured on formed steel decking) with several support beams and/or multiple column attachment "points".

Although the modal responses may dominate the structural behavior at the lowest frequencies, vibration propagation from bay to bay is relatively poorly understood for somewhat higher frequencies where neither modal nor infinite-system response estimates are adequate. At these frequencies one may expect reinforcing beams and column supports to give rise to frequency bands in which vibration transmission is effectively blocked, and others where transmission is relatively unimpeded; one would also anticipate structural damping to have a significant effect on the attenuation with distance from the driving point.

Because both the distribution (transport) and the dissipation of vibratory energy on a floor are likely to be affected by the presence of partitions, furniture and people, it would be interesting to investigate the spreading of vibrations in a number of typical floor structures before and after the buildings are finished and occupied, in order to quantify these effects.

Although floors above grade are likely to be of major interest, floors on grade also merit some consideration, particularly because heavy vibration-producing equipment generally is placed on grade and also because vibration-sensitive items are also often placed on the ground floor or in the building basement to protect them from vibrations.

4.4 Transmission of Vibrations from Floor to Floor

Relatively little is known about how vibrations that are produced on one floor reach the next floor. Does transmission occur primarily via columns, via curtain walls, via partition walls, or via structural cores? The answer undoubtedly is different for different structures and merits investigation particularly for common modern high-rise building designs.

Understanding of the predominant paths would facilitate reduction of the sound transmission, largely by selection of favorable designs, but also by add-on "fixes" such as local isolation or shielding.

4.5 Structures and Joints with Improved Vibration and Thermal Isolation Properties

It is well known that structural discontinuities, such as joints in which there occurs a change of material or of cross-sectional area, generally attenuate the transmission of vibrations. Smaller cross-sections of thermally conductive materials or the introduction of a thermally nonconductive material in place of a conductive material also are known to reduce the conduction of heat. Thus, reductions of heat transfer and of vibration transfer should go hand-in-hand, provided the proper material and configurational choices are made.

It should be of considerable practical interest to identify situations in buildings where it is desirable to maintain large gradients of both temperature and vibration levels — say, near HVAC systems or near curtain walls exposed to external noise/vibration sources — and to devise configurations for the effective simultaneous attenuation of both heat transfer and vibration transmission.

The corresponding design of expansion joints, which are included in buildings to accommodate relative motions due to differential thermal expansion, may constitute an important facet of such an investigation. It would be useful to develop joint designs that avoid metal-to-metal (or other solid-to-solid contact) at all times and that perhaps include rubber or fiberglass for thermal and vibration isolation.

Structures (walls, floors, beams) that include cavities which are filled with sand are known to be relatively highly damped, and thus have the potential for attenuating the transmission of structureborne sound. Although sand-filled cavities appear to constitute a simple and economical means for achieving high damping, virtually nothing is known about their design or optimization. The damping of practical structures by means of sand and other granular media, which perhaps may also be useful from the thermal insulation standpoint, appears to be a potentially fruitful area of investigation.

The applications and effects of the use of viscoelastic damping systems (e.g., a concrete sandwich with an appropriately designed middle layer of asphalt) and of recently-developed high-damping concrete also merit study, although these may be expected to influence heat transfer only minimally.

4.6 Criteria for Sensitive Equipment

In many present installations, e.g., in hospitals, micro-manufacturing facilities and research laboratories, there are found items of vibration-sensitive equipment that function poorly or marginally, or that can be used only during some time periods when activities in the building are at a minimum. These items typically include optical and electron microscopes, balances, microtomes, micro-manipulators, micro-assembly equipment, and various microelectronic and optical manufacturing and processing devices. It is somewhat surprising that meaningful vibration criteria for such items are largely unavailable, so that one generally has no adequate basis for predicting whether a given item will be able to work satisfactorily in a selected location, for determining how much vibration isolation may be necessary, or for judging whether the required amount of isolation can be obtained at all in practice.

It appears that those few equipment manufacturers that supply any vibration criteria at all specify a single number — such as a limiting displacement, velocity or acceleration amplitude — without referring to any frequency dependence or frequency band, and generally also without indicating to which direction or directions of vibration the number refers.

The establishment of meaningful criteria for commonly used items or classes of equipment would be extremely useful. At the very least, a procedure should be delineated for developing such criteria and should be called to the attention of the major manufacturers and to appropriate technical and trade organizations.

5. CONCLUDING REMARKS

This report has presented a brief review of the field of structureborne sound as it relates to buildings, beginning with an overview of the important phenomena and parameters, continuing with a discussion of the major facets of the practical state of the art, and concluding with a listing of some potentially fruitful areas for further applied research.

A report such as this cannot be exhaustive, of course, and necessarily reflects the particular experience and prejudices of the author. It is the author's hope that this report will nevertheless provide some guidance for the reader concerned with structureborne noise in buildings and that it will provide the seeds for the pursuit of further work in this field.

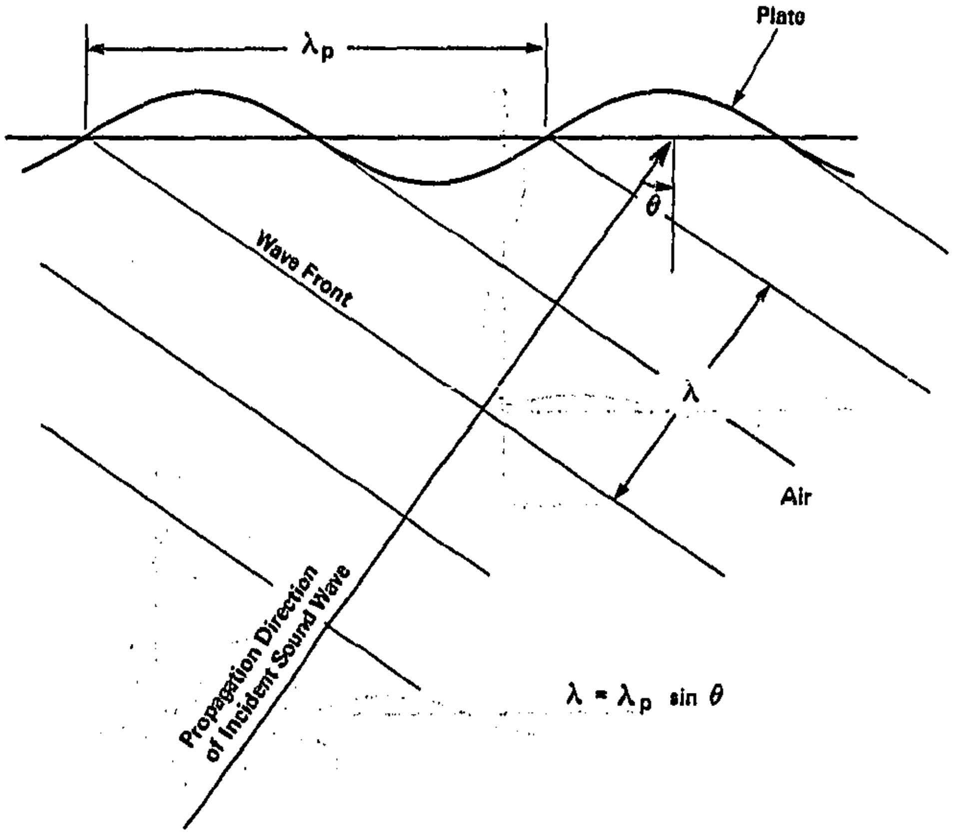


FIG. 1. TRACE-MATCHING OF INCIDENT SOUND WAVE TO FLEXURAL WAVE ON PLATE. NOTE THAT THIS GEOMETRIC MATCHING CAN ONLY OCCUR AT FREQUENCIES FOR WHICH THE ACOUSTIC WAVELENGTH λ IS SMALLER THAN THE PLATE FLEXURAL WAVELENGTH λ_p.

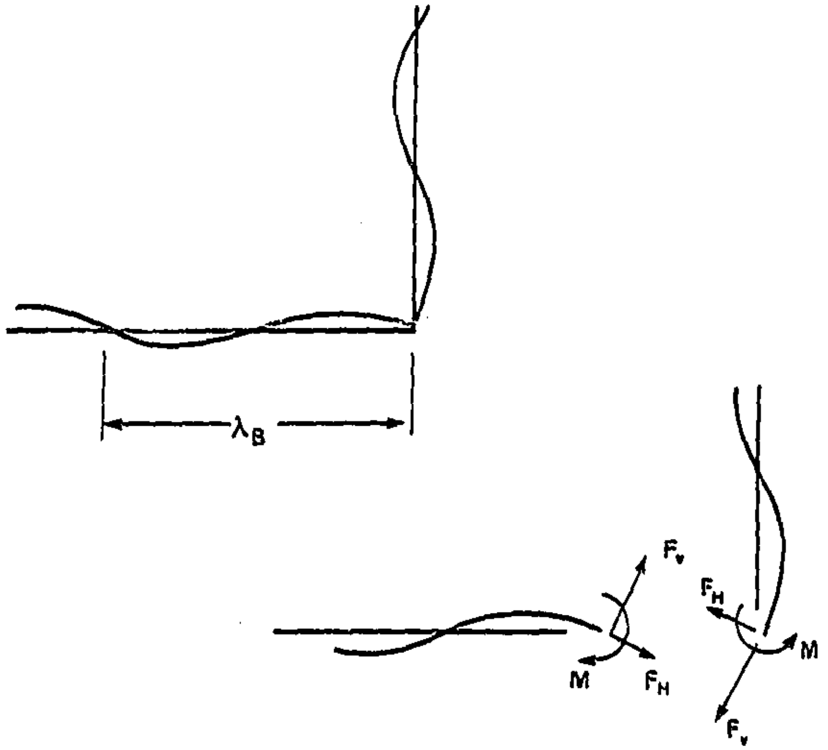
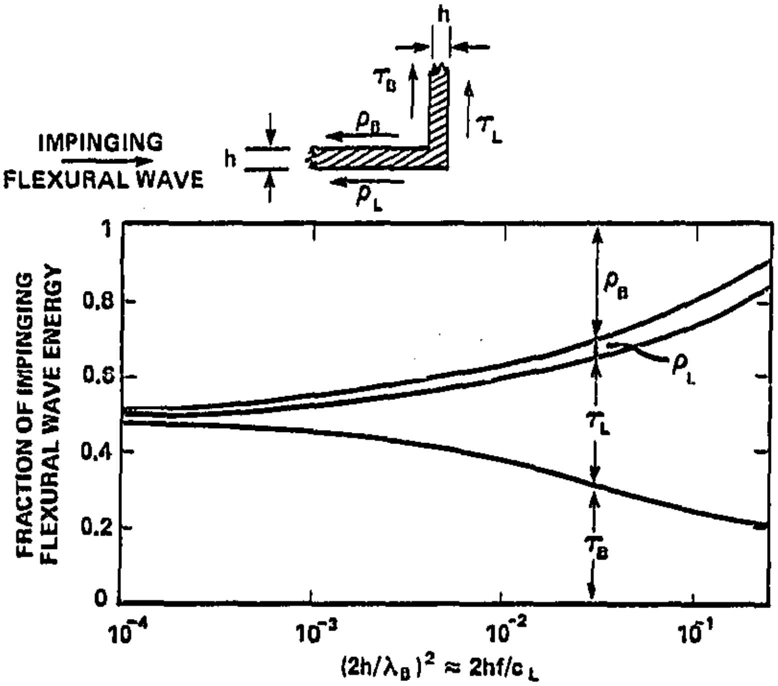


FIG. 2. FORCES AND MOMENTS AT RIGHT-ANGLE JUNCTION. INTERACTION OF THESE LEADS TO INTERCHANGE OF FLEXURAL AND LONGITUDINAL WAVE ENERGY.



Fractions of Impinging Energy:

τ_B	Transmitted in bending waves
τ_L	Transmitted in longitudinal waves
ρ_B	Reflected in bending waves
ρ_L	Reflected in longitudinal waves

h = thickness

λ_B = bending wavelength

c_L = longitudinal wavespeed

f = frequency

FIG. 3. ENERGY CONVERSION ASSOCIATED WITH BENDING WAVE IMPINGING NORMALLY ON RIGHT-ANGLE JOINT BETWEEN TWO LIKE PLATES. AFTER [CREMER, 73].

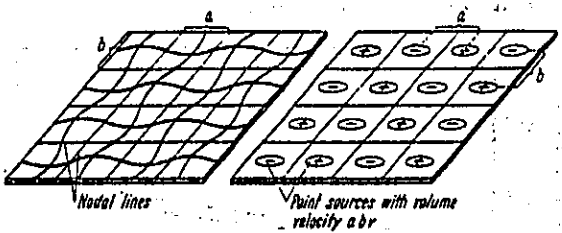
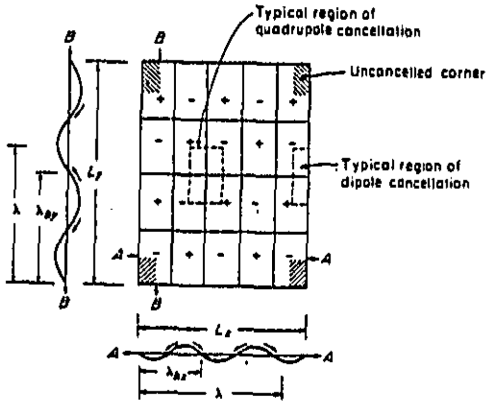
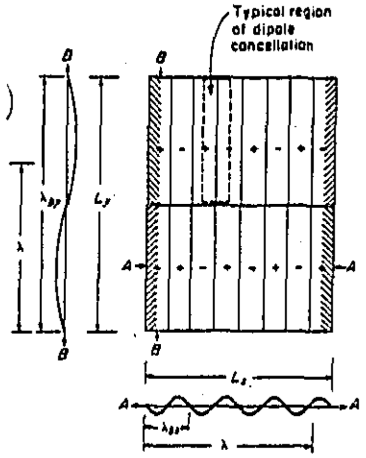


FIG. 4. PANEL VIBRATING AT A FLEXURAL RESONANCE, VISUALIZED IN TERMS OF CELLS CONSTITUTING OPPOSITELY PHASED POINT SOURCES. FROM [CREMER, 73].



(a) Mode for which all cell edges are shorter than the acoustic wavelength λ. Arrows on sections show air movement along surface. Sound fields from cells cancel, except at corners. Sound radiation is due only to corners.



(b) Mode for which one cell edge is longer and one is shorter than the wavelength λ in air. Sound fields from adjacent cell halves that are "acoustically near" each other cancel; others do not. Sound radiation is due only to uncancelled edges.

FIG. 5. NET SOUND-RADIATING AREAS ON PANELS VIBRATING AT A FLEXURAL RESONANCE. FROM [VER, 71].

BIBLIOGRAPHY

Allen, D.L., "Vibrational Behavior of Long-Span Floor Slabs," *Canadian Journal of Civil Engineering*, 1(1), 108-115 (1974)

> Reviews human response to steady and transient floor vibration. Summarizes approaches to estimating floor fundamental frequency and associated damping, as well as initial amplitude of vibration due to "heel drop." Suggests initial design considerations to reduce annoyance and discusses three fixes: added partitions, "damper posts," and tuned absorbers.

Allen, D.L. and Swallow, J.C., "Annoying Floor Vibrations — Diagnosis and Therapy," Sound and Vibration, 9, 12-17 (March 1975).

Asztely, J., "The Uses of Viscoelastic Materials for Noise Reduction on Ships," *Noise Control and Vibration Insulation*, 8(8) 297-299 (October 1977)

> For typical ships, the loss factor is 1 to 5 × 10^{-3} in the hull and 1 to 3 × 10^{-3} in the deck house. Noise reductions of 5 to 10 dBA can be reached by applications of damping layers. This paper describes damping applications on one particular ship, together with results and general damping recommendations.

Atherton, G.H., Polensek, A., Corder, S.E., "Human Response to Walking and Impact Vibration of Wood Floors," *Forest Products Journal*, 26(1), 40-47 (October 1976)

> Tests employing human evaluators were made on 24 full-size wood-joist floors. Vibration amplitude was found to be the best single indicator of human response, but an indicator that also includes damping and frequency was found to be better. Static and geometric characteristics of the floors were found not to correlate well with human response.

Berendt, R.D., Winzer, G.E., Burroughs, C.B., "A Guide to Airborne, Impact and Structure Borne Noise Control in Multifamily Dwellings," U.S. Department of Housing and Urban Development, September 1967

> Cites noise among the greatest drawbacks of apartment living. Factors contributing to the problem include: lightweight structures, poor acoustical design, poor workmanship, mechanization (labor-saving devices, appliances). Discusses impact noise on floors, noise from wall-contacting appliances, piping; squeaking floors.

Bhattacharya, M.C., and Crocker, M.J., "Forced Vibration of a Panel and Radiation of Sound into a Room," *Acustica,* 22 (1969/70), 275-294

> Analytical solution for acoustically hard room with one wall consisting of a flexible panel, which is excited to modal vibrations by externally incident sound waves.

Brooks, J.E. and Maidanik, G., "Loss and Coupling Loss Factor of Two Coupled Dynamic Systems," *J. Sound and Vibr.,* 55 (3), 315-325 (1977)

> Paper examines experimental methods that can be used to evaluate loss and coupling loss factors for use in Statistical Energy Analysis. Formalism is used to determine sensitivity with which these factors can be estimated for two coupled systems, but extensions to more complex configurations are indicated.

Buhlert, K.-J. and Feldmann, J., "Ein Messverfahren zur Bestimmung von Körperschallanregung und - übertragung" (A Measurement Procedure for Evaluation of Production and Transmission of Structureborne Sound), *Acustica,* 42, 108-113 (1979)

> Procedure for determining "structureborne-sound sensitivity" of buildings is developed, based on reciprocity. Good agreement with direct measurements is reported.

Chaumette, A., "Transmission des Vibrations a la Jonction de deux Plaques Rectangulaires" (Transmission of Vibrations at the Junction of Two Rectangular Plates), Centre Scientifique et Technique du Batiment, N/Ref. GA/79-509, Sept. 1979

> Summarizes principles and hypotheses of statistical energy analysis, then applies SEA (in terms of modal analysis and theoretical coupling coefficient) to junctions of plates. Mathematical analysis only.

CIB - Commission Acoustique W51, "Compte Rendu de la 3eme Reunion du Groupe 'Structures' Tenue les 8 et 9 Mars 1978" (Transactions of the 3rd Meeting of the "Structures" Group held March 8 and 9, 1978)

Principal themes: general considerations of SEA, methods for obtaining coupling and loss factors, methods for prediction of isolation between locations.

- Leseur (INSA, Lyon) is studying transmission of bending waves at corners in terms of coupled parts of modes.

*• Gibbs (U. of Liverpool) is studying same problem from basic theoretical viewpoint, with Davis (Aston U.) doing same complimentary experiments.

*• Girard (CEBTP) made extensive measurements in coupled rooms, placing sound absorption strategically so as to pick out contributions from individual paths and permitting evaluation of coupling factors.

*• Henderieckx (CSTC) has T-junction laboratory to study flanking; good agreement with SEA, except at low frequencies.

- Mackenzie and Craik (Heriot-Watt U.) used SEA to consider "short-circuiting" of walls by ventilation ducts. Also reported on coupling factors as measured in ASA paper [Craik 79].

*• Kierzkowski (Building Research Institute, Warsaw) described simple method for measuring isolation of floors and walls. Standard tapping machine used for impact noise testing; also as airborne noise source when working against steel plate.

- Gerretson (TNO, Holland) presented theoretical analysis of multi-path sound transmission, based on considering only bending waves and gross parameters of coupled walls to predict energy flow at junctions. Good agreement with measurements.

Work in Progress:

Mathieu (SCTB): Transmission through assemblages of concrete partitions

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*Asterisk identifies papers cited separately in this bibliography.

Karfalk (Chalmers U., Sweden): Transmission of forces exerted by machines on floors

Vermeir (U. of Louvain): Traffic noise and absorption of materials

Sewell (BRE): Measures *in situ* after several years, effects on critical frequency and damping

Kierzkowski (ITB): Ventilation and street noise problems

Gerretsen (TNO): Traffic and industrial noise, research on double walls.

Craik, R., and Mackenzie, R., "The Use of Statistical Energy Analysis in Building Acoustics," Paper LL1, June 1979 Meeting of the Acoustical Society of America

Total loss factors of each of 104 subsystems of a building structure were measured, as well as subsystem energy levels obtained for a number of different sources. Total loss factor of walls and floors is essentially equal to the sum of the predicted coupling loss factors; internal damping has little effect.

Coupling loss factors were calculated from energy distributions measured with various sources. Results are generally in fair agreement with theoretical predictions. Method also useful for prediction of sound from room to room, taking indirect paths into account.

Cremer, L. and Heckl, M. *Structure-Borne Sound*, translated and revised by E.E. Ungar. Springer-Verlag, New York, 1973.

Cunliffe, A.R., "Effects of Woodwool Shuttering in Party Floors on the Flanking Transmission of Sound between Maisonettes," *Applied Acoustics*, 11 (1978), 241-246

Vibration measurements indicate that these floors provided excessive flanking transmission between rooms.

Davies, J.C., and Gibbs, B.M., "The Theoretical Derivation and Measurement of Vibration Transmission Coefficients in Structures," 3rd Meeting of Structures Group of CIB, March 1978

Initial investigations of mean square amplitudes of bending waves generated at junction of two plates due to an incident bending wave, using applications of theories of Cremer, Bhattacharya, Kihlman. Also measurements of transients by means of an event recorder. Work still in progress.

Done, G.T.S. and Hughes, A.D., "The Response of a Vibrating Structure as a Function of Structural Parameters," *J. Sound and Vibr.,* 38(2), 255-266 (1975)

> A mathematical study of simple systems, analyzing response of a structure to an oscillatory force for variations in structural parameters, with a view toward manipulating these parameters to achieve a desired response.

Dym, C.L. and Klabin, D., "Architectural Implications of Structural Vibrations," *Architectural Record,* 157, pp. 125-127 (1975).

Elmallawany, A., "Criticism of Statistical Energy Analysis for the Calculation of Sound Insulation--Part I: Single Partitions," *Applied Acoustics,* 11 (1978); 305-312

> Theory and laboratory experiment were found to agree, except at low frequencies and at resonances. SEA can take better account of flanking effects.

Fahy, F.J. and Westcott, M.E., "Measurement of Floor Mobility at Low Frequenices in Some Buildings with Long Floor Spans," *J. Sound and Vibr.,* 57(1), 101-129 (1978)

> Driving point mobility measurements were made in some modern concrete and concrete/steel buildings at frequencies between 4 and 35 Hz. Damping ratios for incomplete and unoccupied buildings were found to lie between 1 and 3 percent, whereas values between 6 and 14 percent were determined for occupied buildings. Peak mobilities for all buildings studied were generally between 10^{-5} and 10^{-6} (m/s)/N.

Fuerst, P., "On the Describability of Pollution by Structure-borne Sound in Living Rooms," Inter-Noise 79, paper M4-C, pp. 913-917 (1979)

> Relates vibrations to audible sound and suggests limiting curve for vibration, based on both audible and tactile acceptability.

Fukushini, T., Furukawa, S., Yamamoto, T., "Influence of Underground Railway Vibration on Buildings and a Method for Estimation of Vibration Noise," Inter-Noise 75, pp. 391-394 (1975)

> Show results of attenuation measurements for vibration travelling along the ground surface, measured along three axes. Suggest that room vibrations be estimated by applying attenuation data, and that noise in room be obtained from combined radiation from all surfaces. Agreement with measurements appears to be good.

Gaukroger, D.R., Heron, K.H., Skingle, C.W., "The Processing of Response Data to Obtain Modal Frequencies and Damping Ratios," *J. Sound Vibr.*, 35(4), 559-571 (1974).

> It is shown that modal frequencies and damping ratios of a multi-degree-of-freedom system may be derived from the Fourier Transform of the one-sided autocorrelogram of the response of the system to transient and random excitations. The excitations need not be known in detail, but certain spectral conditions must be satisfied.

Gibbs, B.M. and Gilford, C.L.S., "The Use of Power Flow Methods for the Assessment of Sound Transmission in Building Structures," *J. Sound Vibr.*, 49 (1976) 267-286

> Models buildings as joined plate elements and applies Statistical Energy Analysis. Uses measured coupling, radiation and damping factors and shows good agreement for 1/4 scale model tests.
>
> Very useful summary of many important aspects.

Gilford, C.L.S. and Gibbs, B.M., "Internal Damping as a Factor of Sound Propagation in Building Structures," Proc. 7th Intern. Congress of Acoustics, Budapest, 1971, 4, pp. 85-88, Paper 20A15

> Reports measurements made by decay rate and admittance methods for some common building materials. Indicates effects of frequency and amplitude.

Girard, J., "Plumbing Noise," Inter-Noise 73, paper C22 Z 12, pp. 223-232 (1973)

Plumbing noise is transmitted to walls via attachments. Discharges and taps are believed to be primary noise sources.

Girard, J., "Mesure en Laboratoire des Facteurs de Couplage Entre Parois d'une Jonction en Te," (Laboratory Measurement of Coupling Factors between Partitions of a T-Junction), 9th International Congress on Acoustics, Madrid, July 1977

The approach used here makes use of the SEA relations. In two rooms incorporating a wall with a T-junction (the other walls being double, so that they do not affect the experiment), various walls of the junction are vibrated by means of an electrodynamic shaker. The results are interpreted in terms of simultaneous equations in terms of the loss factors, for which one then solves. Self-consistent results are obtained by various measurements. Separate path contributions can be identified.

Girard, J., "Sonorite des Installations Hydrauliques dans les Batiments d'Habitation" (Noise of Water Installations in Residential Buildings), 3rd Meeting of Structures Group of CIB, March 1978

Reports sound transmission measurements using a standard sound source.

Gösele, K. and Voigtsberger, C.A., "Der Einfluss der Installationswand auf die Abstrahlung von Wasserleitungsgeräuschen" (The Effect of Partition Walls on Radiation of Plumbing Noise), *Acustica,* 35, 310-315 (1976)

Sound radiation from massive partition walls, excited by flow in attached water pipes, was found to vary as -20 log (mass). Second panel wall can reduce noise, but flanking may play an important role.

Gutowski, T.G. and Dym, C.L., "Propagation of Ground Vibration: A Review," *J. Sound Vibr.,* 49, 179-194 (1976)

Discusses models of sources and spreading, damping properties of soils. Reviews instrumentation for ground vibration measurement and summarizes some measured data.

Gutowski, T.G. and White, R.W., "Vibration Generated in Parking Facilities," Inter-Noise 76, pp. 255-258 (1976)

Reports results of low-frequency vibration measurements.

Harris, C.M. and Crede, C.F., Eds. *Shock and Vibration Handbook,* McGraw-Hill Book Co., New York. Second Edition (1976)

Heckl, M., "Structure-borne Sound in Buildings," Inter-Noise 75, pp. 335-342 (1975)

Reviews relations for sound transmission through homogeneous and inhomogeneous plates and indicates method for selecting favorable mounting points for vibration sources.

Discusses flanking transmission and presents some corresponding results calculated by statistical energy analysis.

Heckl, M. and Nutsch, J., "Körperschalldämmung und - dämpfung" (Attenuation and Damping of Structureborne Sound), Chapt. 21 of *Taschenbuch der Technischen Akustik* (*Handbook of Technical Acoustics)*, Springer-Verlag, Berlin 1975, ed. by M. Heckl and H.A. Muller

Discusses vibration isolation and related material and structural properties. Indicates attenuation magnitudes due to spreading and structural discontinuities (same as *Structureborne Sound* book). Presents information on material damping, use of viscoelastic layer, and reradiation of sound.

Hendrieckx, F. and Vermeir, G., "La Transmission Acoustique par les Structures" (Acoustic Transmission by Structures), 3rd Meeting of Structures Group of CIB, March 1978

Laboratory measurements on T-junctions show a difference between the vibration and noise reductions, indicating that radiation from plates is also important. Calculation of acoustical transmission by SEA agrees well with measured data in some frequency regions. Some *in situ* measurements have also been made to study flanking effects.

Hwang, C. and Pi, W.S., "Investigation of Vibrational Energy Transfer in Connected Structures," Northrop Corp., Aircraft Division Report NOR73-ID5, July 1973, NASA-CR-124450

Examines basics of statistical energy analysis and introduces new formulation involving strong coupling. Presents study of energy transfer based on wave equations and discusses results of tests on three connected substructures.

Ishii, K. and Tachibana H., "Field Measurement of Structure-Borne Sound in Building," Proc. 9th International Congress on Acoustics (1977), P 39, paper C39, p. 117

In an unfinished 10-floor hotel of steel frame reinforced concrete construction, floor slab on 4th floor was excited and vibrations were measured on walls and floors of several rooms on same and other floors.

It was found that higher frequencies are attenuated more rapidly than low frequencies (1.5 dB/floor at 63 Hz and 4.5 dB/floor at 2KHz) and that attenuation in horizontal direction with distance is about equal to that in vertical direction.

Ishii, K. and Tachibana, H., "Field Measurements of Structure-borne Sound Propagation in Buildings," Joint Meeting of Acoust. Soc. of Am. and Acoust. Soc. of Japan, Paper L10, December 1978

Results reported at 9th ICA were reviewed. Data obtained for a second building were found to be in good agreement with those for the first.

First building was re-studied, this time exciting railway tunnel under building instead of floor in a given room. At several floors above, same propagation characteristics were obtained as before.

Junger, M.C. and Feil, D., *Sound Structures and Their Interaction*, The M.I.T. Press, Cambridge, MA (1972).

Kath, U. and Kuhl, W., "Untersuchungen zur Körperschall--Pegelabnahme in Gebäuden" (Investigations Pertaining to the Attenuation of Structureborne Sound in Buildings), *Acustica*, 40 (1978), p. 272-3

Measurements show that the response of a 30cm concrete wall backed by earth fill differs little from that of unback filled wall above about 200 Hz.

Data showing frequency variation of level reduction per floor are summarized; reductions with load bearing walls seem to be about twice those with curtain wall structures.

Measurements made in building with massive concrete columns indicate that these are primary conductors of structureborne sound.

Kihlman, T., "Transmission of Structure-Borne Sound in Buildings--A Theoretical and Experimental Investigation," Report 9:1967, National Swedish Institute for Building Research

Calculates transmission coefficients for plate crossings, then assumes reverberent vibration fields on finite plates and evaluates average coefficients numerically for specific configurations. Applies statistical energy analysis and reports experimental results that show good agreement.

Kihlman, T. and Plunt, J., "Structure-borne Sound in Ships, a Study of Different Waveforms," Proc. 8th International Acoustical Congress, London, 1974, Vol. II, p. 587

As the result of many measurements, authors conclude that waves other than flexural must also be taken into account.

Koopman, G.H. and Petyt, M., "Building Vibrations and Acoustics," *J. Sound Vibr.*, 28(3), 471-485 (1973)

Discusses work done at ISVR, on (1) responses of buildings to sonic booms, (2) response of buildings to atmospheric turbulence, (3) vibration of building components, e.g., corner-supported slabs, cantilever shear walls, (4) finite element programs, and (5) building acoustics.

Kravontka, S.J., "High Travel Induced Elevator Vibration," Inter-Noise 75, pp. 379-382 (1975)

Qualitative discussion of vibration induced in tall structures and the need for codes.

Kudo, N., Oiwa, K., Suzuki, S., "Reduction of Solid-Borne Noise Emitted from the Wall of a Pumping Station Using Noise-Proof Panels," Inter-Noise 77, pp. B674 - B679 (1977)

Discusses measurements made on a pumping station showing much noise radiation comes from exterior walls. Panels supported resiliently from that wall were found to produce effective noise reduction.

Kuhl, W., "Körperschallpegel, Luftschallpegel und Schalldämmung Haustechnischer Anlagen" (Levels of Structureborne and Airborne Sound, and Sound Attenuation of Mechanical Systems of Buildings), *Acustica*, 43 (1979), 32-44

Presents means for estimating structureborne sound levels corresponding to permissible NR levels in rooms.

Reports measured vibration and noise levels for the following types of equipment and suggests isolation requirements: Air conditioning systems, air cleaner pumps, large axial fans, centrifugal pumps, air compressors, central vacuum systems, reciprocating compressors, refrigeration turbines, stand-by diesel generators, elevator systems, and oil burners and furnaces.

Kuhl, W. and Kaiser, H., "Absorption of Structureborne Sound in Building Materials without and with Sand-filled Cavities," *Acustica*, 3 (1952), 179-188

Measurement results are reported for loss factors of brick and concrete as function of frequency and amplitude. Effect of added sand is to increase damping.

Kuhl, W. and Wallherr, H., "Untersuchungen zur Körperschalldämmung bei Rohrleitungen" (Investigations of Structureborne Sound Attenuation on Plumbing Pipes), *Acustica*, 42 (1979), 37-46

Investigates effects of pipehangers, branches, concrete "blocking masses" attached to pipes and vibration level changes that pipes experience at wall penetrations. Also indicates the attenuation of structureborne sound due to joints (cracks) and makes some recommendations concerning the isolation of pipe systems.

Lekkas, G. "Mesure de la Sonorite des Installations Hydrauliques," (Measurement of Noise of Water Installations) 3rd Meeting of Structures Group of CIB, March 1978.

> Reports noise levels of 4 faucets commonly found in Greece, as measured with standard generator.

Lesueur, C., Guyader, J.L., Cacciolati, C., Boisson, C., "Transmission du Bruit par les Systems Couples," (Transmission of Noise by Coupled Systems), 3rd Meeting of Structures Group of CIB, March 1978.

> Have conducted a critical study of SEA in terms of background assumptions, parameter sensitivity (by numerical study), and region of validity.
>
> Also have begun careful basic study of coupled structures in general, which they hope to simplify in order to make it practically useful.

Macadam, J.A., "The Measurement of Sound Radiation from Room Surfaces in Lightweight Buildings," *Applied Acoustics*, 9, 103-118 (1976).

> Where radiation efficiency of surfaces differs from unity (i.e., below the coincidence frequency), more than vibration measurements are needed to evaluate radiation. Macadam uses a microphone near the vibrating surface and an accelerometer to measure local power radiation (pressure x velocity, time-averaged) at several points; then sums over area. Sound field in receiving room must be low, so that measurement is not distored by power transmitted from sound field to the panel surface.

Mahig, J., "Noise and Vibration Transmission Through Some Building Structures," *Inter-noise 74*, pp. 653-656 (1974).

> Experiments with a shaker driving a concrete slab on a gravel base indicate that there exists a pass band for vibration transmission on such structures. It was found that vibrations often decay rapidly with distance from the shaker and that significant noise often results from application of even small vibratory forces.

Mahig, J., Elliott, H.J., Jr., Gentile, R.J., "Noise and Vibration Transmission Floor and Walls," *Building Systems Design*, pp. 18-20, July 1972.

> Measurements were made with a shaker driving a 6 in. concrete slab floor on grade. It was found that vibrations decay rapidly with distance from a shaker and that little transmission occurs above 1 kHz. Concrete block walls resting on the floor were found not to vibrate horizontally, but to transmit vibrations to the upper floor via their vertical vibrations. Sound in the ground level room was attributed essentially only to the floor vibrations (of that room).

Mead, D.J., "Wave Propagation and Natural Modes in Periodic Systems: I. Monocoupled Systems; II. Multi-coupled Systems With and Without Damping," *J. Sound Vib.*, 40(1), 1-40, 1975.

Melzig-Thiel, R., "Peculiarities and Results of the Pre-Determination of the Structure-Borne Sound Excitation of Buildings by Machines," *Inter-Noise 79*, Paper M3-C, pp. 909-912 (1979).

> Describes measurement of machine vibration on a test foundation and then predicting vibrations of structure where machine is to be installed. Indicates range of errors obtained by this method.

Melzig-Thiel, R., Meltzer, G., "Messung und Berechnung der Eingangsadmittanzen von Gebäudedecken" (Measurement and Calculation of Driving Point Admittances of Building Roofs), *Proc. 7th Intern'tl. Congress on Acoustics, Budapest, 1971*, 4, Paper 20V3, pp. 577-580.

> Presents methods for estimating fundamental frequency and effective mass of plate-like structures, and suggest method for estimating admittance as function of frequency. Reasonable agreement with measured results is shown.

Monk, R.G., "Mechanically Induced Vibration in Buildings," *Noise Control and Vibration Reduction*, 3(3):369-373 (1972).

> Elementary discussion of vibration criteria and of vibration isolation.

Morse, P.M. and Ingard, K.U., *Theoretical Acoustics*, McGraw-Hill Book Co., Inc., New York (1968)

Murray, T.M., Hendrick, W.E., "Floor Vibrations and Cantilevered Construction," *Engineering Journal*, Am. Institute of Steel Construction, 14:85-91 (No. 3) (1977).

Suggests values of damping associated with various floor structure types and presents means for predicting fundamental resonance frequency. Amplitude due to "heel drop" is obtained by multiplying static deflection resulting from 600 lb weight by a dynamic load factor (DLF). A table of DLF vs. frequency is included. Prediction method is shown to give results that agree well with measurements.

Murray, T.M., "Acceptability Criterion for Occupant-Induced Floor Vibrations," *Sound and Vibration*, 13(11), pp. 24-30 (November 1979).

Nakamura, S., Koyasu, M., Ochiai, H. "Analysis of Footstep Noise in Daily Life of an Apartment House," *Inter-Noise 75*, pp. 375-378 (1975).

Reports footfall-induced noise in typical Japanese apartment, where occupants wear no shoes. Noise results from impacts and from creaking of wood.

Nelson, H.N., "Vibration and Noise Transmission in Building Structures," *Acoustics and Vibration Progress*, Chap. 4, Vol. 1. Edited by R.W.B. Stephens and H.G. Leventhall, Chapman and Hall, London, 1974.

Reviews classical transmission loss and gives references to work on TL of complex partitions and to flanking. Discusses wave propagation on infinite bars and plates, vibrations of finite plates and bars, wave transmission of structural joints. Also discusses modal density and statistical energy analysis.

Entire article is of literature review type; no references published after 1970 appear. 91 refs.

Nilsson, A.C., "Attenuation of Structure-Borne Sound in Superstructures on Ships," *J. Sound Vib.*, 55(1):71-91 (1977).

Presents analysis based on considering structure as waveguide for flexural waves, assuming contribution of longitudinal waves to be small. Theoretical predictions are found to be in good agreement with experimental data. Model seems to be particularly suitable for periodic structures, for which statistical energy analysis may be inadequate.

Nilsson, A.C., "Reduction of Structure-Borne Sound in Simple Ship Structures: Results of Model Tests," *J. Sound and Vib.* 61(1):45-60 (1978).

> Experimental measurements yield good agreement with predictions made on basis of two-dimensional flexural wave-guide model, analyzed by SEA. Effectiveness of damping and of isolation are investigated.

Otteson, G.E. and Vigran, T.E., "Measurement of Mechanical Input Power with an Application to Wall Structures," *Applied Acoustics* 12:243-251 (1979).

> Uses direct multiplication of force and velocity signal to measure input power and steady-state dissipation.

Pavić, G., "Measurement of Structure Borne Wave Intensity, Part I: Formulation of the Methods," *J. Sound Vib.* 49(2):221-230 (1976).

> Formulates methods for measurement of intensities in one and two-dimensional flexural systems, using a few transducers distributed over a small area.

Petyt, M. and Mirza, W.H., "Vibration of Column-Supported Floor Slabs," *J. Sound Vib.* 21:355-364 (1972).

> Gives results of finite-element analyses for resonance frequencies of square plates, rectangular plates, and square plates with many point-supports. Also indicates effects of joint rigidity and finite area of column cross-section.

Plunt, J., "Empirical Formulas for Structure-Borne Sound Levels of Ship Machinery," *Inter-noise 78*, pp. 795-798 (May 1978).

> From regression analysis of empirical data, velocity level predictions (as function of shaft power) are described for main propulsion diesels, reduction gears, and auxiliary diesels. Details and prediction constants appear in other reports and are not included in this paper.

Rusnak, T.J., "Development of Empirical Relationship for the Prediction of Damping in Steel-Framed Buildings," Ph.D. Thesis, Purdue University; Dept. of Civil Engineering, May 1978. AD A054438

Reviews data on damping of entire buildings, gleaned from the literature and obtained from natural and artificial excitation. Empirical relation is developed from regression analysis.

Includes review of measurement systems and extensive bibliography.

Sadowski, J., *et al.* "The Influence of Materials and Construction on the Acoustic Climate in Dwellings and Its Effect on Residents' Health," Building Research Institute, Institute of Social Medicine, Medical Academy, Warsaw. Project No. OS-202-2, Phase 1 Final Report. January 1975. Appendix 4b:

Survey showed that greatest annoyance was due to traffic noise (33%), yard (18%), neighboring dwellings (18%), plumbing (10%).

Appendix 2C:

Review of dynamic properties of materials and structures: measurement methods (Includes system used by author.)

Appendix 2b:

Some aspects of measurement of vibr. propagation. Review of criteria.

Sadowski, J., Wodziński, L, and Kierzkowski, M., "Simplified Method of Measuring Sound Insulation of Partitions and Attempts of Using it for an Assessment of an Extent of Flanking Transmission in Ferroconcrete Buildings," 3rd Meeting of Structures Group of CIB, March 1978.

Modification of standard tapping machine, tapping against steel plate, is used as standard sound source. Method was found to yield same noise reductions as with pistol shot and loudspeaker sources, for several rooms/directions in a building.

Sewell, E.C., and Utley, W.A., "The Effect of Resilient Fillings on Direct and Flanking Sound Transmission with Cavity Masonry Walls," *J. Sound Vib.* 34(1):131-142 (1974).

> Some measurements have shown that cavity walls filled with foam (to provide increased thermal insulation) produced more direct and flanking sound transmission than unfilled walls. Theoretical study shows that this effect is ascribable primarily to the stiffness of the foam.

Smart, D.G., "A New Charted System for the Specification of Structure-Borne Noise Control," *Applied Acoustics* 5:223-235 (1972).

> Charts for relating vibration data to sound pressure levels and NC or NR curves.

Spång, K., "Experiences in Reducing Building Noise Problems by Use of the Viscoelastic Damping Layer Technique," *Inter-noise 75*, pp. 355-358 (1975).

> Describes concrete slab with viscoelastic interlayer used for floated slab in subway. Also describes REDJC foil with viscoelastic material and sand and reports results of measurements made in a building with floors damped by that system.

Steffen, F., "Körperschallanregung von Fundamenten durch Maschinen" (Excitation of Structureborne Sound in Foundations by Machines), *Proc. 7th International Congress on Acoustics*, Budapest 1971, 2:657-660, Paper 24V1.

> Vibrations produced by a machine depend on the foundation to which it is mounted. Author suggests measurements made on foundation with known admittance be used to characterize the machine; then, if one knows the admittance of other foundations, the responses of these foundations can be predicted.

Steffens, R.J., "Structural Vibration and Damage," (Some notes on aspects of the problem and a review of available information). Department of the Environment, Building Research Establishment, Her Majesty's Stationery Office, London (1974).

> Reviews some complaints concerning vibrations due to pile driving, railroads, road traffic, aircraft, blasting. Discusses factors involved in structural response:

resonance, damping. Lists some natural frequency data for buildings and structural elements. Reviews human sensitivity to vibration and structural damage criteria (-both topics are not up to date). Reports some cases of severe vibrations that have been observed, as well as vibration data measured for several sources. Also discusses wind-induced deflections of structures.

Tukker, J.C., "Application of a Measuring Method for the Dynamical Behavior of Building Structures," *Applied Acoustics* 5:245:264 (1972).

Driving point impedance is measured using a steel ball falling from a given height as a driving source, after having "calibrated" the system by use of a force gage. Accelerometer near impact point, feeding into peak-holding sound level meter, is used as readout. Method seems to give results in reasonable agreement with high-frequency theory.

System has also been used for measurement of sound-transmission. Suggests approach to estimation of structure-borne sound levels.

Ungar, E.E., and White, R.W., "Footfall-Induced Vibrations of Floors Supporting Sensitive Equipment," *Sound and Vibration*, 13, pp. 10-13 (October 1979).

van den Eijk, J. and Bitter, C. "Neighbour's Footsteps," *Proc. 7th International Congress on Acoustics*, Budapest 1971, 4:113-116, Paper 20A24.

Summarizes results of study that indicates that people hear neighbors' footsteps more often than they are annoyed by them. Heavier floors reduce incidence of hearing and of annoyance.

Ver, I.L. and Holmer, C.I., "Interaction of Sound Waves and Solid Structures." Chapter 11 of *Noise and Vibration Control*, L.L. Beranek, Ed., McGraw-Hill Book Co., New York (1971)

Westphal, W., "Ausbreitung von Körperschall in Gebäuden" (Spreading of Structureborne Sound in Buildings), *Acustica*, 7:335 (1957).

Wöhle, W. and Elmallawany, A., "Generalized Model of the Application of Statistical Energy Analysis for the Sound Propagation in a Complicated Structure," *J. Sound Vib.* 40:233-241 (1975).

Sets up SEA matrices for calculating sound resulting in one room due to sources in one or more other rooms and indicates computer algorithm for solution. Indicates good agreement with experimental data for transmission loss of double and triple windows, but does not show from where values of the various coefficients are obtained.

Yeh, C.T., Hartz, B.J., and Brown, C.B., "Damping Sources in Wood Structures," *J. Sound Vib.* 19(4):411-419 (1971).

Experiments show material damping to vary little with wood type. Nail joints, nailing devices, and adhesives can increase damping. Moisture content increases damping of wood.

Yeh, C.T., Hartz, B.J., and Brown, C.B., "The Prediction of Damping in Nailed and Glued Wood Structures," *J. Sound Vib.* 19(4):421-435 (1971).

Reviews damping of nailed and glued joints. Develops prediction methods based on tests of small samples. Suggests arrangements that maximize damping.

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

An overview of the current state-of-the-art of structureborne sound in buildings is presented. A general introduction to the field of structureborne sound is included with a discussion of important phenomena. Summaries of recent investigations described in the technical literature are discussed relevant to excitation and local response, propagation, radiation, and control of structureborne sound in buildings. Topics for future research in structureborne sound in buildings are presented based upon this review. An annotated bibliography of recent investigations is appended.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Acoustics; architectural acoustics; sound transmission; noise; noise control; building acoustics; structureborne noise

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