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Building acoustics as a scientific discipline: Manfred Heckl's research on airborne and structure-borne sound transmission

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ABSTRACT

This paper describes examples of the research contributions of Manfred Heckl to building acoustics. From his broad range of theoretical and experimental research on structural dynamics and acoustics, he provided underlying principles and practical methods, of relevance to both researchers and practitioners concerned with the assessment and control of noise and vibration. The examples of his work considered highlight his ability to give rigorous physical insights and, at the same time, offer appropriate simplifications. The examples are: the use of an analogy to room acoustics for the treatment of edge damping of plate structures; invoking reciprocity to establish a relationship between the transmission loss and impact-noise isolation of floors; reference to the dynamic characteristics of infinite and semi-infinite systems for estimating the mobilities of source and receiver structures in buildings.

1. INTRODUCTION

From the late 1950s, Manfred Heckl published and presented his research on a wide range of topics with important contributions to mechanical, aero-space and, as highlighted in this paper, building engineering. I did not know Manfred Heckl personally, although I met him and attended as many of his conference presentations as I could. This appreciation is from a member of his audience and from a reader of his journal articles and books. They have provided invaluable knowledge throughout my research career in building acoustics and, indeed, do so today. Whilst the origins of the research reported in his single-authored papers are clear, I do not know the details of the contributions of his collaborator and co-author Professor Lothar Cremer, see for example his earlier publication [4]. A case in point are the early editions of the scientific monograph 'Structure-borne Sound' [5-7]. Close colleagues and students of Heckl could provide an answer. Sadly neither author is around to correct me, so I take full responsibility for any misinterpretations or wrong assumptions made.

Building acoustics is often viewed as the least scientific of the engineering disciplines, but Manfred Heckl did not treat it as such. His research continues to have relevance to building acoustics because of present trends in building: the design and construction of multi-occupancy lightweight buildings, the development of new construction materials and the introduction of increasingly powerful and complicated mechanically services in buildings. Three examples of his research findings are described, which could be sub-titled: analogy, reciprocity and infinity. Whilst the original journal articles are cited, reference also is made to the three editions of the monograph 'Structure-borne Sound' [5-7], which contain important aspects of the journal articles.

2. ANALOGOUS TREATMENT OF DAMPING OF PLATE STRUCTURES

If employed carefully, new problems can be addressed analogously by relating to problems in more mature research areas. The example given is of localized damping of structural plates, due to frictional effects of riveted and bolted beam attachments, and of other connected plates, not previously considered at the time of Heckl's article [1]. In it, he referred to the approach to localized surface absorption in rooms, developed in over fifty years of room acoustics [2]. Both relate to reverberation time, which is relatively easy to measure. The 'absorption coefficient' γ (the ratio of bending wave energy absorbed to bending energy incident) of a strip L of damping, at a plate edge, is given by:

$$\gamma = (13.8\pi S / c_g L)(1/T - 1/T_0) \tag{1}$$

S is plate area, c_g is bending wave group velocity, T_0 is the reverberation time of the bare plate and T_1 of the plate with the damped edge. This gives a procedure for estimating the total damping of complicated structures composed of several plates, from the measured reverberation time:

$$1/T = \frac{c_g}{13.8\pi S} \sum \gamma_i L_i + 1/T_0 \tag{2}$$

From this, the relationship between the total power P into a plate, of mass M, and the mean square response velocity is:

$$v^2 = \frac{P}{M} \left(\frac{c_g}{\pi S} \sum \gamma_i L_i + \frac{13.8}{T_0} \right)^{-1} \tag{3}$$

Figure 1 shows the absorption coefficient of a beam bolted to a plate with viscous material at the interface. The five bolts are spaced at 100mm intervals. The maxima at 100 Hz and 250 Hz coincide with frequencies where the bolt distances are multiples of one-half bending wavelength. These resonances generate enhanced damping effects that could be exploited in specifying materials and geometry. Likewise, the highest absorption will result from consideration of the relationship between material viscosity and plate impedance. These relationships can be experimentally confirmed using reverberation time measurements.

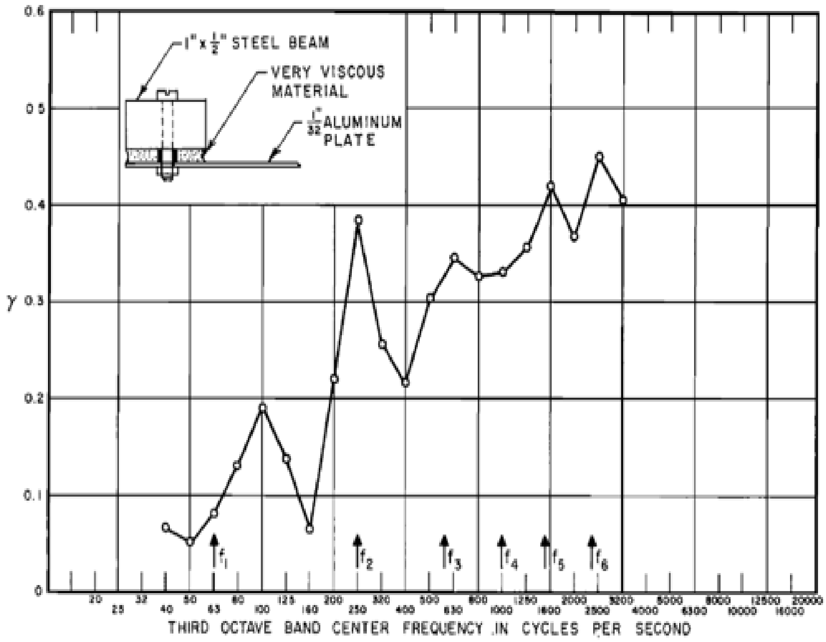

Figure 1. Absorption coefficient of beam bolted to a plate with viscous material at the interface (Figure 5 of [1]).

Junctions with other plates are treated in the same way as for damping attachments. Figure 2 shows the absorption coefficient of a junction between a lightly damped and a heavily damped plate. This is analogous to a reverberation room with an open aperture into an anechoic chamber. The work was an important complement to the development of the sub-structuring approach in Statistical Energy Analysis [3]. Related to this is Heckl's contribution: the concept of the loss factor matrix.

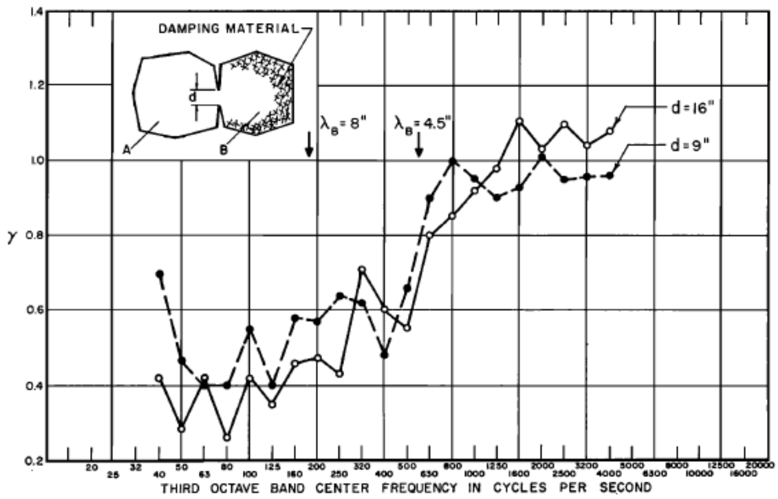

Figure 2. Absorption coefficient of a junction between a reverberant plate and a heavily damped plate (from Figure 4 of [1]).

3. RECIPROCITY AND THE RELATIONSHIP BETWEEN TRANSMISSION LOSS AND IMPACT ISOLATION

In vibro-acoustics, the principle of reciprocity is invoked to circumvent problems of accessing structural elements for excitation and response measurement, and/or for establishing transfer paths in the presence of other transfer paths [7]. Of importance is obtaining the correct relationship between the field variables, which must be interchangeable such that their product yields the energy or power [8], see Figure 3.

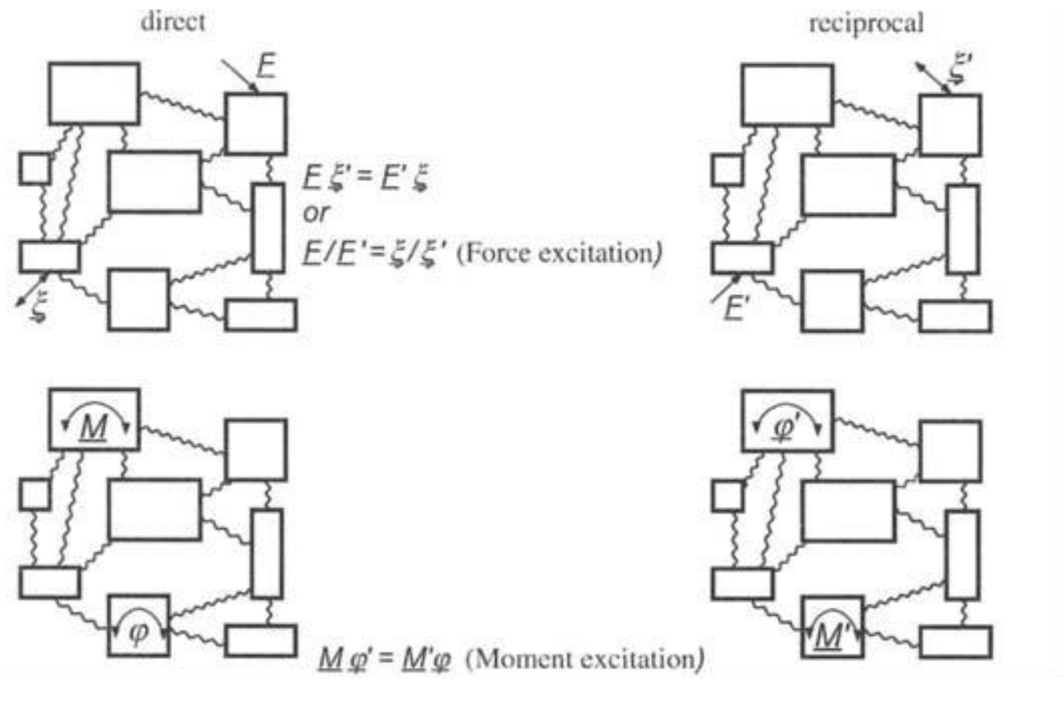

Figure 3. Reciprocity and mutual energies (Figure 2.11 of [7]).

In the following application of reciprocity, Heckl and Rathe considered the relationship between airborne sound transmission and impact sound isolation of floors [9]. Intuitively, there should be a relationship for homogeneous floors, but what of composite floor constructions? Figure 4 represents a floor A over an enclosed space, including a limp wall B.

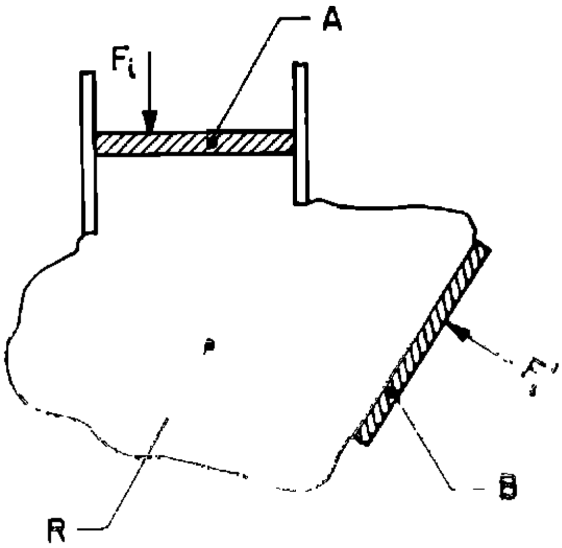

Figure 4. Schematic of reciprocal relationship between impact and airborne sound transmission (Figure 1 of [9]).

The space is described by its room constant, $R = \frac{S\overline{\alpha}}{(1-\overline{\alpha})}$

For a point force F_i into the floor, the resultant reverberant sound pressure:

$$\left\langle p^2 \right\rangle = 4\rho\, c\, F_i^2 / R \qquad (4)$$

Assuming pressure doubling at the surface and mass-law behaviour, the velocity of the wall B, of surface mass m is:

$$v_B^2 = 2\left\langle p^2 \right\rangle / \omega^2 m^2 = 8\rho\, c\, \kappa\, F_i^2 / \omega^2 m^2 R \qquad (5)$$

where the factor of proportionality $\kappa = \frac{P}{F_i^2}$

Reverse the procedure, to obtain the velocity of the floor A when excited by the sound field generated by a point force on wall B:

$$v_A^{'2} = \beta\, 4\rho^2\, c^2\, k^2 \kappa\, F_i^{'2} / \left(2\pi\, \omega^2 m^2 R\right) \qquad (6)$$

where $\beta = \dfrac{v_A^{'2}}{\left\langle p^{'2} \right\rangle}$

The force and velocity points are interchanged reciprocally to give:

$$\beta / \kappa = \frac{4\pi}{\rho c k^2} \tag{7}$$

κ relates to the impact sound level L_N and β to the sound transmission loss TL, and by manipulation:

$$L_N + TL = 10 \log k^2 F_T^{'2} / 4\pi R_0 \, p_0^2 \tag{8}$$

R_0 =10m^2 and p_0 = 2.10^{-5} pa. The sum-quantity is independent of the floor properties, but requires the force spectrum of a standard tapping machine F_T^2, which from Equation 20 of [9] gives in octaves:

$$L_N + TL = 43 + 30 \log f \tag{9}$$

This relationship holds for a range of concrete floors as shown in Figures 5.

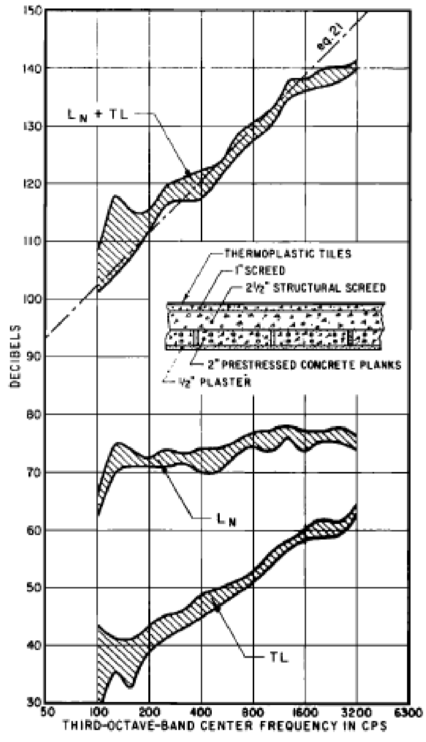

FIG. 4. Range of transmission loss and impact-noise levels of four 5½-in. concrete floors using precast concrete planks. [After Parkin, Purkis, and Scholes.[11]]

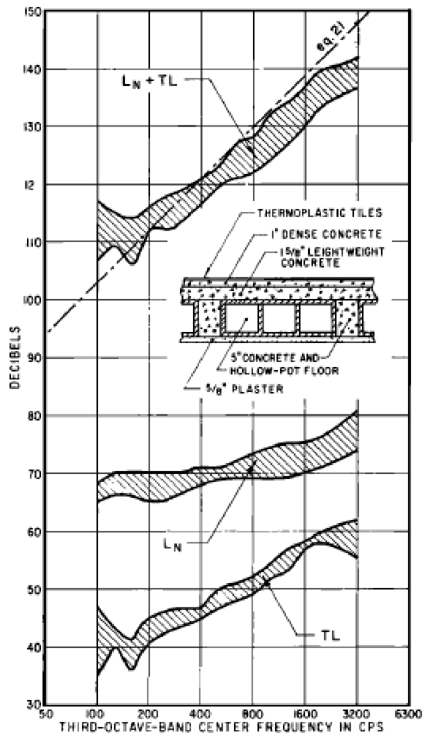

FIG. 5. Range of transmission loss and impact-noise levels of four concrete and hollow-pot floors. [After Parkin, Purkis, and Scholes.[12]]

Figure 5. Transmission loss and impact sound level of concrete floors (Figures 4 and 5 of [9]).

For a floor with a resilient layer of natural frequency f_n the relationship is given by Equation 21 in [9]:

$$L_N + TL = 43 + 30\log f - 10\log\left(1 + f^4 / f_n^4\right) \qquad (10)$$

Heckl is careful to highlight where reciprocity does and does not apply, see Figure 6. For example, it does not hold when there is acoustic leakage through the floor, because the impact and airborne sounds then travel along different paths.

It is somewhat surprising that such relationships are not used more extensively, when preliminary estimates of sound insulation are required.

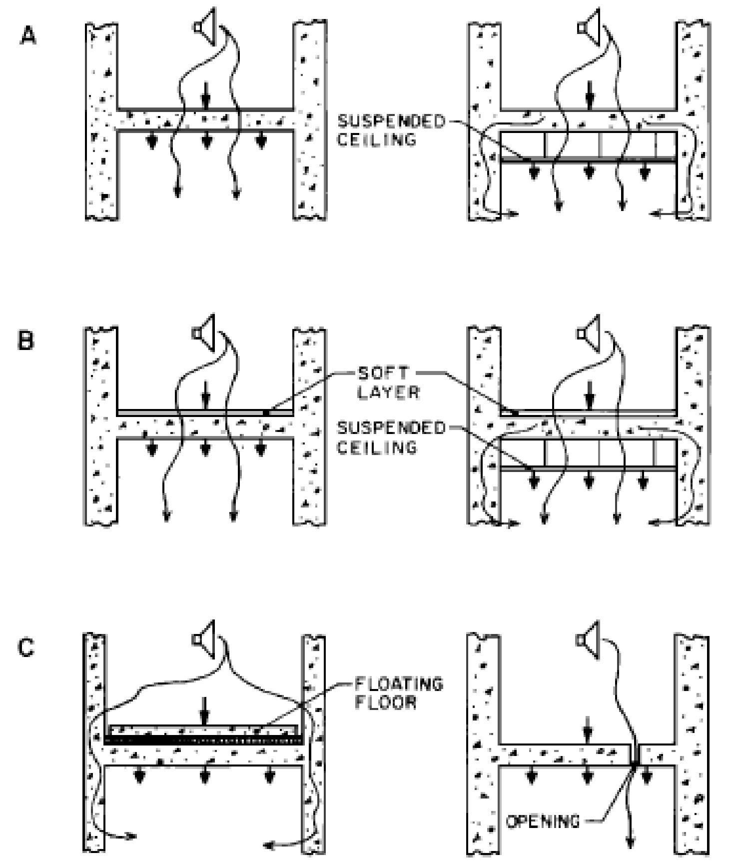

FIG. 2. Applicability of theoretical behavior. Examples under A: Both Eq. (14) and Eq. (21) hold. Examples under B: Eq. (14) [and Eq. (24)] holds. Examples under C: neither Eq. (21) nor Eq. (14) holds.

Figure 6. Applicability of reciprocity (Figure 2 of [9]).

4. DYNAMIC CHARACTERISTICS OF INFINITE AND SEMI-INFINITE SYSTEMS

In this section, examples of the author's work are given of how the impedance/mobility expressions, summarized in Heckl's compendium [10] and in monographs [5-7], have provided essential input to this area of sub-structuring in vibro-acoustics. The structure-borne power from vibrating machines into receiver structures is determined by the source activity (either the velocity of the free source or the blocked force when attached to an inert structure), and the structural dynamics of the source and receiver, either the impedance or its inverse, mobility. This discussion uses mobility.

Figure 7 shows the interaction between an active source and a passive receiver represented by the inverse electric circuit analogy [11].

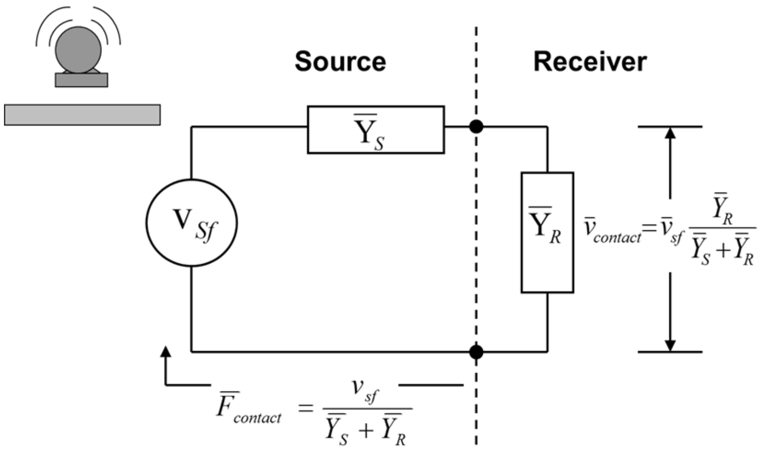

Figure 7. Inverse analogous electric circuit representation of contact force and contact velocity.

The vibrating source is represented by the free source velocity (the velocity of the freely suspended source under otherwise normal operation) and the source mobility (the complex ratio of response velocity to an applied force, again when freely suspended). The receiving structure is represented by the receiver mobility. The transmitted power is the real part of the complex power, from the complex product of contact force and contact velocity:

$$P = \left|v_{sf}\right|^2 \frac{\mathrm{Re}(\overline{Y}_R)}{\left|\overline{Y}_S + \overline{Y}_R\right|^2} \qquad (11)$$

The expression requires complex mobilities for all source-receiver mobility conditions. The expression simplifies by assuming that the matched mobility condition occurs rarely and only in narrow frequency bands [12]. The expression becomes the approximation:

$$P \approx \left|v_{sf}\right|^2 \frac{\mathrm{Re}(\overline{Y}_R)}{\left|\overline{Y}_S\right|^2 + \left|\overline{Y}_R\right|^2} \qquad (12)$$

This assumption allows all terms to be measured or calculated as real values, which can be expressed as band-averages favoured by building acousticians.

Mechanical installations and light-weight building elements are often complicated and the dynamic analysis of which is seldom straightforward. In compiling a compendium of mechanical impedances [10], Heckl drew from his own work and that of Cremer and others, in extracting the underlying infinite and semi-infinite dynamic behavior. This leads to frequency-average and high-frequency asymptotic values of point and transfer mobility. Of importance is the concept of the characteristic mobility of a thin plate-like receiver structure, which is that of an infinite plate of the same material and thickness:

$$Y_{char} = \frac{1}{8\sqrt{B'm'}} \qquad (13)$$

m' is the mass per unit area and B' is the bending stiffness. The characteristic mobility is frequency invariant and is real-valued. For ribbed or framed plate structures, the mobility at the reinforcing points can be approximated by the characteristic beam mobility:

$$Y_{beam} = \frac{1}{2m'c_B(1+j)} \qquad (14)$$

where c_B is the bending wave velocity.

The mobility at the contact points of mechanical installations is largely determined by the material and geometry of the machine base around the contacts. Figure 8 shows the measured point mobility at four mount points of a flange base of a medium size centrifugal fan.

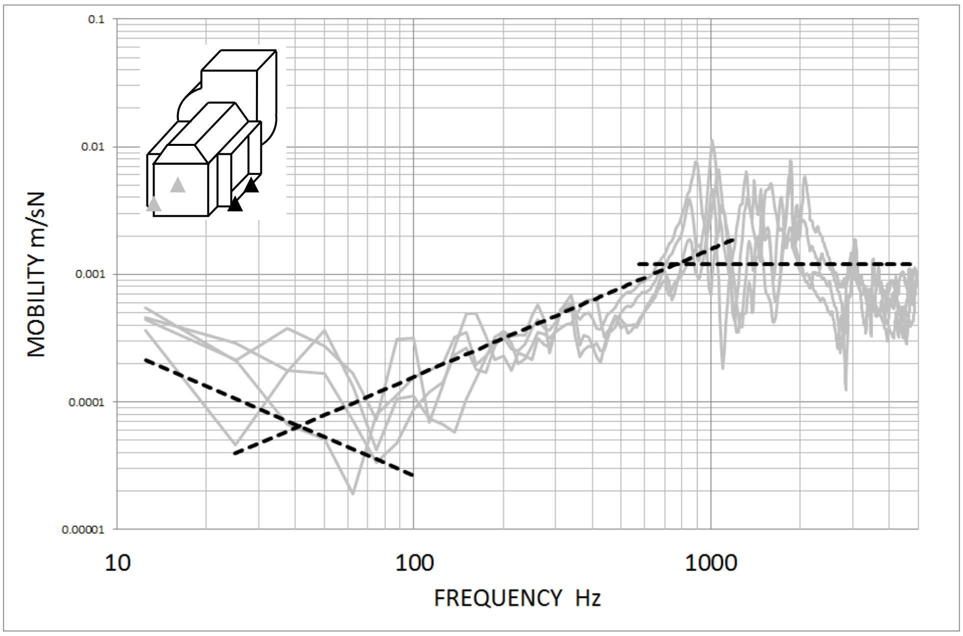

Figure 8. Measured point mobility at four points of a fan base (faint lines) and estimated (dashed lines), from[12].

Resonant plate behavior is evident above 800 Hz, which although modelled in detail by Petersson and Plunt [13], can be approximated using characteristic values. When combined with simple expressions for rigid body motion (below 40 Hz) and for stiffness controlled motion (between 40 Hz and 800 Hz), a trend curve results, useful for estimating source mobility and thence structure-borne power.

What of inhomogeneous building elements? It is seldom if ever possible to measure mobilities, prior to installing machines. In seeking a method for calculating the mobility of ribbed plate structures, such as timber-joist floors, reference is again made to characteristic plate and beam mobilities for point values, combined with Hankl functions for transfer values [5-7]. Figure 9, from Mayr and Gibbs [14], shows the measured and calculated real parts of point and transfer mobility of a timber-joist floor. The curves lend themselves to frequency band averaging for prediction of installed powers from machines attached to the floor at any location.

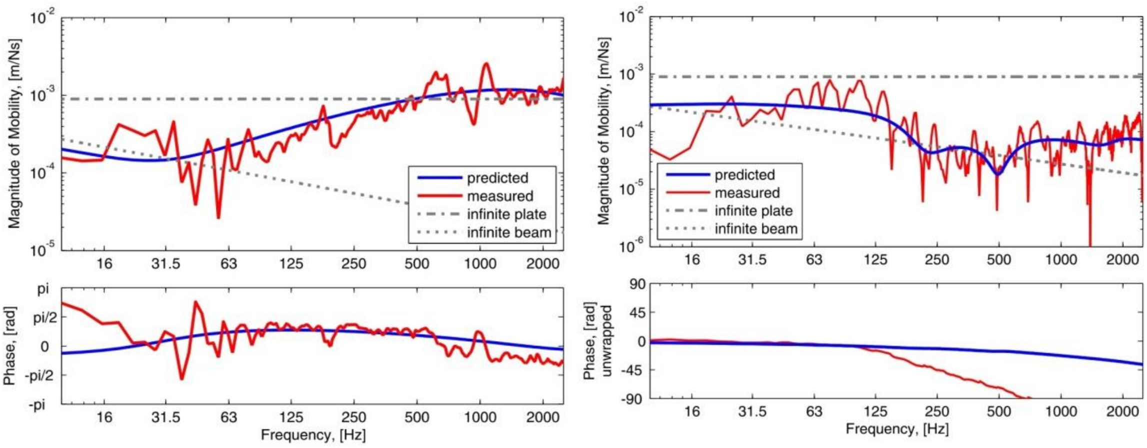

Figure 9. Point mobility over a joist (left) and transfer mobility across a joist (right): measure (red line) and calculated (blue line); shown are characteristic plate (dot-dashed line) and beam mobilities (dotted line).

Can a general curve of point mobility of ribbed or framed lightweight building elements be formed? Figure 10 shows the real part of the measured mobility of a timber-joist floor normalised with respect to the characteristic sheathing plate mobility and plotted as a function of distance from a fixing point, and normalised with respect to the bending wavelength in the sheathing plate. Also shown are characteristic values of beam mobility, for the effect of the joists at low frequency, and the characteristic plate mobility for high frequency. There is a straight-line interpolation between the two asymptotic values.

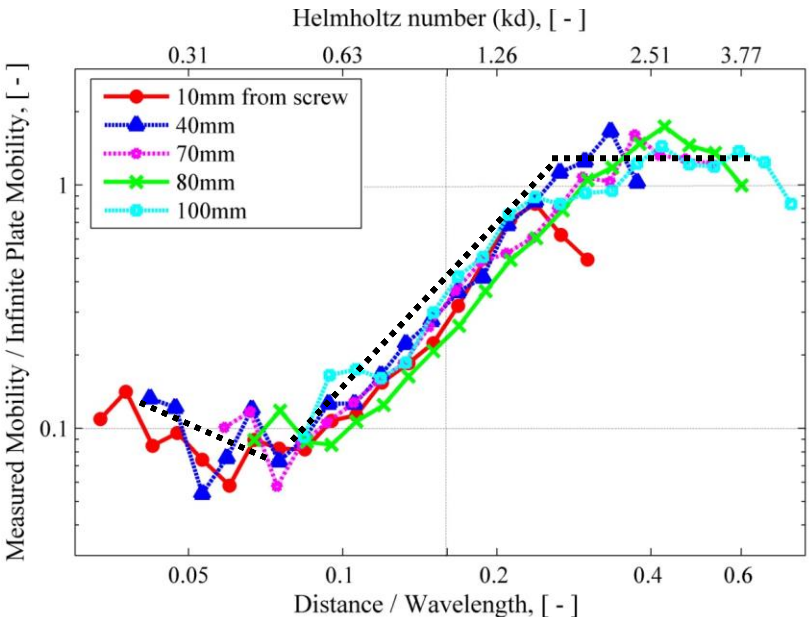

Figure 10. Real part of point mobility, normalised to characteristic plate mobility, as a function of ratio of distance to bending wavelength (lower scale) and Helmholtz number (upper scale), from [14].

5. CONCLUDING REMARKS

This paper describes only three examples of the many research contributions of Manfred Heckl to building acoustics, which hopefully have highlighted his ability to give physical insight and, at the same time, offer appropriate simplified methods. His work has continued relevance to building acoustics. For example, the work reported in Section 4 points to the possibility of assembling a compendium of mobilities of building services equipment and of building structural elements, based on Manfred Heckl's compendium.

Acknowledgements

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