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SOUND INSULATION OF DOORS—PART 1: PREDICTION MODELS FOR STRUCTURAL AND LEAK TRANSMISSION

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Examination of sound insulation of doors presupposes two separate transmission paths to be considered: the structural transmission through the door leaf and the leak transmission through the slits. In this paper, simple prediction models for both transmission paths are presented which are applicable for most types of passage doors. The practicability of the selected models are of great concern to obtain a high degree of utilization in product development. Most doors are designed nowadays as double-panel structures with sound absorbing and fire-resistant materials in the air cavity. Strong interpanel connections are often present at least in the edges of the door. Sharp's double-panel prediction model was found appropriate for modelling both single- and double-panel doors. The slit transmission can be estimated at least by two different theories. The simple model assumes perfect transmission through the apertures. The more profound Gomperts model enables the evaluation of structurally regular slits. The total sound reduction index of doors is predicted from the area-weighted sum of the structural transmission and the slit transmission. Acoustical structure and airtightness of the door shall be developed hand-in-hand to obtain the optimum performance of the door. The prediction models presented in this paper are verified in the second part for 18 steel doors and timber doors [1].

1. INTRODUCTION

The sound insulation requirements for doors have increased due to increased consciousness of acoustics and due to accompanying policies stating the specifications of building products. Doors are usually the weakest sound-insulating elements between rooms and therefore need careful acoustic design. The requirements for partition walls range usually from $R'_w = 40$ up to 60 dB, while commercial doors are available usually from $R_w = 25$ to 35 dB. Single-leaf doors are available for special purposes at least up to 48 dB but they are seldom used. In fact, twin doors are preferred when higher insulation than $R'_w = 35$ dB is required.

It is well known that imperfect sealing of a door can impair essentially the total sound reduction index of the door. The sound insulation performance of a door can be defined by the set of numbers $R_{w,struct}/R_{w,total}/R'_{w,struct}/R'_{w,total}$ dB, where $R_{w,struct}$ and $R_{w,total}$ are the weighted sound reduction indices by ISO 717-1 in the

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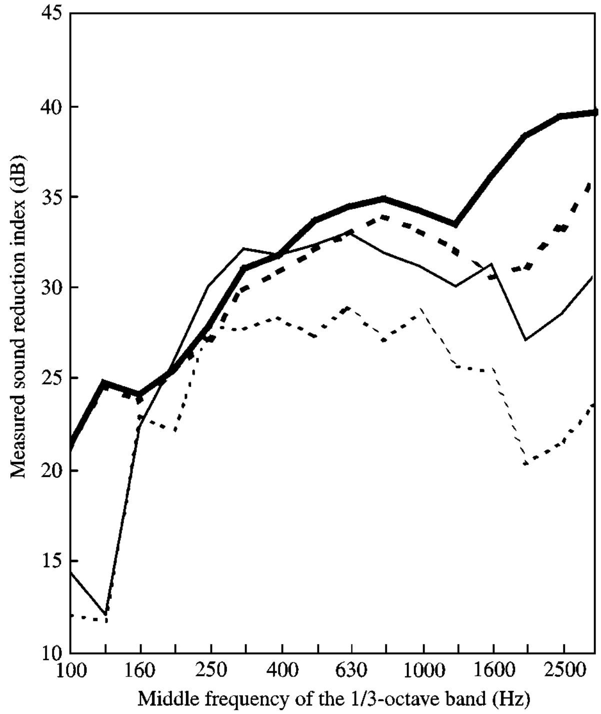

Figure 1. An example of a door with a measured performance of $R_{w,struct}/R_{w,total}/R'_{w,struct}/R'_{w,total} = 36/33/30/24$ dB. - - -, *In situ*, normal mounting; ——, *in situ*, tape-sealed; **——**, laboratory, tape-sealed; **- - -**, laboratory, normal mounting.

laboratory when the door is tape-sealed or normally mounted, respectively [2]. $R'_{w,struct}$ and $R'_{w,total}$ are the corresponding values *in situ*. The former pair of numbers can be called the laboratory performance and the latter pair of numbers can be called the field performance, respectively. $R_{w,struct}$ is used as the official sound insulation value of a building element (R_w). For doors this quantity can be very misleading regarding the performance *in situ*. The dependence of the field SRI on the workmanship is even stronger than for lightweight walls.

One example of the sound insulation performance is given in Figure 1. The door is the same as the door T1 in reference [1]. The measurements were carried out according to ISO 140/III or ISO 140/IV. It is clear that the acoustical product development is not finished with such a disperse performance. Too much effort has been wasted to improve the structure of the door leaf. The same field performance could have been obtained with a much simpler structure of the door leaf and by improved the sealing and mounting specifications.

Doors are probably the most exacting building elements, as far as sound insulation is concerned. However, the sound insulation of doors has not been discussed exhaustively in the literature. Gomperts studied the sound insulation of slit-shaped apertures and applied the theory to the slits of a door [3]. Jones used a simplified model for estimating the effect of sound leaks on the total sound insulation of partitions [4]. Hongisto *et al.* presented some sound intensity flow patterns of doors obtained by a two-microphone intensity method [5]. The sound leaks could be easily located by using discrete point-by-point measurements. Hongisto has also studied preliminarily the effect of sound leaks to the total sound insulation of doors using the Jones model for partition walls [6]. Finally, Hongisto studied theoretically and experimentally the effectiveness of structural improvements when sound leaks are present [7]. Both leak and structural sound insulation have to be developed hand in hand if proper acoustical doors are desired.

The aim of this paper in two parts is to fill the gap in the literature concerning the sound insulation of doors. In this first part, the prediction methods of sound insulation are presented so that the structural sound transmission can be controlled at an adequate level by using easily available basic physical data. Both single and double panels will be studied. The effect of sound slits (slits between the door and the frame) on the total sound transmission through doors is studied by two models. The input data is also simple, containing cross-sectional areas and dimensions of the slits.

In the second part, several prediction and measurement results are presented concerning both structural transmission and leak transmission.

2. SOUND TRANSMISSION THROUGH DOORS—GENERAL DESCRIPTION

Sound transmission through doors is assumed to comprise two factors: structural transmission and leak transmission, having sound transmission coefficients τ_{struct} and τ_{leak} respectively. This is elucidated in Figure 2. The areas are S_{struct} and S_{leak} respectively. The sound leaks can comprise, e.g., regular slits, irregular apertures, holes, etc. The transmission through door frames is ignored here since the area of frames is usually below 10% of the door area, the mass is higher than the mass of the door and the transmission coefficient of the frames is difficult to determine experimentally.

The structural sound reduction index of a door (denoted by R_{struct}) is usually determined by tape-sealing the slits and the lock device. The SRI of the door without tape sealing (i.e., normal mounting) is denoted by R_{total}, where "total" refers to the sum of leak transmission and structural transmission. The total sound reduction index of a door can be calculated by the area-weighted sum of transmission coefficients as

$$R_{total} = 10\log\left(\frac{1}{\tau_{total}}\right) = 10\log\left(\frac{1}{\tau_{struct} + \tau_{leak}}\right)$$
$$= 10\log\left(\frac{S_{total}}{S_{struct}\,10^{-R_{struct}/10} + S_{leak}\,10^{-R_{leak}/10}}\right), \quad (1)$$

where $\tau = W_t/W_i$ is the transmission coefficient determined by the incident W_i and transmitted W_t sound powers (see Figure 2) and S_{total} is the total area of the door, or $S_{struct} + S_{leak}$.

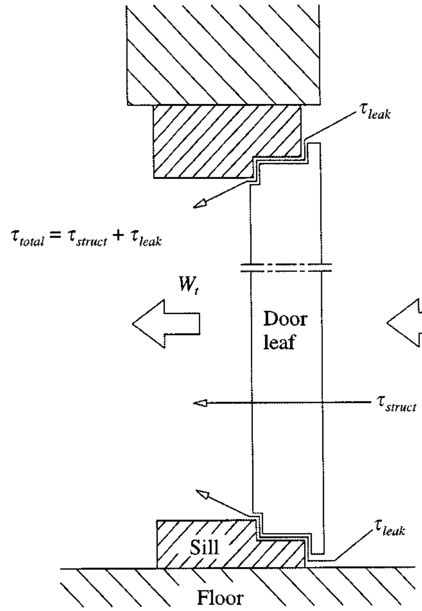

Figure 2. The principle of sound transmission through doors (cross section, side view). The leak transmission and the structural transmission are separated.

To study the structural transmission and the leak transmission of a specified door it is not necessary to use the real areas of sound leaks. If the areas are equal for each transmission path $S_{total} = S_{struct} = S_{leak}$ in equation (1) it is easy to compare the sound reduction index of the leak path and structural path. Hence, by using equation (1) and neglecting the area terms, the leak SRI can be calculated simply by

$$R_{leak} = -10\log(10^{-R_{total}/10} - 10^{-R_{struct}/10}). \qquad (2)$$

Thus, R_{leak} represents the SRI averaged over the area of the door. The areas are not needed either because this examination concentrates on the general comparison of the leak path and structural path. According to equation (2), it is evident that whatever structural improvements are made in the door leaf, the value of R_{leak} is always the upper limit of R_{total}.

Let us suppose that the aim is to increase the structural SRI of a door (labelled by 1) by ΔR_{aim} by changing only the acoustic properties of the door leaf structure. The SRI of a new door (labelled by 2) is not directly the sum of the previous structural SRI and the desired increase in SRI ($R_{struct,1} + \Delta R_{aim}$). The leak transmission, that remains constant, has to be taken into account. Instead, the new total SRI is

$$R_{total,2} = -10\log(10^{-R_{struct,2}/10} + 10^{-R_{leak}/10}). \qquad (3)$$

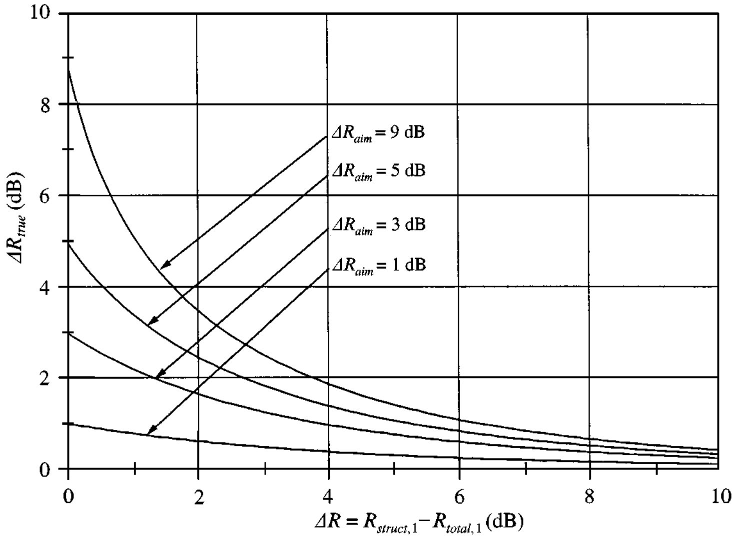

Figure 3. The true improvement (ΔR_{true}) of the total SRI as a function of measured difference between sealed and unsealed door (ΔR) for four different values of desired improvement in structural SRI (ΔR_{aim}).

The achievable increase in total SRI by changing merely the acoustical structure of the door is denoted by $\Delta R_{true} = R_{total,2} - R_{total,1}$. It can be derived from equations (1) and (3) in the form

$$\Delta R_{true} = R_{total,2} - R_{total,1} = -10\log(10^{-(R_{struct,1}+\Delta R_{aim})/10} + 10^{-R_{total,1}/10} \ldots$$

$$\ldots - 10^{-R_{struct,1}/10}) - R_{total,1}. \quad (4)$$

The behaviour of ΔR_{true} is presented in Figure 3. The leak transmission is assumed to be constant. It can be seen that improving the acoustical structure by ΔR_{aim} is a very inefficient way to raise the total SRI when $\Delta R > 3$ dB. For example, if the structural changes could lead to an increase of 5 dB but the difference between the tape-sealed door and the normal mounted door were $\Delta R = 3$ dB, the true improvement would be only $\Delta R_{true} = 1{\cdot}8$ dB. This graph shall be applied frequency by frequency, and not directly to the analysis of frequency-weighted data like R_w.

For the purposes of product development, it is essential to improve the single number value $R_{w,total}$ of the door. The only way to do this is to increase the total SRI at those frequencies where unfavourable deviations from the ISO 717-1 reference curve occur. Structural changes are of no use if the unfavourable deviations coincide with frequencies where ΔR is significant. This is often the case at high frequencies. It the unfavourable deviations occur at low frequencies where also sound leaks are usually less significant, solely structural changes effective at low frequencies may be profitable without a need to improve the sealing.

TABLE 1

Acoustical properties of most common materials used in lightweight building elements [7, 10, 26]

Material	ρ (kg/m^3)	hf_{cr} (m/s)	η
Steel (S)	7800	12·4	0·0002
Glass	3000	12·7	0·002
Aluminium	4000	12	0·0001
Lead	11 000	48	0·02
Gypsum board	770	35	0·006
Chipboard (CB)	950	23	0·01
Plywood	708	20	0·02
Hardboard (HB)	950	37·7	0·02
Fiber board (FB)	300	38	0·05
Perspex	1200	27·7	0·04

3. SOUND TRANSMISSION THROUGH THE DOOR LEAF

Prediction of the structural sound reduction index of lightweight double partitions has been discussed widely. There are two main approaches. The conventional methods are based on the determination of panel impedances [8]. The statistical energy analysis is mainly based on the examination of the energy flow between statistically resonating structures [9]. In the following sections, a carefully selected set of simple prediction models will be described that is appropriate for doors.

3.1. THIN SINGLE PANELS

The sound reduction index of a thin unbounded single panel R (dB) is calculated by [8, 10, 11]

$$R = \begin{cases} 20\log mf - 48, & f < 0{\cdot}5 f_{cr}, \\ 20\log mf + 10\log\left[\eta\left(\dfrac{f}{f_{cr}} - 1\right)\right] - 44, & f \geqslant f_{cr}, \end{cases} \tag{5}$$

where m (kg/m^2) is the mass per surface area, f (Hz) is frequency, f_{cr} (Hz) is the lowest coincidence frequency or the critical frequency and η is the acoustical loss factor. The terms -48 and -44 dB were selected to cover the sound incidence angles from 0 to 78°, which has proved to be the appropriate range for modelling the incident, diffuse sound field in most test laboratories. Between frequencies $0{\cdot}5f_{cr}$ and f_{cr} a linear interpolation is applied.

A material database sufficient for most cases is given in Table 1. The critical frequency can be calculated when the thickness h (m) of the panel is known. The

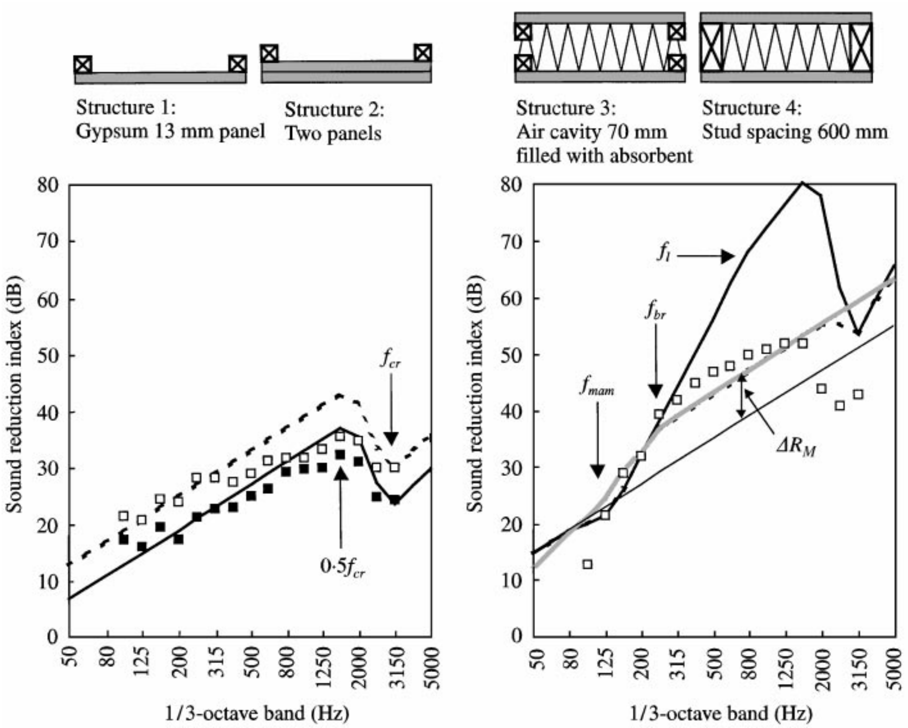

Figure 4. The principle of the calculation of SRI for single panels (left): ——, structure 1, 29 dB; - - -, structure 2, 35 dB; ■, structure 1, 28 dB (measured); □, structure 2, 32 dB (measured); and double panels (right): ——, structure 3, 47 dB; □, structure 4, 43 dB (measured); - - -, structure 4, A 45 dB; ▬, structure 4, B 46 dB; ——, structure 4, C. The last dB-value in the label text is R_w. Cases A–C used for structure 4 are explained in section 3.6.

natural resonances of thin single panels are usually far below 100 Hz and they are therefore omitted in this study.

The validity of equation (5) is well known. The method of mounting (clamping, etc.) and the size of the specimen affect the results by few decibels especially at low frequencies [8, 10, 26]. Because the theories presented so far give different results, no model responding to mounting and size of the specimen is included in this study.

The shape of the SRI-curve according to equation (5) is presented in Figure 4.

3.2. ISOLATED DOUBLE PANELS WITH SOUND ABSORBING CAVITY

Isolated double panels consist of two isolated leaves separated by an air cavity. In the following equations it is assumed that no reverberant sound field exists in the cavity either parallel or perpendicular to the panels. No standing wave resonances occur either. This assumption means that the cavity is filled with a material that cancels the amplification by reverberation in the cavity. The attenuation of sound when passing through the material is ignored. This is a reasonable assumption especially for doors because the thickness of the cavity is small. The sound reduction index R (dB) of unbounded ideal double panels is calculated by [8, 11]

$$R = \begin{cases} R_M, & f < f_{mam}, \\ R_1 + R_2 + 20 \log fd - 29, & f_{mam} < f < f_l \\ R_1 + R_2 + 6, & f > f_l, \end{cases} \tag{6}$$

where R_M is the sound reduction index according to the mass law

$$R_M = 20 \log Mf - 48, \tag{5a}$$

where M (kg/m^2) is the total mass of both panels and the contents of the cavity m_{cav} (glue, absorbents, etc.),

$$M = m_1 + m_2 + m_{cav}. \tag{7}$$

The sound reduction indices of the individual leaves R_1 and R_2 (dB) are calculated by equation (5) or they are obtained by measurements.

Equation (6) presents three linear equations with three different slopes and two discontinuity points. The first transition frequency occurs at the mass–air–mass resonance of the double-panel system f_{mam}. For a diffuse field it is calculated from [11]

$$f_{mam} = \frac{1}{2\pi} \sqrt{\frac{1{\cdot}8 \rho_0 c_0^2}{d} \frac{(m_1 + m_2)}{m_1 m_2}}, \tag{8}$$

where d (m) is the thickness of the cavity separating the panels. The constants are $\rho_0 = 1{\cdot}18$ kg/m^3 and $c_0 = 343$ m/s. The value of d (m) is the inside distance between panels, whether the air cavity is treated by absorbent or not.

The transition frequency f_l occurs when the cavity thickness d becomes larger than one-sixth of the wavelength of sound in the cavity [11],

$$f_l = c/6d. \tag{9}$$

Above this frequency the coupling between the leaves via the airborne path becomes very weak. The previous model has been verified in several references and it has been found valid [4, 6, 8, 11–13]. An example of the prediction according to equation (6) is shown in Figure 4.

3.3. THE EFFECT OF CAVITY ABSORBENTS

The theory presented in section 3.2 assumed that the cavity is anechoic. In real-wall structures, the amount of absorption materials and their absorption coefficients vary. There are several experimental studies concerning the effect of absorption materials inside the double-panel cavity. Loney did not present any models for the problem but he found that the SRI does not depend linearly on the thickness of the material: “The first inch has the greatest effect” [14]. Narang studied the effect of fiberglass density and flow resistance but did not give any mathematical models for their effect [15]. Green *et al.* used a statistical approach for certain double-panel structures [16]. Novak used a model in his paper to predict the absorption inside the cavity where flow resistance and complex impedance of the absorption was used as a parameter [17]. Prediction results were in fairly good agreement with measurement results below the Helmholtz frequency, when reduced values of flow resistance was used for absorbents. The Helmholtz frequency is comparable to the limit frequency f_l in equation (9).

The model developed firstly by Mulholland *et al.* [18] will be used in this study, The advantages of the model are that the acoustical data is easily obtained. The model was later improved by Cummings and Mulholland and the theory proved to give good results [19]. In reference [18] the absorbent was located on the edges of the cavity. In reference [19] the panels themselves could have an absorption coefficient. These models presuppose numerical integration to obtain diffuse field transmission coefficients and this model is therefore not a “simple algebraic model” in its pure sense.

Assume that the average width of the air cavity is S (m) perpendicular to the panel surface, the depth of the air cavity is d (m), the surface masses of the panels 1 and 2 are m_1 and m_2, and the absorption coefficient of the boundaries is $\alpha = 1 - |a|^2$. The transmission coefficient at a sound incidence angle θ is then obtained as [19]

$$\tau(\theta) = \left| \frac{x_1 x_2}{1 - y} - \frac{x_1 x_2 y(1 - y^n)}{n(1 - y)^2} \left[1 - \frac{a(1 - y^n)}{(1 - a y^n)} \right] \right|^2, \tag{10}$$

where $n = S/(2d \tan\theta)$. The term $x_i = 1/(1 + \mathrm{j}\omega m_i \cos\theta/(2\rho c))$ corresponds to the sound transmission through leaves 1 and 2 and the term $y = (1 - x_1)(1 - x_2)\exp(-\mathrm{j}2kd\cos\theta)$ corresponds to the reverberant sound inside the cavity. The resonant transmission above the critical frequency is not considered in terms x_i. The contribution of resonant sound transmission could be added directly to the expression of x_i, because x_i describes the transmission coefficient through individual panels. The improvement of prediction models is unfortunately beyond the scope of this study.

The diffuse field transmission coefficient is obtained by integration:

$$\tau_{diff} = \int_{\theta=0}^{\theta_1} \tau(\theta) \sin\theta \cos\theta \, \mathrm{d}\theta \Big/ \int_{\theta=0}^{\theta_1} \sin\theta \cos\theta \, \mathrm{d}\theta. \tag{11}$$

The appropriate value of the limiting angle is $\theta_1 = 78^\circ$. Normal sound incidence ($\theta = 0^\circ$) cannot be used because n becomes infinite.

An example of the prediction result according to equations (10) and (11) is shown in Figure 4.

3.4. DOUBLE PANELS WITH RIGID INTERPANEL CONNECTIONS

Rigid interpanel connections are always present for typical door constructions, at least at the periphery of the door leaf. Therefore, the previous model for isolated double panels is far too optimistic as it produces strong overestimations at high frequencies. The prediction model has to consider also the transmission through the interpanel connections. The model developed by Sharp has been found appropriate for this purpose [11].

The contribution of sound transmitted through the connections, or sound bridges, is significant above the bridging frequency, which is, for line-type connections [20],

$$f_{br} = f_{mam}\left(\frac{\pi b f_{cr}}{2c}\left(\frac{m_1}{m_1+m_2}\right)^2\right)^{1/4}, \tag{12}$$

where b (m) is the distance between the line-type rigid connections (m). Typical line connections are wooden studs, and in the case of doors, the perimeter (frame body) of the door leaf.

For point-type connections the bridging frequency is correspondingly [20]

$$f_{br} = f_{mam}\left(\frac{\pi^3 e^2 f_{cr}^2}{8c^2}\left(\frac{m_1}{m_1+m_2}\right)^2\right)^{1/4}, \tag{13}$$

where e (m) is the distance between the point-type rigid connections.

Above the bridging frequency the sound reduction index cannot exceed the mass-law curve R_M expressed by equation (5a) by more than ΔR_M. In other words, the sound reduction index curve is parallel to the mass-law curve above f_{br} at a distance ΔR_M of it. That is,

$$R_D = R_M + \Delta R_M, \qquad f > f_{br}. \tag{14}$$

For line-type connections one has [11, 20]

$$\Delta R_M = 10\log b f_{cr} + 20\log\left(\frac{m_1}{m_1+m_2}\right) - 18, \tag{15}$$

where f_{cr} is the highest critical frequency of the two panels and m_1 is the mass of the other panel. For point connections one has correspondingly

$$\Delta R_M = 20\log e f_{cr} + 20\log\left(\frac{m_1}{m_1+m_2}\right) - 45, \tag{16}$$

where f_{cr} is the critical frequency of the panel supported by the point connections and m_1 is the mass of the other panel.

The previous model for sound bridges was developed further by Qu and Wang to cover also resilient connections between the double panels [21]. Resilient bridges are not used for doors in Part 2 of this paper and, therefore, the model is not presented here.

An example of the prediction according to equation (6) supplied by equations (14) and (15) is shown in Figure 4.

3.5. TWO PANELS ATTACHED TOGETHER

One interesting special case arises when two panels are attached together without an air cavity. When two panels are attached close together with screws, glue or other adhesive material, the total sound reduction index can be calculated, to a first approximation, by using the single-panel values R_i given by equation (5) for each contributing panel i and calculating the net SRI by the energy principle:

$$R = 20 \log \sum_{i=1}^{n} 10^{R_i/20}. \tag{17}$$

This approach has been tested by Sharp. Equation (15) gives the smaller overestimations the more independently individual panels vibrate. The critical frequencies of individual panels also stay in place [11]. As far as the author is aware, there is no simple model that could consider all possible interpanel connection mechanisms. An example of the prediction according to equation (17) is shown in Figure 4.

3.6. EXAMPLE OF THE PREDICTION MODELS FOR STRUCTURAL TRANSMISSION

The theories presented in sections 3.1–3.5 are applied for a few basic structures presented in Figure 4. The measurements were made according to ISO 140/III in the laboratory. On the left of Figure 4 the single-panel theory is presented. Structure 1 is a single gypsum board panel. Structure 2 comprised two gypsum boards attached together. In both cases the panels were screwed on a wooden frame spaced by 600 mm on one side of the panel. The screw spacing for attaching the panels against the studs was also 600 mm. Structure 1 was calculated by equation (5) and structure 2 was calculated by equation (17). On the right side of Figure 4 the double panel theory is presented. In structure 3, a 70 mm thick air cavity was filled with absorbent 80 kg/m^3. In structure 4, rigid wood studs were added to structure 3 forming line-type interpanel connections with a distance $b = 600$ mm (sound bridges). Structure 3 was calculated by equation (6) when wood studs were not present (ideal double panel). Structure 4 was calculated by three different methods A–C. A: equations (6), (14) and (15) when wood studs were present ($b = 600$ mm); B: equations (6), (10), (11), (14) and (15) when wood studs are present ($b = 600$), the absorption coefficient of the cavity absorbent is $\alpha = 0{\cdot}95$ and the width of the cavity is $S = 600$ mm. C: mass law according to equations (5a) and (7).

The model gives satisfactory results except at one point. The double-panel theory does not consider the critical frequencies of individual panels when interpanel sound bridges are present. This is because the value of ΔR_M is added to the value given by the mass law by equation (5a) where resonant transmission is not considered. To a first approximation, the value of ΔR_M could be added to the values given by equation (17). The improvement of calculation models is unfortunately beyond the scope of this study.

3.7. SANDWICH PANELS

It is a very common solution for doors that the interpanel cavity is accomplished by using thick, adhesive core material (like mineral wool) and the panels are glued to the core. Sound transmission through sandwich panels is much more complicated than through single or double panels. The essential difference between double panels and sandwich panels is that the core material has a low shear modulus. Because of the sandwich structure, the shear modulus of the whole structure can be approximated by the shear modulus of the core [22]. Sandwich structures produce two kinds of vibrations at the relevant frequency range of building acoustics: flexural (symmetric) and dilatational (antisymmetric). Flexural modes occur parallel to the panel and dilatational modes occur perpendicular to the panel (transverse). Both types of vibration are dispersive: that is, the propagation speed of the sound in the solid material depends on the frequency [23].

Dilatational modes are often the reason for the poor sound insulation of sandwich panels, because the wavenumber of dilatational vibration can occur at the coincidence region: i.e., the wavelength of dilatational vibration in the panel is larger than the wavelength in the surrounding air and the airborne sound cannot short-circuit the sound radiated by the panel.

Sandwich panels have been studied by several researchers. However, no simple prediction method has been developed, in which a small number of parameters would explain reasonably most of the phenomena of sandwich panels. The models presuppose material data that is not directly available but they have to be determined. In most cases this is neither possible nor reasonable. The range of different skin–core–skin combinations is large and obviously the development of simple model covering all core materials is not possible.

One special property of sandwich panels is considered in this study. The skin–core–skin system acts like a mass–spring–mass system like double panel. There is a mass–core–mass resonance frequency called dilatational resonance f_d calculated by [23]

$$f_d = \frac{1}{\pi}\left[\frac{E_c(m_1 + m_2)}{t_c m_1 m_2}\right]^{1/2}, \tag{18}$$

where E_c (N/m^2) is Young's modulus of the core (flatwise), m_1 and m_2 (kg/m^2) are the surface masses of panels 1 and 2, and t_c (m) is the thickness of core. The dilatational resonance frequency corresponds to the mass–air–mass resonance frequency of double panels. Dilatational resonance occurs at much higher frequencies than f_{mam} because the thickness of the solid core materials is much higher than that of air. The SRI of sandwich panels is approximated in this study by using mass law by equation (5a) and notating the position of f_d.

4. SOUND TRANSMISSION THROUGH THE SLITS (SOUND LEAKS)

The total sound reduction index of the door can be calculated from the area-weighted sound reduction indices as

$$R_{total} = 10\log\frac{R_{struct} + S_{slit}}{S_{struct}\,10^{-R_{struct}/10} + S_{slit}\,10^{-R_{slit}/10}}, \tag{19}$$

where S_{struct} is the area of the door leaf, S_{slit} is the area of the slits, R_{struct} is the (calculated) SRI of the door leaf and R_{slit} is the (calculated) SRI of slits and apertures. To the first approximation, the sound transmission coefficient of sound-leaking areas is assumed to be perfect. This approach has been used also by Jones in the case of partition walls [4]. In the Jones model one has $R_{slit} = 0$ dB. (Note: The abbreviation R_{leak} in section 2 is not directly comparable to R_{slit} because the former was averaged over the area of the specific door under investigation.)

The shape of the apertures is often slit shaped around the door periphery. To the second approximation, the SRI of slit-shaped apertures is predicted by the theory of Gomperts [3] presenting the sound reduction index of a slit-shaped aperture in the form

$$R_{slit} = 10\log\left(\frac{2n^2\left\{\begin{array}{l}\sin^2(K(L+2E))/\cos^2(KE) + \\ (K^2/2n^2)[1+\cos(K(L+2E))\cos(KL)]\end{array}\right\}}{mK\cos^2(KE)}\right), \tag{20}$$

where m, n are constants dependent on the nature of the incident sound field and the position of the aperture in the wall, $K = kW$ where k is the wave number in air $(= 2\pi f/c_0)$, W (m) is the width of the slit in the plane of the wall, $L = D/W$ and D (m) is the depth of the slit (= the thickness of the adjoining structure). Acoustical damping in the aperture is ignored in this expression. The end correction E of the aperture where both ends are provided with an infinite flange is calculated by [3, 24]

$$E = \frac{1}{\pi}\left(\ln\frac{8}{K} - \gamma'\right), \tag{21}$$

where $\gamma' = 0{\cdot}57722\ldots$ is Euler's constant. It should be noted, that E is frequency dependent.

The SRI of a slit R_{slit} is naturally at a minimum at resonance frequencies f_{slit} of the slit calculated by

$$f_{slit} = N\frac{c}{2(D+E)} \quad (N = 1, 2, 3, \ldots), \tag{22}$$

and at a maximum at antiresonances.

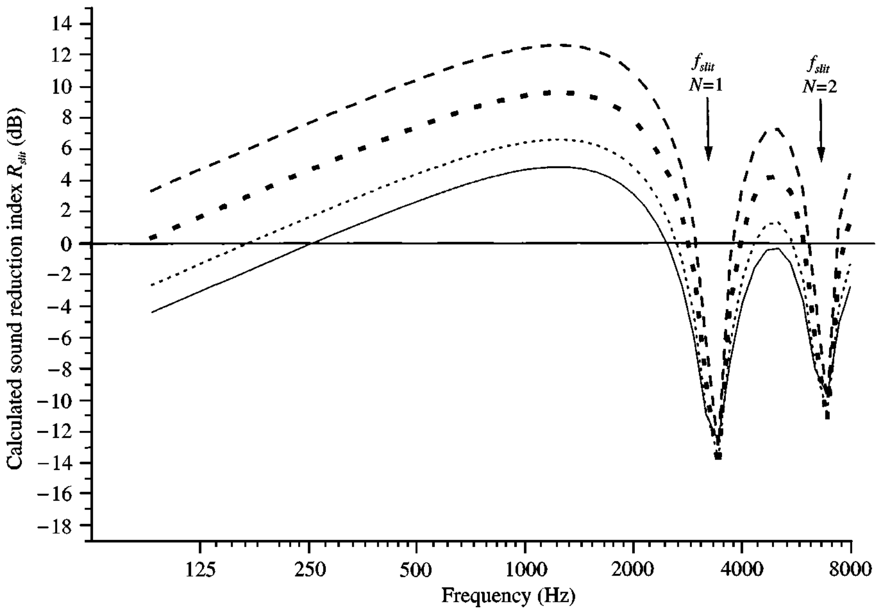

Figure 5. The sound reduction index of a slit of depth $D = 45$ mm with varying widths W of the slit calculated by equation (21). w values (mm); ——, 3; ....., 2; ---, 1; – – –, 0·5.

The predicted SRI of a slit is shown in Figure 5. The calculation was made in 1/9-octave bands. The constants were selected for $m = 8$ and $n = 1$ as adviced by Gomperts and Kihlman [18]. The sound reduction index of ideal slits has been studied experimentally by using sound intensity method [25]. The Gomperts theory was in good conformance with predictions.

5. DISCUSSION

1. It was shown, theoretically and also by one example, that the total SRI of a door is equally dependent on both leak transmission and structural transmission. Therefore both transmission paths have to be studied simultaneously. The total sound reduction index can be calculated by area-weighted sum of the two transmission coefficients.

2. When the sound insulation of a door is improved, the first thing is to determine, which one is the weak point, the structure or the sealing. A method was developed based on two tests on the same door: the normal test with original seals and a test with tape-sealed door having all slits properly sealed. The first test yields the total SRI of the door and the second test yields the structural SRI of the door. These two tests allow the leak SRI of the door to be calculated. This knowledge is necessary when the most effective development method, structural or sealing improvement, is selected. As a simple rule, structural improvements were found ineffective if the difference in sound reduction index between the tape-sealed and the normally operating door is above 3 dB.

3. A simple theory for predicting the structural SRI was presented. Sharp's model was used for estimating the SRI of double panels provided with cavity absorbent. The model developed by Cummings and Mulholland was used for estimating the SRI of double panels without cavity absorbent. In both cases, the effect of interpanel connections, or sound bridges, were estimated by Sharp's model. The model was presented in one case and it proved to be good especially below the critical frequencies of individual panels. The theories by Cummings and Mulholland were in conformance with the theory by Sharp when the cavity was sound absorbing below the critical frequency of individual panels.

4. Two theories for predicting the slit transmission were presented. Gomperts' theory, which applied for slit-shaped apertures, requires the shape of the regular slit as input data. The SRI of a slit is highest just before the slit resonance and lowest at slit resonances. Slit resonances occur at wavelengths corresponding to integral multiples of half-depth of the slit. For typical doors, this resonance occurs above 2000 Hz. Jones' model is not frequency dependent and the transmission is perfect ($\tau = 1$) at all frequencies. It can be applied to apertures of any shape.

The validity of the previous theories will be studied in the second part of this paper where also the discussion and conclusions will be presented [1].

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