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A Unified Treatment of Direct and Indirect Sound Transmission By Power-Flow Considerations

By BARRY M GIBBS

The University of Aston in Birmingham

1. Introduction Power-flow techniques were successfully developed in considering the problem of structural vibration in the aerospace industry (1). The flow of vibrational energy from one structural element to another, or into the surrounding medium is assumed to be analogous to the passage of heat between bodies having different temperatures. The flow of energy is thought proportional to the difference in vibrational energy of the elements and depends upon the degree of coupling (coupling coefficient) between them. In finite systems some energy will return to the first system. The total power-flow from the ith to the jth system is expressed as,

$$\Pi_i^{\,j} = \omega E_i \eta_i^{\,j} - \omega E_j \eta_j^{\,i},$$

where E_i is the total energy in the ith system and $\eta_i^{\,j}$ is the coupling coefficient from the ith to the jth system.

In problems involving junctions of thin plates and of plates radiating into the surrounding air, the modal densities of the bending wave and pressure wave fields are fairly high. In this situation the above equation is often modified (2).

$$\Pi_i^{\,j} = \omega \eta_i^{\,j} \eta_i \left\{ \frac{E_i}{n_i} - \frac{E_j}{n_j} \right\}$$

where n_i and n_j are the respective modal densities.

The direct transmission through a thin panel forming a partition between two rooms has been solved (3) by considering the source room, panel and receiver room as separate systems in a power-flow network. However, in attempting to apply the same techniques to indirect and direct transmission of sound in building structures due regard must be made to the limitations resulting from the finite thicknesses of the elements encountered; except at higher frequencies, modal densities will be low, boundary conditions will be complicated and attention must be made to the generation of shear and longitudinal waves as well as to bending waves.

2. Theoretical Considerations In the transfer of sound from one room to another, each wall, floor, ceiling and air volume enclosed is considered as a separate system with vibrational energy flowing in, some flowing out, and some being internally dissipated. At structural discontinuities such as corners, T-junctions and cross-junctions, bending waves will generate longitudinal and shear waves. However, only bending wave fields will be considered as being efficiently coupled to the room modes when discussing radiation.

In gauging the validity of the method simple structures were first considered, such as the junction of four finite concrete plates (fig. 1a). If bending waves are excited on one plate, bending wave fields will result on the other plates, along with longitudinal and transverse waves. In describing the flow of energy to each subsystem (ie plate) a simple diagram can be used (fig. 1b).

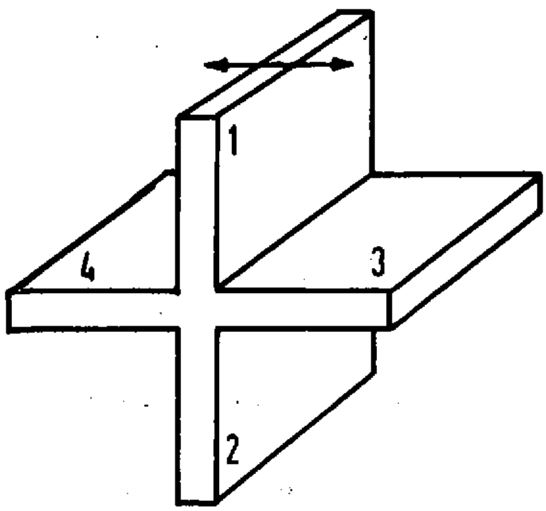


fig.1(a).

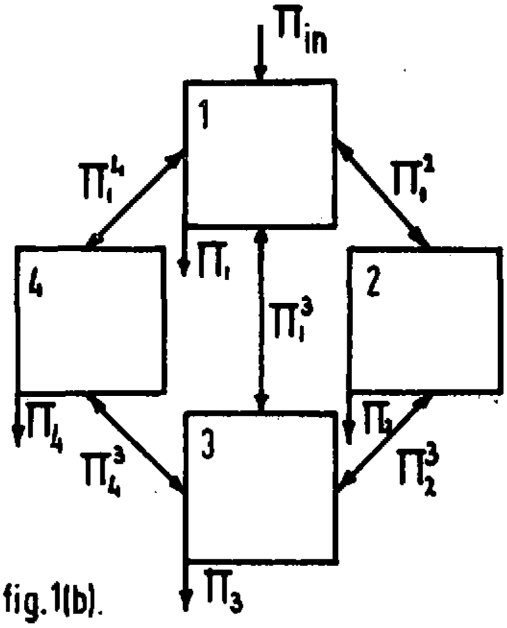


fig.1(b).

In each subsystem the internal energy dissipation is given by,

$$\Pi_i = \omega E_i \eta_i ,$$

where η_i is the loss-factor of the ith system. Initially considering bending waves only and assuming that plates 2 and 4 are equal such that no power flows between them, a steady-state energy balance equation is produced for each subsystem.

$$\sum_{j \neq i} E_j \eta_{ji} = E_i(\eta_i + \sum_{i \neq j} \eta_{ij})$$

The L.H.S. describes energy coming into the ith plate and the R.H.S. gives the energy going out and that being internally dissipated. Energy balance equations are produced for each plate, resulting in a set of simultaneous equations which give the values of the normalised energy level E_i/E_1 of each plate. The problem is made more complicated by the existence of longitudinal and shear waves for which power-flow terms must be added on both sides of the energy balance equations.

3. Coupling coefficients The various coupling coefficients between different wave types and for different junctions and materials must be calculated. By considering an obliquely incident bending wave at a junction of semi-infinite plates and by assuming continuity of displacement, bending moments, and shear forces at the junction, the amplitudes, and hence the energies, of the different wave types resulting on each plate can be calculated (4). Similar procedures are used when considering incident longitudinal and shear waves. From these 'transmission coefficients' the corresponding coupling coefficients are easily derived.

4. Experimentation Experimental measurements involved the use of quarter-scale models of simple structural elements. The validity of quarter-scaling had been confirmed by consideration of wave velocity (Young's modules), density, and loss-factor of full scale and quarter-scale modals of plates and 'rods' of common

fig. 2

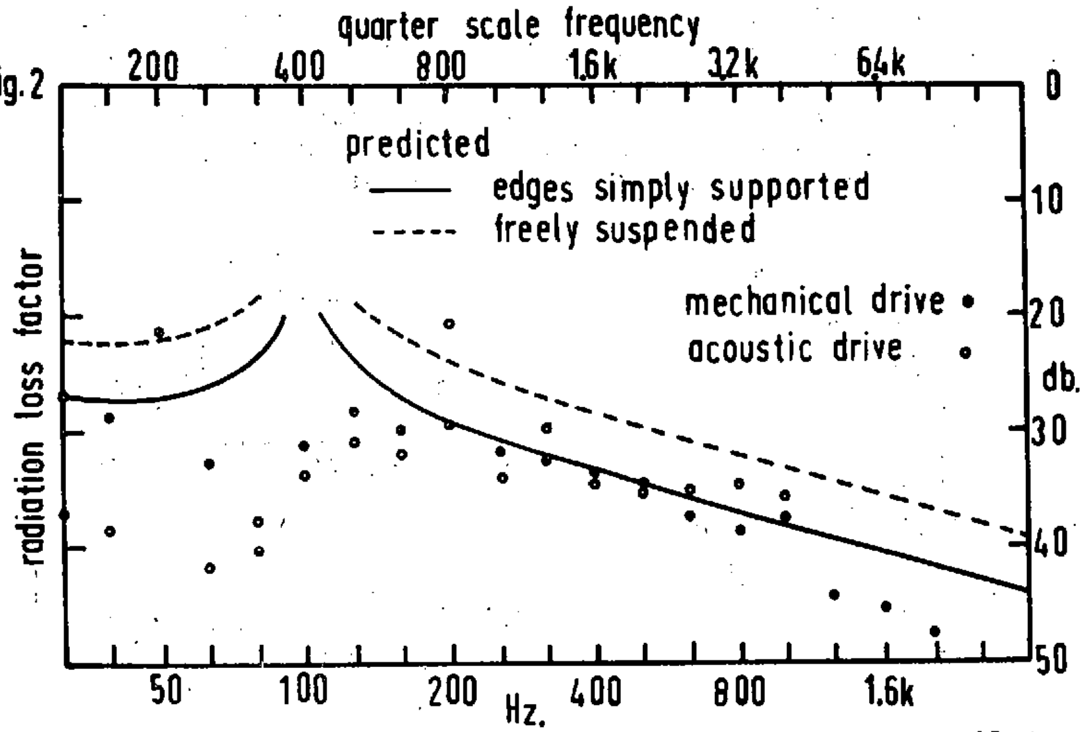


fig. 3

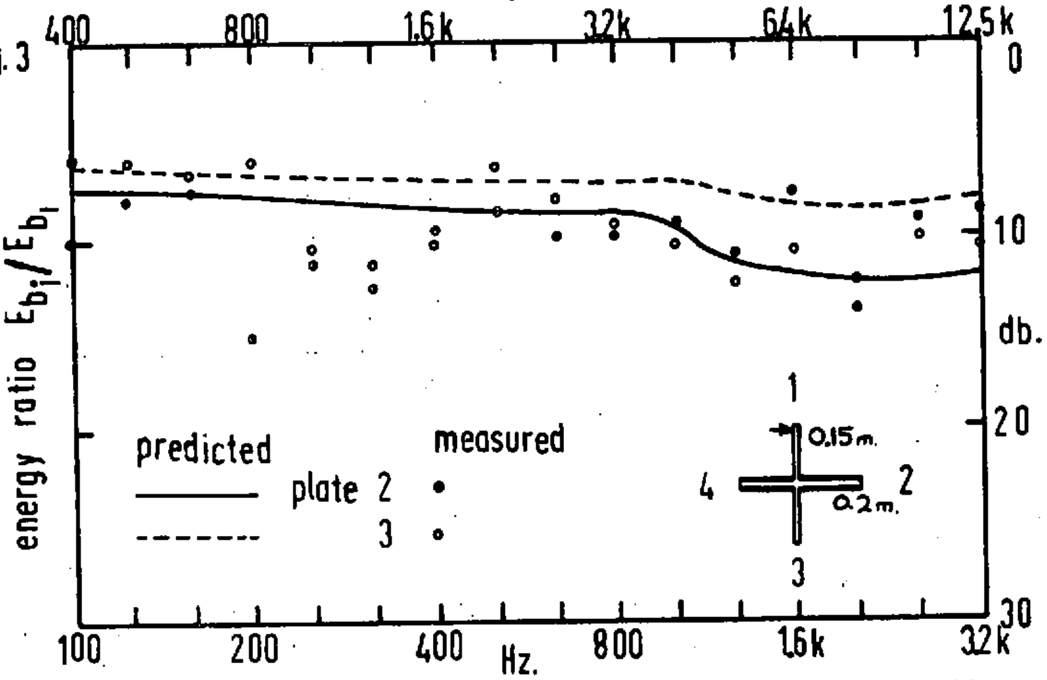
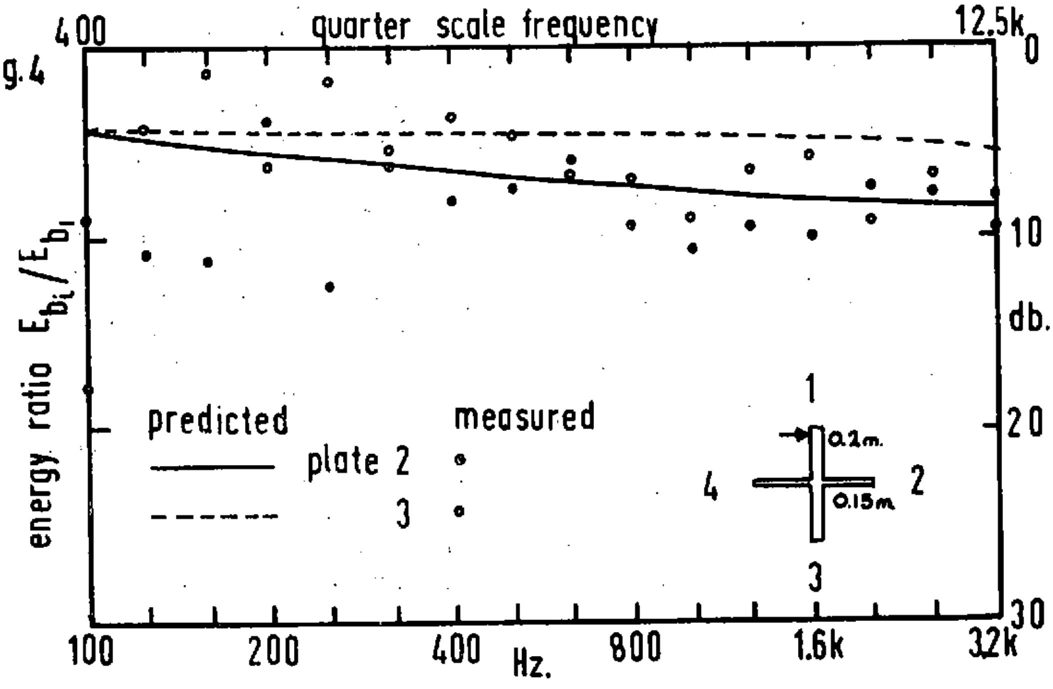


fig. 4



building materials such as brickwork, various concretes, and breeze-block etc.(5).

5. Sound radiation of concrete plates As in reference (3) freely suspended concrete plates were mechanically excited with 1/3 octave filtered random sound. The spacial average of the bending wave energy on the plate and the resultant sound pressure produced in the room were measured. Reciprocally, a sound pressure field was excited in the room by a loudspeaker establishing a bending wave field on the plate. From this, the radiation loss-factor was calculated. Concrete plates of various thicknesses and boundary conditions have been investigated. Fig. 2 gives the half space radiation loss-factor of a baffled concrete plate of dimensions 1m x 0.75m x 0.038m.

6. Structural junctions In the same manner, one plate of a freely suspended junction of plates is mechanically excited by 1/3 octave filtered random sound and the resultant bending wave energies on each plate are measured. Each plate has ten to twenty accelerometers uniformly distributed over the surface. A spatial average of the acceleration amplitude is thus obtained from which can be calculated the bending wave energy,

$$E_b = \frac{h\rho}{\omega^2} \langle a^2 \rangle ,$$

where h is the plate thickness and ρ, the density. $\langle a^2 \rangle$ is the spatial average of the mean square acceleration. Fig. 3 and 4 indicate results obtained for two types of cross-junction of reinforced concrete.

7. Discussion The knowledge gained of the radiation and structural transmission of the simple elements discussed allows the investigator to consider sound transmission in multiple-path systems such as that existing between two adjacent rooms. Noise travelling between rooms which have no common wall (as is found in blocks of flats) can also be considered, although the matrix of energy balance equations will be much more complicated.

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