Helsinki University of Technology
Laboratory of Acoustics and Audio Signal Processing
Espoo 2000 Report 56

Airborne sound insulation of wall structures - measurement and prediction methods

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Dissertation for the degree of Doctor of Science in Technology to be presented with due permission for public examination and debate in Auditorium S4, Department of Electrical and Communications Engineering, Helsinki University of Technology, Espoo, Finland, on the 1st December, 2000, at 12 o'clock noon.

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Abstract

Protection against noise is one of the six essential requirements of the European Construction Product directive. In buildings, airborne sound insulation is used to define the acoustical quality between rooms. In order to develop wall structures with optimal sound insulation, an understanding of the physical origins of sound transmission is necessary. The purpose of this thesis was, firstly, to study and compare the validity of existing physical models to predict the sound insulation of wall structures, and, secondly, to study the benefits of the sound intensity measurement method for determining the sound insulation. To develop the kind of knowledge that is applicable to the improvement of real wall and door structures was the motive behind this study.

Five main results are summarized in the following. 1. It was possible to measure wall structures with a considerably, up to 22 dB, higher sound reduction index with the intensity method than with the pressure method. Thus, the intensity method enables the determination of sound insulation in the presence of strong flanking where the pressure method gives only an underestimate. 2. The sound transmission through doors was modelled by two separate paths: a structural path through the door leaf and a leaking path through the door slits. The structural path was predicted using Sharp's model. The agreement with measurements was reasonably good except at high frequencies where overestimations were obtained. The leaking path was predicted using the model of Gomperts and Kihlman. The agreement with measurements was good for free apertures. 3. Thirteen existing prediction models of double panels were compared. The variations in predicted sound reduction indices were high, 20 ... 40 dB. Further work is needed to rank different models according to their reliability for practical structures. In addition, there is an obvious need to develop a hybrid model where all the important parameters are considered. 4. A new flanking mechanism could be observed *in situ* for a floating floor covering over a concrete slab. Identical floor structures in adjacent dwellings led to strong flanking transmission at the double panel resonance frequency of the floors. Strong flanking could be avoided by modifying the double structure in one dwelling. 5. In general, the most typical design fault of sound insulating double structures was strong mechanical connections, either in the form of rigid interpanel connections (studs) or in the form of bonded cavity absorbent (sandwich structures). In the case of door structures, efforts are usually wasted on the development of the structure, while the leak transmission may be the main transmission path.

The results of this study are useful when the intensity method is used in the presence of strong flanking sound, the sound insulation of wall and door structures are predicted or improved and when prediction models are developed.

Keywords: Building acoustics, sound intensity method, double structures, doors, flanking sound transmission

Valtteri Hongisto
Seinärakenteiden ilmaääneneristävyys - mittaus- ja ennustusmenetelmät

Tiivistelmä

Meluntorjunta on yksi kuudesta olennaisesta vaatimuksesta Euroopan rakennustuotedirektiivissä. Rakennuksissa käytetään ilmaääneneristävyyttä kuvaamaan huoneiden välistä akustiikkaa. Jotta voitaisiin kehittää ääneneristävyydeltään optimaalisia seinärakenteita, on ymmärrettävä äänen läpäisyyn liittyvä fysikaalinen perusta. Tämän väitöksen tarkoitus oli tutkia ja vertailla seinärakenteiden ääneneristävyyden ennustamiseksi olevien fysikaalisten mallien validiutta sekä tutkia intensiteettimittausmenetelmän etuja ääneneristävyyden mittauksissa. Työn motiivina oli kehittää sellaista tietämystä, joka on sovellettavissa todellisten seinä- ja ovirakenteiden parantamiseen.

Viisi päätulosta on tiivistettynä seuraavaan. 1. Painemenetelmään verrattuna intensiteettimenetelmällä voitiin mitata seinärakenteita, joilla on huomattavasti, jopa 22 dB, korkeampi ääneneristävyys. Näin ollen intensiteettimenetelmä mahdollistaa ääneneristävyyden määrittämisen voimakkaankin sivutiesiirtymän vallitessa, jolloin painemenetelmällä saadaan vain alaestimaatti. 2. Äänen läpäisy oven läpi mallinnettiin erikseen ovilehden rakenteelliselle läpäisylle ja rakojen vuotoläpäisylle. Rakenteellisessa läpäisyssä käytettiin Sharpin ennustemallia. Ennusteet olivat hyvin yhteneväisiä mittaustulosten kanssa lukuunottamatta korkeita taajuuksia, jossa ennusteet yliarvioivat ääneneristävyyden. Vuotoläpäisy laskettiin Gompertsin ja Kihlmanin ennustemallilla. Ennusteet olivat hyvin yhteneviä mittaustulosten kanssa avoimilla raoilla. 3. Kolmeatoista olemassaolevaa ennustemallia kaksinkertaisille rakenteille vertailtiin keskenään. Eri ennustemallien välillä oli suuria, 20...40 dB vaihteluja. Lisätyötä tarvitaan, jotta mallit voitaisiin asettaa järjestykseen niiden luotettavuuden mukaan tutkittaessa käytännön rakenteita. Lisäksi näyttäisi olevan selkeä tarve yhdistelmämallille, joka ottaisi yhtäaikaa huomioon kaikki tärkeimmät parametrit. 4. Uudentyyppinen sivutiesiirtymämekanismi havaittiin kenttäolosuhteissa kelluvalle lattiapäällysteelle. Kaksi samanlaista kaksinkertaista lattiarakennetta vierekkäisissä huoneissa aiheuttivat voimakkaan sivutiesiirtymäläpäisyn rakenteen resonanssitaajuudella. Voimakas sivutiesiirtymä voitiin välttää muuttamalla kaksoisrakennetta toisessa huoneistossa. 5. Yleisesti ottaen yleisin suunnitteluvirhe ääntäeristävissä rakenteissa olivat voimakkaat mekaaniset kytkennät, jotka esiintyivät joko jäykkien koolausten ja liimattujen sandwichrakenteiden muodossa. Ovirakenteiden tapauksessa taas uhrataan yleensä liikaa vaivaa rakenteellisen läpäisyn parantamiseksi kun vuotoläpäisy on yleensä pääasiallinen äänen läpäisyreitti.

Tämän työn tulokset ovat hyödyllisiä kun käytetään intensiteettimittaus-menetelmää voimakkaan sivutiesiirtymän läsnäollessa, kun ennustetaan tai parannetaan ovi- ja seinärakenteiden ääneneristävyyttä tai kun kehitetään ennustusmalleja.

Avainsanat: Rakennusakustiikka, äänen intensiteettimenetelmä, kaksois-rakenteet, ovet, sivutiesiirtymät

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PREFACE

The author began to work in the Laboratory of Ventilation and Acoustics at Turku Regional Institute of Occupational Health in 1993 after graduating from the University of Turku in physics. The laboratory was built in 1988 for research on the physical work environment. The first large building acoustical research project began in 1994, which was the starting point of this study. The aim was to apply the intensity method to product development of doors and walls. To generate accurate intensity maps, a two-dimensional moving device (robot) was designed. Intensity mapping was found to be very useful for localizing the sound leaking areas of doors and mobile walls. According to literature, the robot device was unique worldwide in terms of sound insulation measurements. Previous investigations concentrated mainly on comparing the intensity method and the pressure method in a two-room laboratory using the manual scanning method. Publication [I] dealt with the intensity measurement facility and the practical measurement experiences gathered using the intensity method at discrete points. The effect of a sound-absorbing specimen on the accuracy of intensity measurements was also studied.

After 1995, models for predicting the sound insulation of single and double panels were surveyed. Sharp's model was found to be very applicable to real structures because, unlike most of the other models, it considered the mechanical coupling between the panels. This model was studied preliminarily in the author's thesis for a licentiate of technology degree.[1]

Participation in the working group ISO / TC 43 / SC 2 / WG 43 (Building acoustics) was of great interest during 1996-1999 because it dealt with the determination of sound insulation using the intensity method. The standardization work finished in 1999 when the laboratory standard, ISO 15186-1, was accepted.

Two challenging development projects were carried out during 1997-1999. The aim was to improve the sound reduction index of a ship cabin door and a ship cabin wall by 2…4 dB without increasing significantly the mass of the product. This was difficult because the original products were very optimal. However, an improvement of 4 dB could be obtained for the door and 2 dB for the wall. Surprisingly, no significant scientific articles had been published concerning the sound insulation of doors. Publications [II] and [III] were written on this subject. The first version of SRICALC-software was programmed during this investigation to facilitate the calculations of sound transmission via structure (door leaf) and sound leaks (door slits).

In 1998, major modifications in the laboratory were accomplished. Another reverberation room was built beside the first one. This modification enabled measurements using the pressure method. So far, all measurements had been carried out using the intensity method in a semianechoic receiving room (see Publications [I] and [III]). The first tests in the new laboratory were carried out using small and heavy multilayer structures of area 2.5 m^2. It was found that the maximum measurable sound reduction index of the laboratory was exceeded when heavy specimens were tested using the pressure method. The intensity method seemed to succeed better. In Publication [IV], this issue was studied.

Field measurements seldom result in scientifically interesting conclusions. One exception to this was presented in Publication [V]. It summarizes the application of the intensity method *in situ* for localizing flanking sound transmission paths in buildings. Also the prediction methods, developed earlier, could be successfully applied in problem solving *in situ*.

Further development of SRICALC was found necessary according to Publication [III] because large discrepancies were found between the predictions and measurements at high frequencies. Also new product development projects presupposed better models to facilitate our understanding of sound transmission in complex structures. The prediction of the behaviour of sandwich panels (glued structures) was also found necessary. To develop a more precice and a more extensive prediction model, a new research project, ERVE, was started in 1999. In the initial stage of this project, existing models for predicting the sound insulation of double panels were reviewed. Preliminary results were presented in Publication [VI]. This project will yield more results in the near future.

The author started to write this thesis in February 2000 after the first submission of Publications [IV]...[VI]. The revision of this thesis started on June 6th and permission for publication was given on October 17th, 2000.

ACKNOWLEDGEMENTS

I owe my sincere thanks to my thesis supervisor and instructor, Professor Matti Karjalainen at Helsinki University of Technology, for his advice and support during this study.

My deepest thanks are directed to my laboratory colleagues and/or co-authors, Mr Jukka Keränen, Mr Mika Lindgren and Ms Riikka Helenius at our Institute for their assistance in measurements and practical arrangements. I would also like to thank my co-authors Mr Hannu Koskela, the head of the laboratory, and Mr Kalevi Nieminen at the Finnish Institute of Occupational Health, for the development of the intensity measurement robot. Without this machine, sound intensity measurements at discrete points would have been less interesting. I also appreciate the early work of my co-author Mr Vesa Viljanen from Promethor Ltd in our laboratory and his support of my studies.

This work was financed by the Finnish Institute of Occupational Health. The projects, from which the results were mainly obtained, were supported by the Finnish Development Centre for Technology (Tekes) and several building product manufacturers. I am very greatful for the possibility to co-operate with them.

I owe my sincere thanks to Dr Gustav Wickström, the director of the Turku Regional Institute of Occupational Health, for support and for placing the acoustics laboratory at my disposal.

I would like to express my thanks to the reviewers of this work, Dr Rauno Pääkkönen from the Tampere Regional Institute of Occupational Health and Dr Seppo Uosukainen from the Technical Research Centre of Finland. Their comments were very valuable for this thesis. I would also like to thank Dr Juhani Parmanen from the Technical Research Centre of Finland, and Dr Jukka Starck from the Finnish Institute of Occupational Health, for giving valuable comments on this thesis.

Mrs Jacqueline Välimäki has revised the language of this work. I appreciate her contribution very much.

Finally, I would like to thank my family for their patience and support.

Turku, October 25th, 2000

Valtteri Hongisto

LIST OF PUBLICATIONS

This thesis is based on the following publications, which are referred to by Roman numerals. They are presented in the order of writing.

[I] V. Hongisto, K. Nieminen, H. Koskela, V. Viljanen and M. Lindgren
"Test procedure and automatic system for sound insulation measurement using the sound intensity method"
Noise Control Engineering Journal 45(2) 1997 85-94.

[II] V. Hongisto
"Sound insulation of doors - Part 1: Prediction models for structural and leak transmission"
Journal of Sound and Vibration 230(1) 2000 133-148.

[III] V. Hongisto, J. Keränen and M. Lindgren
"Sound insulation of doors - Part 2: Comparison between measurement results and predictions"
Journal of Sound and Vibration 230(1) 2000 149-170.

[IV] V. Hongisto, M. Lindgren and J. Keränen
"Enhancing maximum measurable sound reduction index using sound intensity method and strong receiving room absorption"
The Journal of the Acoustical Society of America, Accepted for publication (in October 2000).

[V] V. Hongisto
"*A case study of flanking transmission through double structures*"
Applied Acoustics, Accepted for publication (in July 2000).

[VI] V. Hongisto
"*Calculation of the sound insulation of double panels - Comparison of the existing models*",
Proceedings of Internoise 2000, August 27-30, Nice, France, Vol 2, 1243-1246.

The author of this thesis has also written Publications [I], [III] and [IV] being entirely responsible for their scientific content. My co-authors' contributions are described in Acknowledgements.

The author's thesis for the licentiate of technology degree[1] and four conference papers [2,3,4,5] are closely related to this work.

1 GENERAL INTRODUCTION

Protection against noise is one of the six essential requirements, which have been stated in the European Construction Product directive.[6] The construction works must be designed and built in such a way that the noise perceived by the occupants or people nearby is kept down to a level that will not threaten their health and will allow them to sleep, rest and work in satisfactory conditions. The quantities that define the acoustical quality of constructions in buildings are airborne and impact sound insulation between rooms, airborne sound insulation of facades, reverberation time of rooms and noise level caused by technical installations.

The noise control starts from the definition of the target level. The target levels in buildings are not standardized but some general rules can be presented. For example, in living rooms, the A-weighted noise level should not exceed 30 dB in the daytime. This concerns both domestic noise from neighbourhood and environmental noise. The recommended A-weighted sound level in office rooms, classrooms or conference rooms is 35...45 dB. In control rooms in industrial workplaces, the range is 55…70 dB, depending on the need for concentration of the workers. In industrial halls and other noisy buildings, the average noise level should be limited to 85 dB. Otherwise, the risk of hearing impairment is considerably increased and hearing protectors should be used. In such environments, noise can be a safety risk, as well.

Airborne sound insulation is the most important physical quantity defining the acoustical quality of buildings. Depending on the activities in the rooms, it may be necessary to place sound insulation requirements to the surrounding walls, either to isolate the room from the neighbouring noisy spaces or vice versa.

The effects of noise on the health of man are so serious that national building acoustical requirements are nowadays followed reasonably well in Finland. In dwelling houses, the sound reduction index (SRI) should be at least R'_w=55 dB. Constructions fulfilling this requirement are well established and accepted construction products can easily be found from handbooks.

On the other hand, real sound insulation problems exist in work environments, in public buildings, in ships or offshore where noise levels produced or tolerated by people are not well defined. The SRI of the wall structure should be designed on the basis of the measured or estimated noise levels on the noisy side of the wall, and the target level on the other side of the wall.

Another problem is the design of facades. The problem can be divided into two categories: isolation of the exterior or interior noise. The former is more typical. The external sound sources are typically car traffic, air traffic or industrial plant. The latter occurs when, e.g. noise produced inside a factory or a power plant is very high and there are other buildings very close to the plant.

There is an obvious need for developing acoustically optimal products or constructions for the following sites:

- Facades and roofs of industrial halls and dwelling houses
- Doors in schools, offices and patients' rooms
- Staff and passenger cabins of ships, including walls, ceilings and doors
- Moving walls used in conference and meeting rooms
- Enclosures and walls of machines and machine rooms
- Industrial control rooms
- Windows
- Wall structures of theatres, cinemas, etc.
- Railway and road traffic noise reducing devices (barriers and tunnels)
- Structures with combined sound insulation and absorption

The problematics of this study are elucidated in the Figure. Optimal sound insulation means that adequate sound insulation is obtained with low production expenses, small mass, thin structure, high stiffness and acceptable fire class etc.. Product-related building acoustical research can be divided into two categories: development of structures and design in buildings. The former takes place mainly in laboratory conditions and the latter in field conditions.

This study is mainly concerned with the former category concentrating on the application and development of the existing methods for predicting and measuring sound insulation. Understanding the behaviour of sound transmission plays the most important role in the design of optimal sound insulation. Prediction models are necessary to get a deep and quantitative understanding of the sound transmission. If the measurements and predictions agree, one can be quite sure that the transmission phenomenon has been understood correctly. If they disagree, either the model or data are incorrect. Constructions which are applied in workplaces, are of great interest. In particular, lightweight double structures are studied because they enable the simultaneous accomplishment of high SRI and small mass.

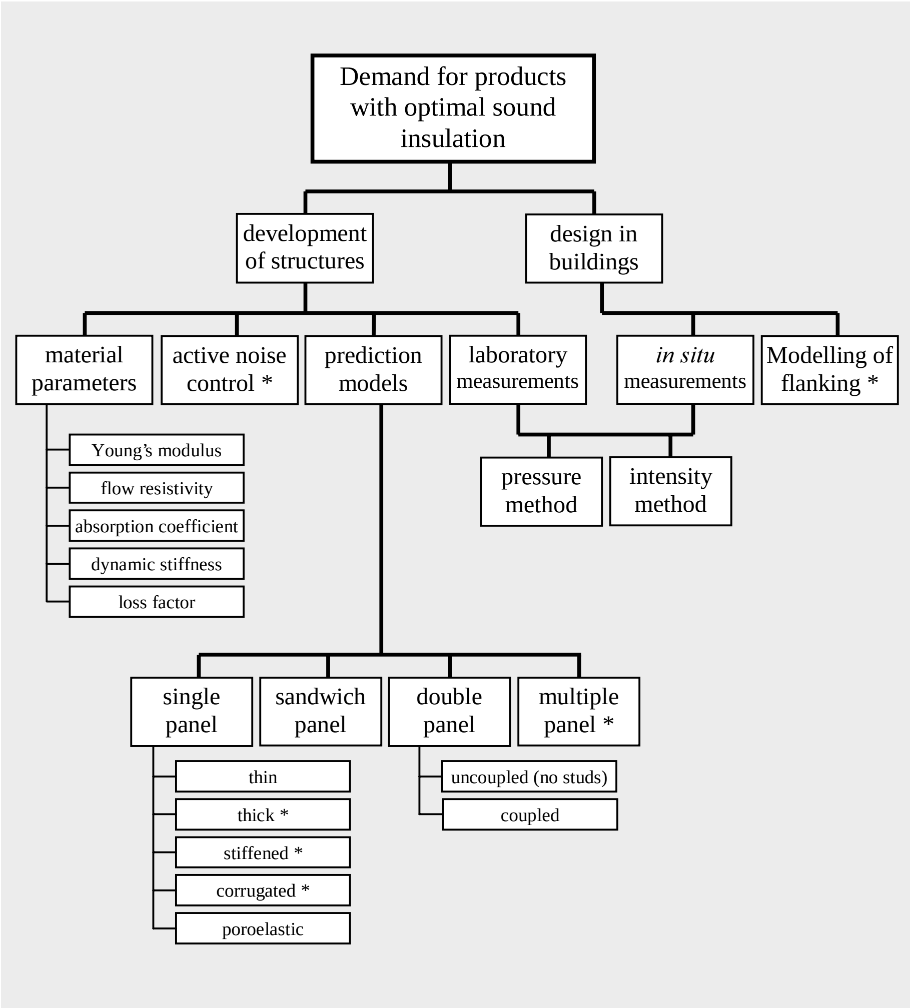

***Figure** - The motive behind this study was to develop products with optimal sound insulation. This study concentrates on the application and development of the existing methods for predicting and measuring sound insulation. The sign * indicates that this subject was not studied in this thesis.*

2 REVIEW OF THE LITERATURE

The purpose of this chapter is to review the literature concerning the measurement and prediction methods of sound insulation. The purpose is to give a more extensive background than that presented in Publications [I]...[VI] to elucidate the problematics of this study (see Figure).

2.1 Measurement of airborne sound insulation

In this section, a general overview of laboratory measurement methods of airborne sound insulation is presented, including recent problematics and developments.

2.1.1 Pressure method

Sound reduction index, SRI, or sound transmission loss, STL, is the most usual product-related acoustical quantity determined in laboratory or field conditions after noise emission measurements of machinery. The first theoretical formulation to determine the sound transmission loss of a partition between two rooms was presented in the 1920's by Davis[7] and Buckingham.[8] The first ASTM standard was based on London's proposal in 1951.[9,10] The principle of this method has remained the same over the years. The present test standards are e.g. ISO 140-3,[11] DIN 52210 Part 3[12] and ASTM E-90,[13] which are, in a physical sense, equal. In this study, this method is called the pressure method. Also the conventional method, the two-room method and the traditional method have been used in the literature.

The sound reduction index, SRI, is defined by

$$R = 10\log\frac{1}{\tau} = 10\log\frac{W_1}{W_2}\ \text{dB} \tag{1}$$

where τ is the transmission coefficient, and W_1 and W_2 (W) are the incident and transmitted sound powers, respectively. The source room is supposed to create a diffuse sound field. Thus, the incident sound power can be determined by the average sound pressure, p_1, (Pa) of the source room in the steady-state situation as follows

$$W_1 = \frac{p_1^2}{4\rho_0 c_0} S \tag{2}$$

where S (m^2) is the area of the test specimen, ρ_0 (kg/m^3) is the density of air and c_0 (m/s) is the speed of sound in air. The transmitted sound power is determined, accordingly, in the steady-state situation, when the sound power radiated by the specimen equals the absorbed sound power in the receiving room

$$W_2 = \frac{p_2^2}{4\rho_0 c_0} A_2 \qquad (3)$$

$$A_2 \approx 0.16 V_2 / T_2$$

where p_2 is the average sound pressure in the receiving room, and A_2 (m^2) is the room absorption area of the receiving room. It is approximated by the Sabine equation, where V_2 and T_2 are the volume and reverberation time of the receiving room, respectively.

Thus, the SRI, using the pressure method, is determined by

$$R = L_{p1} - L_{p2} + 10\log\frac{S}{A_2} \quad \text{(dB)} \qquad (4)$$

where L_{p1} and L_{p2} are the average sound pressure levels in the source and receiving room, respectively, that is, the SRI is determined indirectly from the average sound levels of the adjacent test rooms.

The sound reduction index is usually determined in third-octave frequency bands at least in the range 100...3150 Hz from which the single-number presentation, or weighted sound reduction index, R_w, is determined according to ISO 717-1.[14]

Eq. (4) presupposes that all sound energy is transmitted via the test specimen. In practice, the specimen is never the only path, via which sound enters the receiving room. A certain part of the total sound energy measured in the receiving room, W_2, is always radiated by other room surfaces. This is called flanking transmission and it is discussed in 2.2.5.

Alternative pressure-based methods have been presented, from time to time, usually to avoid large test facilities. Davies and Gibbs[15] presented a method where repeated short duration impulsive signals were used to determine the SRI of a free standing panel. The direct sound impulse through the panel was separated from disturbing signals, such as reflections from other room surfaces and scattered sound from the panel edges, in time space. This method also enabled the determination of the SRI as a function of the sound incidence angle without the need for an unechoic source room.

Papanikolaeu[16] suggested a method where the source room was replaced by a small pit of volume 1 m^3 in the middle of the reverberant receiving room.

The accuracy of the method was found to be adequate for practical purposes, when small specimens are investigated above the cut-off frequency of the pit, 400 Hz. Unfortunately, no comparison was made with the pressure method.

2.1.2 Laboratory-related factors affecting the measurement

As in the case of any measurement process, the measured value is an approximation of the true value. Even though the pressure method described in Eq. (4) is, in principle, simple, its successful application presupposes severe requirements for laboratories and test arrangements. The measurement environment and measurement arrangements can markedly affect the measured value. In the following pages, the most important findings of the present literature are reviewed.

Mulholland and Lyon[17] proved, both experimentally and theoretically, that the measured SRI of a plasterboard panel could be negative because of strong low-frequency room modes. This phenomenon around 50 Hz was observed using narrow band analysis. Sound transmission at low frequencies, where room modes are not evenly distributed according to frequency, depends strongly on the coupling between room modes and specimen modes. The coupling depends on the geometry of rooms, test aperture, specimen position and loudspeaker position.

Warnock[18] showed, experimentally, that when multiple sources are used in the source room, they should be excited with uncorrelated pseudorandom noise generators. If the signals are time-correlated, i.e. from the same signal source, the sound energy is not well distributed in the source room because of interference patterns and uneven spectral content. This increases the need of spatial averaging in the room.

Warnock[19] investigated the influence of the specimen frame on the measured SRI of a plasterboard wall. When the visible parts of the frames of the test aperture in the receiving room were covered, the measured SRI increased by several dB at some frequency bands just below the critical frequency (see 2.2.1). The reason was assumed to be the flanking via the test aperture frame. Warnock also studied the influence of the position of the specimen (the niche-effect). It was found that by placing the specimen on the receiving room side of the aperture, instead of the central position, a significant increase in measured SRI was observed.

Guy and Sauer,[20] and Cops and Minten[21] extended the investigation of the niche-effect. The central position of the specimen led to the smallest SRI, while the edge position led the to highest SRI. The niche-effect was most significant (up to 10 dB) just below the critical frequency.

The effect of specimen area on the SRI was studied by Kihlman and Nilsson.[22] The influence of the area was most significant for the resonant transmission below the critical frequency, where the edge and corner modes of a panel are. The transmission due to resonant vibration decreases with increasing area because the relative proportion of the perimeter decreases. For forced (non-resonant) transmission, the opposite behaviour was suggested by Sewell[23] for single panels. Above the critical frequency, the SRI does not depend on specimen area. However, the measurement results obtained by Michelsen[24] and Guy *et al*.[25] were not in good agreement with previous theories. There does not seem to be an exhaustive answer to the question of the influence of specimen size. It seems to depend on the wall structure. However, the influence of specimen area seems to be reasonably small, below 5 dB, being less significant than other factors, like the niche-effect.

Craik[26] investigated, theoretically, the influence of typical test room configurations on the measured SRI of a 100 mm thick concrete wall. The SRI depended strongly on the boundary conditions of the specimen. Different laboratory configurations led to different flanking paths. The total loss factor of the specimen depended on the structural boundary conditions of the laboratory walls, especially the wall between the rooms. The total loss factor is the sum of the internal loss factor of the wall material, the coupling loss factor to the surrounding structures and the radiation loss factor to the surrounding media. Depending on the isolation between the partition surrounding the specimen and the receiving room, different amounts of flanking can occur.

Craik concluded that the correct question considering inter-laboratory differences is not “Which laboratory yields the correct answer?” but “Which answer do we want?” Craik suggested that the loss factor should always be measured in connection with SRI to enable the comparison of results obtained in different laboratories with different boundary conditions. The boundary conditions of the specimen have a strong effect on the resonant transmission. This was demonstrated experimentally by Meier and Schmitz[27] for a 100 mm thick brickwall. Two different boundary conditions were used for the same wall. An elastic junction resulted, on average, in 5 dB smaller values of SRI than a rigid junction. When the differences in the total loss factors were considered using a simple correction equation, the sound reduction indices measured in previous conditions were identical. Below the critical frequency of the wall, here 200 Hz, the correction did not work, as expected.

The uncertainty of measured SRI, determined by ISO 140-3, is presented in ISO 140-2.[28] The reproducibility values, which apply between different laboratories, are expected to lie within 2.5 and 9.0 dB, depending on frequency. The repeatability values, which apply in a single laboratory, are expected to lie within 1.5 and 4.5 dB. Both values are largest at low frequencies.

Kruppa and Olesen[29] found that the measured SRI is mainly dependent on the loudspeaker positions at low frequencies (50…200 Hz). The variation of SRI was within 10 dB with different loudspeaker positions. As a sequel to that, Olesen and Pedersen[30] studied the influence of loudspeaker positions on SRI using experiments and modal analysis. The problem in existing laboratories is that the mode density is not smooth at low frequencies because of small room volumes. The sensitivity of the loudspeaker position depends, e.g. on the size of the rooms, the absorption in the test rooms, the positioning of the test specimen, the niche geometry, the measurement direction and the mounting of the test specimen. The influence of none of the above factors could be dealt with separately.

The main result of the work of Olesen and Pedersen was that a procedure could be developed to find loudspeaker positions that reasonably represent the average of all the loudspeaker positions of the source room. Usually, two or three carefully selected positions suffice. This method resulted in annex C of ISO 140-3, which is excepted to decrease the reproducibility values to below 400 Hz.

Recently, the results of an extensive round robin test were reported by Fausti *et al*.[31] A total of 24 laboratories was involved in the round robin test, justifying significant statistical conclusions. The reproducibility was considerably higher above 315 Hz than expected by ISO 140-2.[28] R_w varied between 47 and 52 dB for a double wall structure. For single panels the results were between 26 and 29 dB.

Later, Smith *et al*.[32] suggested that the lining material of the test aperture (built-in frame) was probably the principal factor for the large reproducibility values. Laboratories with wooden and metal frames yielded, on average, smaller sound reduction indices than laboratories with concrete frames. Predictions with a SEA model agreed with this observation. However, the exclusion of laboratories with wooden frames from the statistical calculations did not decrease the reproducibility below the accepted level. It was suggested that the sill-reveal ratios during the laboratory test should be standardized in a similar manner as for glass specimens in the present ISO-standard.

The large differences during this last interlaboratory test proved that more instructions are needed in ISO 140-3. The problems are mainly caused by differences in laboratory structures. In particular, the mounting of the specimen and the design of the test aperture seem to have a strong influence on the result. More research is needed to obtain better agreement between present and new laboratories.

2.1.3 Sound intensity method

Until the middle of the 1970's, the only acoustical quantity that could be measured accurately was the sound pressure. The amplitude part of sound pressure is a scalar quantity, which gives no information about the direction and the magnitude of the energy flow. In order to identify and quantify sound sources and sound transmission paths in machines, selective wrappings with lead, screens and anechoic chambers were necessary to suppress the background noise and reverberation, respectively. Measurement of sound insulation required two diffuse and heavily isolated adjacent rooms (the pressure method).

Sound intensity $\underline{I}$ (W/m^2) is a vector quantity, which describes the sound power per unit area. It is defined as the product of sound pressure p (Pa) and particle velocity $\underline{u}$ (m/s), which is a vector quantity. The first instruments to measure one-dimensional sound intensity in a wide frequency range were developed in the middle of the 70's by several researchers worldwide. A thorough review of the history, theory and applications of the intensity method has been presented later by Fahy[33] who was also one of the first pioneers of this issue. The development of Fast Fourier Transform analyzers, digital technology and acoustic transducers enabled the direct measurement of sound intensity. Commercial measurement equipment became established in the beginning of the 1980's. Simultaneously, Gade presented technical reviews of the two-microphone intensity method for practical purposes.[34,35,36]

There are intensity probes where the particle velocity is determined directly using an ultrasonic particle velocity transducer.[33] However, the two-microphone technique (p-p) is the most usual method to determine the one-dimensional particle velocity $\underline{u}_x$. The time-averaged particle velocity in direction x is determined by the time-averaged pressure gradient between two microphones using Euler's equation

$$\underline{u}_x = -\frac{1}{\rho_0 \Delta r} \int \left(p_B - p_A \right) dt \qquad (5)$$

where Δr (m) is the distance between the microphones A and B, t (s) is time, and p_A and p_B are the pressures sensed by the microphones A and B, respectively. Thus, the phase information contained in the pressure signals is fully utilized in the two-microphone intensity technique. To calculate the intensity, the pressure is determined by the average of the two microphone signals by $(p_A+p_B)/2$.

The distance between the microphones is usually set at Δr = 6 ... 50 mm, depending on the frequency range of interest.[34] The main assumption of the two-microphone method is that the inherent phase difference between the microphones is negligible. This is realized by selecting two microphones from the production batch, which have as similar a phase response as possible (phase matched microphones).

In practice, there is always some inherent phase mismatch between the microphones and the channels of the analyzer so that a small residual intensity, $L_{I,R}$, is produced. The pressure-residual intensity index, $\sigma_{pI,0}$, is determined as the difference between the pressure level and intensity level when both microphones are exposed to the same sound pressure (phase and amplitude). This is explained also in Appendix.

The validity of the sound intensity measurement is described by the pressure-intensity indicator, F_{pI},

$$F_{pI} = L_p - |L_I| \quad \text{dB} \tag{6}$$

where L_I and L_p (dB) are the average sound intensity level (dB *re* 1 pW) and the average sound pressure level (dB *re* 20 μPa) at the measurement surface, respectively.

The value of F_{pI} increases with increasing extraneous sound. In practical measurements, F_{pI} is usually larger than 3 dB. The value of F_{pI} is zero only in a free field condition for a propagating plane wave. (The exact value is F_{pI}=0.1 dB because of the effect of residual intensity.) When measurements are made close to a sound source, F_{pI} is larger than zero although the environment is anechoic.

It is essential to keep F_{pI} markedly smaller than $\sigma_{pI,0}$ during acoustical measurements. To guarantee that the measured intensity is not excessively biased by the residual intensity, the following criterion is applied:

$$F_{pI} < L_d = \sigma_{pI,0} - K \quad \text{dB} \tag{7}$$

where L_d is the dynamic capability index of the intensity measurement system and K (dB) is the bias error factor. When K=10 dB, the accuracy of intensity measurement is better than 0.5 dB. When K=7 dB, the accuracy is better than 1.0 dB.

The requirements for sound intensity probes are determined in IEC 1043, which gives the minimum values of $\sigma_{pI,0}$.[37] The highest values of $\sigma_{pI,0}$ in commercial probes lie within 20 and 30 dB, when the 12 mm microphone spacer is used.

The main application of the intensity method was the direct determination of sound power. The determination of one-dimensional intensity is usually adequate because the determination of the sound power presupposes the movement of the probe normally to a hypothetic surface that encloses the sound source (surface integral).[38] The vector nature of intensity is lost because the orientation of the probe is not fixed.

The intensity method found its application in building acoustics in 1980, when Crocker *et al*.[39,40] determined the sound transmission loss of panels. The incident sound power was determined as by the pressure method but the transmitted sound power was determined directly in the vicinity of the test specimen by

$$W_2 = IS \qquad (8)$$

Thus, the intensity sound reduction index could be determined by

$$R = L_{p1} - L_I - 6 \quad \text{dB} \qquad (9)$$

where L_I is the average sound intensity level in the vicinity of the test specimen, typically at a distance of 10...30 cm. It is measured in discrete points in the form of a grid or by manual scanning. The density of the measurement grid is usually 10...50 cm.

The first international building acoustical measurement standard exploiting the intensity method was published on 1995 as ISO 140-5 Annex E[41] as a supplementary tool for façade measurements. The laboratory method ISO 15186-1 was published in 1999.[42]

It is usual that a small aperture (gap) is formed between the test specimen and a planar intensity measurement surface. A significant proportion of the transmitted power may be transported via this gap leading to underestimation of radiated sound intensity. The understimation can be significant especially in the neighbourhood of the critical frequency, where the radiation of sound at large angles (θ>75 °) is stronger than that perpendicular to the specimen. The best situation is to avoid any gaps between the measurement surface and the test specimen by placing the measurement surface right in front of the test opening, or niche. If this is not possible, the measurement surface should be a flat box consisting of a large planar part and four narrow strips on the edges of the specimen to make the measurement surface closed.[43,44] Thus, the measurement area, S_m, can be larger than the specimen yielding a small correction, $+10\log(S_m/S)$ dB, to Eq. (9). It should be noted that it is not this correction that leads to different SRI but the potential change in L_I when the peripheral faces (strips) are included in the measurement surface.

F_{pI} is the most significant indicator of the validity of sound intensity measurements. According to ISO 15186-1, F_{pI} should be smaller than 10 dB. This recommendation is based on the investigation of Jonasson.[45] He determined the influence of the reverberation time of the receiving room on the measured SRI. It was found that when F_{pI}<10 dB, the SRI was affected by less than 1 dB. Similar results were presented, e.g. by Cops *et al*..[46] However, it was not justified to conclude that F_{pI} should, in general, be smaller than 10 dB. Unfortunately, the values of $\sigma_{pI,0}$ were not reported by Jonasson and Cops *et al*. so that it is impossible to check the conformance with Eq. (7). The limit of 10 dB is in disagreement with Eq. (7), which is applied also in ISO 9614-series.[38] This discrepancy has not been clarified in the literature.

Van Zyl and Erasmus[47] studied, theoretically, the effect of the receiving room absorption, the specimen size and the flanking ratio on F_{pI}. Flanking ratio was defined as the ratio of sound powers radiated by the flanking surfaces and the specimen. Unfortunately, experimental verification of the theory was not presented.

The most serious problem of the intensity method is that it is not possible to accurately measure specimens which are sound-absorbing on the receiving room side. If the absorption coefficient of the specimen on the receiving room side is zero, which is the ideal case, the net intensity caused by the extraneous noise (e.g. flanking sound, reverberant direct sound and background noise) is zero. A sound-absorbing specimen leads to underestimation of the true intensity radiated by the specimen if the intensity of the extraneous noise is sufficiently high. Thus, the SRI will be overestimated. If possible, the sound-absorbing side should face towards the source room.

A theory for assessing the intensity measurement error caused by a sound-absorbing test specimen was studied by Van Zyl *et al*.[48] and van Zyl *et al*.[44] The error caused by the sound-absorbing specimen depended on the flanking ratio, the specimen area and the receiving room absorption area. However, only one experiment was presented to verify the theory. Machimbarrena and Jacobsen[49] presented some results obtained with a sound-absorbing specimen. The underestimation of sound intensity was obvious. Quantitative analysis of this phenomenon was not presented. With our present knowledge it is not possible to say what are the conditions in which the intensity method gives reliable results with a sound-absorbing specimen.

2.1.4 Intensity method versus pressure method

The advantages of the intensity method were significant compared to the pressure method. A general comparison is presented in Table I. The main advantage was that no special reverberant receiving room was needed and that the measurement of receiving room absorption was avoided. The second advantage was that the intensity radiated by different parts of the panel could be determined. So far, vibration measurements on separate parts of specimens were used. Because the radiation factor of specimens is not well known below the critical frequency, the true radiated airborne sound intensity of a panel could not be reliably determined from vibration measurements. The third advantage was that the intensity method could be applied for determining the flanking sound power from room surfaces other than the separating partition.

The disadvantages of the intensity method were that the measurement technique places more stringent demands on the users and the equipment. The measurement time is dependent on the specimen size. When discrete points are used, the measurement time can be several hours for a 10 m^2 specimen. The determination of $\sigma_{pI,0}$ has to be performed before each measurement to assure that the phase-matching of the equipment is adequate. Adjusting the balance between the sound pressure channels in the source room and the two channels of the intensity probe causes some extra work, as well.

The results obtained with the new intensity method were in good agreement, within 2 dB, with the pressure method. So far, several investigations concerning the differences between the intensity and pressure methods have been published.[21,45,46,50,51,52,53] Typically, the intensity method yielded smaller values of SRI at low frequencies and higher values of SRI at high frequencies than the pressure method.

Table I *- The advantages (+) and disadvantages (-) of the pressure method and the intensity method in determining the sound insulation in laboratory conditions*

pressure method	intensity method
+ fast and simple	+ one reverberation room suffices
+ well-known	+ point method enables source localization
- large uncertainty	+ reverberation time not needed
- two reverberant rooms needed	+ enables determination of flanking paths
- isolated test rooms are necessary to measure heavy structures	+ small test specimens can be measured
	+ smaller uncertainty
	+ fast (scanning method)
	+ isolation of test rooms less necessary
	- several intensity indicators
	- sound-absorbing specimen prohibited
	- sound intensity calibration needed
	- expensive equipment
	- time-consuming (point method)

In the middle of the 80's, the Waterhouse correction was suggested to be used to modify the results obtained by the intensity method closer to the results obtained by the pressure method. The Waterhouse correction takes into account the sound energy reserved close to the boundaries of the reverberant rooms. This correction is important, 1...3 dB, at the lowest frequency bands.[54] It has been also applied previously in ISO 3741 in the case of sound power measurement in a reverberation room.[55]

The correct application of the Waterhouse correction was summarized by Uosukainen.[56] The intensity method gives the correct estimate of the SRI and the Waterhouse correction should be made to the results obtained with the pressure method. For the time being, the pressure method is more popular and the results of the intensity method are corrected. This is in contradiction with the theory and the problem should be clarified during the next revision of the ISO 140 series.

It is well known that the uncertainty of sound insulation measurements using the pressure method is large at low frequencies because the transmission rooms are small compared to the wavelength.[28,29,30] With the intensity method, only the incident sound power W_1 is determined indirectly using Eq. (2), while the transmitted sound power is measured directly. This leads to smaller uncertainty of the intensity method. Thus, the intensity method yields results which are closer to the true value of SRI.[45,51] Pedersen[57] recently introduced a new method, which enables precision measurements at low frequencies, 50…160 Hz using the intensity method in laboratory conditions. In this method, the backwall of the receiving room is strongly absorbing and the incident sound power is determined in the vicinity of the specimen using the sound pressure. With these two modifications, the uncertainty was very small at 50...160 Hz. This new method will probably be applied in ISO 15186-3.

Recently, Machimbarrena and Jacobsen showed that the differences between the pressure and the intensity method can be smaller than 1 dB in the frequency range 50...10 000 Hz.[49] This presupposed that the measurements were carried out in large test rooms, using adequate intensity measurement equipment, which is capable of measuring the sound intensity accurately in a wide frequency range. They used a single 12 mm microphone spacer in the intensity probe.[58] The intensity analyzer was equipped with the possibility to improve the residual pressure-intensity index by correcting for phase mismatch.[59]

The pressure method can be successfully applied in laboratory conditions when the measured SRI is 6 dB smaller than the maximum measurable SRI, $R_{\max}$.[11] This is determined when the test opening is filled with a heavy multilayer structure, which eliminates the direct transmission through the test opening. It is well known that the intensity method is less sensitive to flanking than the pressure method. However, there is no substantiation of the numerical differences between R_{max} and the maximum measurable SRI using the intensity method, $R_{I,max}$.

2.2 Prediction of sound insulation

In this section, a general overview of the prediction models of sound insulation will be presented. Practicable prediction models of lightweight double panels were of most interest but also other wall types are briefly reviewed. "Practicable" means that the model is reasonably easy to transfer into a PC program and the physical calculation parameters of the wall are easy to measure or derive from other quantities. Before reviewing this issue, a short general introduction to different types of single walls is given.

2.2.1 Single panels

Impervious single panels can be divided into four main types (see Figure): thin panels, corrugated (profiled) panels, stiffened (ribbed) panels and thick monolithic walls. In addition, poroelastic panels are categorized as single panels. The main physical factors controlling the sound transmission through impervious single panels are[60]

- surface mass, which is mainly responsible for the forced vibration,
- bending stiffness, which together with surface mass determines the critical frequency of the panel,
- dimensions, which together with bending stiffness and surface mass determine the lowest natural resonances (normal modes) of the panel,
- loss factor, which determines the amplitude of resonant vibration, and
- sound incidence angle.

Critical frequency is the lowest coincidence frequency of a single panel. At coincidence, the wavelength of sound in air and the bending wave coincide and the SRI collapses. Non-resonant, or forced, vibration mainly determines the transmission behaviour below the critical frequency. This is called the mass-controlled region where the slope of the SRI-curve is 6 dB/octave. At and above the critical frequency, resonant vibration determines the sound transmission coefficient. This is called the stiffness-controlled region where the slope of the SRI curve is 9 dB/octave. Resonant vibration occurs also below the critical frequency, but the radiation efficiency of the modes is not significant below the critical frequency except at the lowest normal modes, where radiation can be very strong. Between the lowest normal modes and the critical frequency, air effectively shortcircuits the radiation of the panel because the wavelength sound in air is larger than in the bending wave of the panel.[60]

The most referred to prediction model for thin infinite panels was presented by Cremer in 1942.[61] This theory included the effect of bending stiffness and the sound incidence angle θ. The model of Cremer has been applied in several other models dealing with more complex structures. According to Bhattacharya and Guy, the most essential limitation of the model was that it was not directly applicable to finite panels.[62] As a result, the description of the coincidence phenomenon, which is presented in most acoustical handbooks, is not valid in practical walls. This is because freely propagating flexural waves can not exist in a finite plate. The wavenumbers of the plate are defined by the dimensions and the boundary conditions of the panel. Therefore, the position of the coincidence frequency is independent of the sound incidence angle. The angle of incidence will, however, alter the transmission coefficient, but a perfect coincidence exists only at critical frequency.

In general, the transmission coefficient $\tau(\theta, f)$ is smallest at normal sound incidence and approaches unity at grazing sound incidence. Cremer applied the Paris equation

$$\tau_d(f) = \frac{\int_{\theta=0}^{90^\circ} \tau(\theta, f) \sin\theta \cos\theta \,\mathrm{d}\theta}{\int_{\theta=0}^{90^\circ} \sin\theta \cos\theta \,\mathrm{d}\theta} \tag{10}$$

to calculate the diffuse incidence transmission coefficient τ_d from the individual angle-dependent transmission coefficients, $\tau(\theta, f)$, where f (Hz) is the frequency of sound.

Since then, it has generally been accepted that the maximum sound incidence angle of Eq. (10) should be smaller than 90 °. Better agreement with all theories has been obtained by limiting the maximum sound incidence angle to approximately 78...85 ° (field incidence). The theoretical basis for changing θ was that grazing angles do not exist in laboratories because the rooms are small and the specimen is mounted inside a deep aperture.

Corrugated panels are used particularly in industrial façades and roofs because of their low weight and relatively high stiffness in the direction of grooves. Practicable prediction models for corrugated panels were presented, e.g. by Heckl,[63] Cordonnier-Cloarec *et al*.[64] Hansen,[65] and Lam and Windle.[66,67] The essential feature of corrugated panels is the orthotropicity of bending stiffness. It is significantly higher in the direction of grooves. This leads to two separate critical frequencies and lower SRI than that of a thin panel with the same mass.

Ribbing (stiffening) of panels is useful when the bending stiffness has to be markedly increased. One example is a metal ship deck (bulkhead). In practice, most panels are more or less stiffened with studs. The spacing between stiffeners is reasonably wide, e.g. 600 mm for typical plasterboard walls. In such cases, the behaviour of the studded panel above 100 Hz resembles that of a thin panel and the stiffening is neglegted.

A well-known model for ribbed panels was presented by Maidanik.[68] Because of the addition of the mass of the ribs, the SRI should increase compared to the situation without ribs. However, the subdivision of the panel into smaller sub-panels reduces the SRI compared to a smooth thin panel with the same mass. Low-order subpanel resonances usually control the sound insulation at middle and high frequencies.[69] Later, Elmallawany[70] combined the previous theory with statistical energy analysis of single panels, which was introduced by Crocker and Price.[71] The predicted and measured results were in good agreement.

Thick monolithic walls, typically thicker than 100 mm, are dealt with separately from thin panels. According to Ljunggren,[72] a monolithic wall is usually considered to be acoustically thick when the thickness of the panel is greater than 1/3…1/6 of the bending wavelength. Typical materials which are classified as thick panels are brick, heavy concrete and porous concrete. Because of large bending stiffness, the critical frequency is very low, typically below 200 Hz. In the case of thick walls, there is a gradual shift from bending waves to shear waves as the frequency increases. According to Sharp[73] and Rindel,[74] shear waves begin to dominate sound transmission above a certain crossover frequency. Rindel[75] defined an effective bending stiffness, B_{eff}, which enables the prediction of thick and thin panels with the same model. B_{eff} equals bending stiffness in the case of thin panels. For thick panels, the shear waves also contribute to the effective bending stiffness.

Poroelastic panels are classified as single panels in this study. However, their sound transmission behaviour is completely different from impervious panels because the internal losses play a significant role. The properties of poroelastic panels are usually described by seven parameters, which are flow resistivity, bulk density, *in vacuo* Young's modulus, loss factor, structure factor, Poisson's ratio and porosity.[76] Poroelastic materials are used in cavities in sandwich, double and multiple walls. Stiff poroelastic sheets are used in sandwich panels. Porous absorbents are also used in structures where combined room absorption and sound insulation is desired (e.g. roofs of factories).

Light porous sheets are typically used to attenuate the cavity resonances and they are not used in sandwich panels. If the cavity is thin and the porous layer is thin, the attenuation during propagation is negligible but the cavity modes are attenuated. However, if dense absorbents are used in thick cavities, the mass of the absorbent begins to increase the total SRI of the wall and the attenuation during propagation through the porous layer can be significant, especially at middle and high frequencies.

2.2.2 Lightweight double panels

Several studies have been published on the prediction of the sound insulation of double wall constructions. In this section, these models are reviewed. This section also serves as an introduction to Publication [VI], in which the literature review was omitted due to page limitations. It should be noted that all models are reviewed as such. The improvement of the models is beyond the scope of this thesis.

A clear division between double panel models can be made in terms of the interpanel connections. Firstly, those models are reviewed where interpanel connections were not considered. Such double walls are also called ideal or uncoupled double walls.

The first well-known model was introduced by Beranek and Work.[77] It was based on wave behaviour of sound. The propagation of sound in the cavity was dealt with according to the impedance approach, which also enabled the modelling of multiple layers. Beranek and Work were interested only in normal sound incidence angles, which limits the general application of the model. In addition, the bending stiffness of individual panels was not included in the model.

Immediately after that, London[78] presented a progressive-wave model, where the influence of the sound incidence angle was considered. The diffuse-field SRI was calculated using Paris' equation. Moreover, London introduced a real part to the panel impedance, i.e. panel resistance as an addition to the mass reactance term. Its value was obtained, in the absense of a defined measurement method, by trial and error, according to the best agreement with the predicted and measured value for a single panel. The resistance term has not been used in later models. The model was restricted to double panels with empty cavities. Neither asymmetric panels nor loss factors were considered. The models of Beranek and Work, and London are often referred to as classical models. They are based on the assumption that the wall is infinite in size.

In 1966, White and Powell[79] presented a mode-coupling model for resonant transmission of a finite rectangular panel. The statistical mechanical approach of Lyon and Maidanik[80] was applied to wall structures. The energy flow through a coupled multiresonant system was considered as an analog of a heat transmission problem. This model took the area of the wall into account but neither cavity absorbents nor the cavity thickness was considered. The validity of this model for practical walls has been found questionable in several references.

London's model could not predict the behaviour of sound in the cavity for oblique sound incidence angles. Mulholland *et al*.[81] and Cummings and Mulholland[82] presented alternative models where ray tracing was applied to take the lateral sound propagation in the cavity into account. The cavity absorption was described either by the absorption coefficient of the panel[81] or the absorption coefficient of edges of the cavity,[82] like in room acoustics. However, the attenuation of sound while propagating through the sound-absorbing material was not taken into account and, nor was the bending stiffness of the panels.

In 1970, Crocker and Price,[71] and Price and Crocker[83] developed the statistical energy analysis in wall structures to the form in which it is known today. The main difference to the model of White and Powell was that non-resonant vibration is considered. Resonant and non-resonant transmission were dealt with separately. The angle-dependence of sound radiation was not considered but the model directly produced the response in the diffuse field. The specimen area was taken into account. The radiation resistance of the panel was calculated according to the theory of Maidanik.[68] The model included considerably more parameters than previous models and the equations were more complicated. However, the modelling of cavity thickness and cavity absorbent was not successful although they appear as parameters.

In 1972, Donato[84] introduced a useful correction to take into account the size of the specimen. This correction could be applied to (classical) models assuming infinite panel size. A more useful form of this correction was presented later by Elmallawany.[85] The correction was strongest at low frequencies where the dimensions of the test aperture were of the same order as the wavelength of sound in air. It is a typical feature of classical models that they underestimate the SRI at low frequencies compared to the measured SRI.

Moreover, Donato facilitated the application of classical models by modifying the integrals to a more analytical form. However, neither cavity absorbents nor unsymmetricity of panels were considered.

Mulholland *et al*.[86] developed the impedance-transfer method of Beranek and Work for oblique sound incidence angles. However, only empty cavities were considered and no experimental results were presented to verify the theory. A similar extension was later presented by Ookura and Saito.[87] The pressure transmission ratio could be determined for each successive layer by its propagation factor and impedance. The model of Delany and Bazley[88,89] was applied for the determination of the impedance and propagation factor of porous materials from measured flow resistivity data. Unfortunately, only the impervious panel, the sound-absorbing cavity material, and the empty cavity were presented as elementary layers. Fringuellino and Guglielmone[90] recently presented a model, which was nearly identical with that of Ookura and Saito.

Alternative progressive impedance methods have been since presented, as well. Hamada and Tachibana[91] based their approach on the utilization of the electronic four-terminal network theory. Each subsystem of the wall was described as a cascade matrix (F-matrix). The matrix method considerably facilitated the equations and the implementation of the algorithm, especially when multiple layers are studied. London's model was used in the calculation of single panels. Thus, the loss factor was not taken into account.

Au and Byrne[92,93] developed the impedance transfer method for predicting the insertion loss of lagging structures. The impedance for flexible and impervious layers, like rubber, and orthotropic profiled panels were introduced as new elementary layers. The disadvantage of their model was that it was designed to calculate the insertion loss of additional isolating layers. A modification of this model to predict the SRI was presented by Ver.[94]

Heckl[95] used stiffness per unit area, instead of impedance-related parameters, as the principal descriptor of the cavity. It was assumed that the cavity is locally reacting. Therefore, this model is restricted to double panels having a sound-absorbing cavity. Instead, the stiffness approach permits the application of this model to sandwich panels. In this case, the cavity absorbent has to be bonded to the surface panels and the dynamic stiffness of the cavity material has to be determined.

The models reviewed above do not take into account the influence of structural interpanel connections, or sound bridges, between the panels. This omission essentially restricts their application to real walls because interpanel connections, typically studs or bindings, can be found in most practical double wall structures.

The influence of sound bridges on the sound insulation of double walls was first studied by Sharp[73,96] in 1973. He presented a simple "spreadsheet" model to predict the SRI of practical double walls. The transmission of the sound between the panels was divided into two paths: via airborne path (cavity coupling) and sound bridges (structural coupling). It was assumed that the boundaries of the cavity are sound absorbing. Firstly, he derived simple analytic equations for the SRI of an uncoupled double panel for diffuse airborne excitation, including sound incidence angles 0 … 78°. The classical model of London was adopted. The integration using Paris' equation was replaced by +5 dB correction for single panels. For rigid sound bridges between panels in a double wall, he applied the rigid point and line impedances introduced by Cremer and Heckl.[97] The only new parameter to be defined was the distance between rigid sound bridges, *b*.

It was found that for ideal uncoupled double walls, the addition of SRI per octave was 6 dB below the mass-air-mass resonance frequency (mass law) and 18 dB above it. Above a certain limit frequency, the slope decreased to 12 dB/octave. Above the critical frequency, the slope was again 18 dB/octave. Instead, the SRI of double walls with sound bridges followed the previous shape until the bridge frequency. Above it, only an addition of 6 dB per octave can be attained. The bridge frequency is usually situated in middle frequencies far below the critical frequency. The distance to the mass-law curve depends on the density of sound bridges; if it is large enough, the SRI follows the mass-law curve. The disadvantages of Sharp's model were that it contained several approximations and presumptions. In addition, the model for sound bridges was valid only below the lowest critical frequency of the panels.

Later, Gu and Wang[98] developed the Sharp's model for flexible sound bridges, which are usually made of steel. It was found that the addition of SRI was steeper, 12 dB per octave, above the bridge frequency. This model presupposes a knowledge of the dynamic stiffness of the studs.

Fahy[60] presented an alternative model for the transmission coefficient via rigid sound bridges. The sound incidence angle was also considered. It was found that transmission via bridges is more important for partitions having low critical frequencies. Fahy also presented two models for uncoupled double walls. The first one applied to a double panel with arbitrary cavity absorption and to a normal sound incidence angle. The second one applied to an arbitrary sound incidence angle but the cavity was empty. The benefit of these models was that the lowest normal mode of the panel was considered. However, resonant transmission and loss factor were not considered. No experiments were presented to verify the theories.

More complex approaches concerning the sound transmission via sound bridges have been given, e.g. by Zaborov,[99] Lin and Garrelick[100] and Craik and Wilson.[101] These models are seldom referred to in the literature.

Green and Sherry[102,103,104] presented statistical equations for predicting the sound insulation of gypsum wallboards partitions. Several equations were presented for different wall types. Because the only physical parameter was surface mass, these models do not apply to other wall types.

The weak point in the models of Sharp, and Gu and Wang, was that the absorption of the cavity boundaries was assumed to be perfect, that is, there were no reflections from the cavity boundaries that could increase the sound energy inside the cavity. Neither empty cavities nor the attenuation of sound while passing through a porous material was considered. This shortcoming was partially rectified by Davy.[105,106] He developed a hybrid model using the ideas of several authors mentioned in this section. The absorption coefficient of the cavity was used to describe the losses in the cavity.

Another weak point in Sharp's model was that the transmission through sound bridges above the critical frequency of the panels could not be modelled. This point was also rectified by Davy. Davy's model was also adopted in the handbook of Bies and Hansen.[107]

Davy also studied the behaviour of the SRI at the mass-air-mass resonance for oblique sound incidence angles θ. It was found that the shape of the SRI-curve around the mass-air-mass resonance is flat for field sound incidence because the resonance frequency does not occur at a single frequency; its value increases with increasing sound incidence angle. This holds especially for an empty cavity. The limiting angle of sound incidence was suggested to depend on the frequency and the area of the panel instead of on a fixed limiting angle using the theory of Sewell.[23]

The sixteen most referred to models, which have been discussed above, have been summarized in Table II. It shows the physical quantities presupposed to make the calculation. It can be seen that the differences are very large. The number of parameters ranges from 4 to 14. The models of Davy and Price and Crocker seemed to be the most versatile ones.

According to this review, there are approximately 20 models for predicting the SRI of double panels. However, the previous work is incomplete at least on two points.

1. The validity of none of the previous models for different double wall types has been investigated properly. The statistical spread of predictions in the case of real double walls was presented, e.g. by Hongisto.[1] He studied Sharp's model for 12 different wall structures. He found that the average difference between the predicted and measured SRI was within 3 dB between 80...1000 Hz. At high frequencies, Sharp's model gave overestimations, but not of more than 5 dB. More similar investigations are needed.

2. The models have not been compared with each other. In the present situation, the validity of the models has to be estimated on the basis of the results presented in the original papers. This is difficult. Typically, only few comparisons between the measurements and predictions were presented in

the original papers so that no statistical impression of the reliability of the models could be given. It is also probable that such results are presented which show good agreement between predictions and measurements.

These two points need more research.

2.2.3 Experimental studies on double panels

In the following, a review of the literature will be presented concerning the influence of different physical parameters on the SRI of double panels. Additional prediction models will not be presented. This review concentrates on experimental studies.

Table II *- The comparison of 16 prediction models on the basis of the physical quantities which are needed in the calculations.*

	<--------------Panels--------------->								<--------------Cavity------------>						Studs		Environment				
Model	m	E	R	η	ν	h	x	y	d	Z	α_p	α_c	s'	x	y	b	K'	V_1	V_2	T_2	θ	N
Beranek and Work[77]	x					x			x	x												4
London[78]	x	x	x		x	x			x												x	7
Mulholland et al.[81]	x					x			x		x										x	5
Mulholland et al.[86]	x					x			x	x											x	5
Cummings and Mulholland[82]	x					x			x			x		x	x						x	7
Price and Crocker[83]	x	x		x	x	x	x	x	x			x		x	x			x	x	x		14
Donato[84]	x	x		x	x	x	x	x	x												x	9
Sharp[96]	x	x		x	x	x			x							x						7
Ookura and Saito[87]	x	x		x	x	x			x	x											x	8
Heckl[95]	x	x		x	x	x			x				x								x	8
Gu and Wang[98]	x	x		x	x	x			x							x	x					8
Fahy (absorbing cavity)[60]	x			x		x	x	x	x	x						x						8
Fahy (empty cavity)[60]	x			x		x	x	x	x							x					x	8
Hamada and Tachibana[91]	x	x			x	x			x	x											x	7
Au and Byrne[92-93]	x	x			x	x			x	x											x	7
Davy[105-106]	x	x		x	x	x	x	x	x			x				x	x				x	12

m	Surface mass (kg/m^2)	α_c	Absorption coefficient of cavity
E	Young's modulus (N/m)	s'	Stiffness of the cavity per unit area (N/m^2)
R	Panel resistance	x	Width (m)
η	Total loss factor	y	Altitude (m)
ν	Poisson's ratio	b	Distance between the studs (m)
h	Thickness (m)	K'	Stiffness of the studs per unit length (N/m)
x	Width (m)	V_1	Volume of the source room (m^3)
y	Altitude (m)	V_2	Volume of the receiving room (m^3)
d	Thickness (m)	T_2	Reverberation time of the receiving room (s)
Z	Characteristic impedance (kg/sm^2)	θ	Angle of sound incidence
α_p	Absorption coefficient of panels	N	Total number of parameters needed

The influence of cavity absorbent on the SRI of double panels was investigated by Beranek and Work,[77] London,[78] Ford *et al*.[108] Utley *et al*.[109] and Loney.[110] It was found that the increase of the SRI as a function of the amount of absorbent was not linear. The first inch of the absorbent had the greatest effect. The position of the absorbent was not very important provided that every sub-cavity was treated similarly. According to Narang,[111] Novak,[52] and Quirt and Warnock,[112] the flow resistivity, rather than the density or absorption coefficient, seemed to be the appropriate parameter to describe the influence of porous cavity absorbents to SRI. It should be noted that in these studies, the cavities were usually thinner than 100 mm, the surface mass of panels was considerably larger than the surface mass of the wool, and the density of the wools was smaller than 140 kg/m^3. The relative influence of the absorbent would be larger if the surface panels were light and thick and dense absorbents were used.

Rindel and Hoffmeyer[113] found that a strong resonance phenomenon can occur in double walls with a stud spacing of 300 mm although flexible steel studs are used. The SRI decreased by 5…15 dB in the range 125…200 Hz compared to stud spacing of 600 mm. Normal resonant modes of 300 mm wide subpanels, which were formed between two adjacent studs, were suggested to explain this phenomenon.

The influence of stud type, stud spacing and screw spacing on the SRI was demonstrated successfully by Quirt and Warnock.[112] Experiments were made with gypsum board double walls. It was demonstrated that stiff studs, like wood, transmit sound much more efficiently between surface panels than flexible studs. The panels were attached to the studs by screws. The influence of screw spacing was detrimental for wood studs. A strong resonance dip could be observed occasionally at middle frequencies, when the spacing of screws and rigid studs was small, between 200 mm and 400 mm. The reason was the horizontal normal mode of the subpanel formed between the studs. In practice, such spacing is very usual. This result is of great importance because, in laboratory conditions, the screw spacing is usually determined but, in practice, the screw spacing can be arbitrary. It is usually denser in practice than in the laboratory.

The sound insulation of glass was studied by Marsh.[114,115,116] Glass has special properties because of its small loss factor. This leads to strong coincidence dip. The sound insulation of single, double and triple glazing (windows) was studied later by Quirt.[117,118] This investigation clearly presented the influence of glass thickness and interpane spacing on SRI. Cavity resonances in windows were very strong because of negligible cavity absorption. Unlike glass and windows, the sound insulation of doors or moving walls has been studied very little, although it is the weakest link of partitions including a door.[119]

Recently, Kang *et al.*[120] suggested that the weighting distribution of sound incidence angles, as proposed by the Paris equation, is not adequate to describe the distribution of the field sound incidence. It could be shown, using the room acoustical ray-tracing modelling, that the distribution of sound incidence angles obeyed Gaussian distribution. By weighting the Paris equation with Gaussian distribution function, considerably better agreement between predicted and measured results could be obtained. Kang *et al.* applied this weighting function with the double panel model of Fahy[60] for empty air cavities. The influence of the new weighting method could be seen especially above the mass-air-mass resonance where the influence of the sound incidence angle is strong. For sound-absorbing cavities, the influence of the new weighting was less significant because the sound is effectively absorbed in the cavity at large sound incidence angles because of the long propagation path inside the absorbent. The applicability of Gaussian weighting function to other models and structures needs more research.

2.2.4 Sandwich panels

Typically, a sandwich panel contains three adhesively connected material layers; two thin panels with one poroelastic layer between them. Adhesive bonding makes the sandwich panel very stiff compared with a thin panel with the same mass. This is also the reason for their popularity. Sandwich structures without the second thin panel are also frequent. They exist typically in pairs so that both absorbing faces point inside the cavity.

The sandwich panel is probably the most difficult wall type to model. It is usually orthotropic, which increases the number of parameters needed. One of the first models was presented by Kurtze and Watters.[121] The SRI of a sandwich panel is typically lower than that of a single panel with the same mass. The core material transmits shear forces, like in the case of thick walls. The properties of sandwich walls can vary considerably depending on the thickness and stiffness of the core material. According to Moore and Lyon,[122] asymmetric and symmetric modes of the panel can be distinguished, both of which can produce separate coincidence effects resulting in a strong reduction of SRI. During asymmetric motion, the thickness of the core material changes during compression and expansion, while during symmetric motion, the panels are in phase and the thickness of the core is constant.

According to Jones[123] and Dym and Lang,[124] the increase in stiffness results in the coincidence effect occurring at markedly lower frequencies than that of a thin panel with the same mass. In the case of asymmetric modes, the core can act as a spring. Like the mass-air-mass resonance for double panels, there is a dilatational resonance frequency, at which the SRI collapses. This resonance has been discussed, e.g. by Ford *et al*.[125] Ford and Lord,[126] and Nordby.[127] The dilatational resonance can be located even at middle frequencies when thick rigid cores are used.

According to 2.2.2, the model of Heckl could also be used to predict the SRI of simple sandwich walls.[95] The dynamic stiffness of the core material is needed for the calculation. This model predicts the position of the dilatational resonance. The critical frequencies of individual surface panels are also considered. However, this model does not take the symmetric modes into account. In the case of symmetric modes, the critical frequency depends on the bending stiffness of the whole sandwich panel. Simple equations to calculate the bending stiffness from the properties of the panels and the core were given, e.g. by Ver and Holmer.[69]

Sound-absorbing linings on the face of the wall have been investigated in some texts. Such linings form an integral part of sound insulating wall, e.g. in industrial noise barriers, roofs and enclosures. A typical structure comprizes, e.g. a thin panel, an absorbent layer glued on the thin panel and a perforated panel, which protects the absorbent from mechanical stress. Unlike what is written in most textbooks, linings do have a positive effect on the SRI. Experimental evidence for this was given by Nordby,[127] Brown *et al*.[128] and Hamada and Tachibana.[91] The improvement of SRI could be achieved at middle and, especially, at high frequencies close to the critical frequency of the wall panels. The effect of a typical 50 mm thick lining was as large as 20 dB at middle and high frequencies. The influence of lining on the SRI depended on the flow resistance and thickness of the absorbent. High density increases the attenuation of sound during its propagation through the absorbing layer. A theoretical formulation of this phenomenon was presented by Trochidis.[129] It was in agreement with the above mentioned experimental studies.

Recently, Bolton *et al*.[76] presented a model to predict the SRI of poroelastic linings in different double and triple panel configurations. The model of Biot was applied for the poroelastic part.[130] The model was more complex than the calculation models of double panels but the configurations that the model can predict were very practicable. The poroelastic layer could be bonded or unbonded to the impervious thin panel(s), or not. The validity of this model should be carefully investigated. In general, more research is needed to develop a simple prediction model that could reasonably predict the SRI of most general sandwich panels.

2.2.5 Flanking transmission between rooms

The SRI of wall structures depends on the test site (see 2.1.2). Firstly, the values in laboratory and *in situ* do not agree. Secondly, the values between different laboratories do not agree. The main reason for the differences is different flanking conditions. Structural sound transmission paths, other than direct transmission, vary to such an extent that large, typically 3...10 dB, differences are obtained. In this study, airborne flanking via pipings is not considered.

The essential difference between laboratory and field tests, using the pressure method, is that the quantity to be measured is, actually, not the same. In laboratory conditions, the direct transmission through the test specimen is of most interest. This is usually arranged by isolating the rooms from each other so that the excitation of receiving room surfaces other than the specimen is negligible. In field conditions, the test rooms can not be isolated from each other. Therefore, flanking is usually stronger *in situ* than in laboratory conditions, leading to lower values of SRI *in situ*. In addition, the specimen is mounted in the laboratory in a manner which is not usual *in situ* leading to different coupling loss factors.

In field conditions, flanking transmission is usually stronger than direct transmission, e.g. the difference between the sound powers radiated by the partition and other surfaces is larger than 3 dB. Therefore, the modelling of flanking is probably the main issue of current building acoustical research. Tools are needed to design appropriate structural solutions *in situ* using the SRI data obtained in laboratory conditions.

One of the first prediction models was presented by Gerretsen[131] in 1979. It was a simplification of the SEA model for two adjacent rooms. This model was later supplemented by several papers where also the impact sound transmission was included.[132,133] His work served as a basis for the European standard series EN 12354, of which part 1[134] is involved in the prediction of airborne flanking transmission between rooms. The calculation is based on the summation of direct and flanking transmission coefficients, where the sound reduction indices and dimensions of flanking walls are needed. In addition, the velocity level differences between the walls have to be determined by vibration transducers and hammer impacts. A European standard, ISO 10848, is under preparation to determine this quantity.[135]

Metzen[136] studied the accuracy of EN 12354-1 for 31 locations in Germany. Thick masonry walls were mainly investigated. The predicted R'_w by the EN model was approximately 2 dB higher than that measured. Further work is needed to reduce the bias of the model.

The SEA approach is basically simpler than the EN model. In addition, the system can be larger than just two rooms. Lately, this approach has been developed for the sound transmission in buildings, e.g. by Craik.[137,138]

Both EN and SEA are correct above the critical frequency.[139] Because non-resonant flanking sound does not propagate over the junctions of walls, non-resonant vibration can not be dealt with by the EN model. Therefore, previous work has concentrated on monolithic masonry walls with low critical frequency.

Sound transmission through double structures is much more complicated than through thick walls. Flanking in double structures was studied experimentally by Lang.[140] It was concluded that specific flanking laboratories are needed to study their behaviour.

In only a few experiments has flanking via lightweight multilayer structures been modelled.[139,141] It has been concluded by, e.g. Gerretsen and Nightingale[142] that research should be increased on this issue in future. Present prediction models do not apply to lightweight double structures as such because their critical frequency is usually higher than 1500 Hz and the junctions of lightweight walls are more complex.

There are no experimental reports involving the effect of double panel resonance on flanking paths. Resonance takes place, e.g. in floating floor coverings. It is possible that double panel resonance leads to a strong reduction in the SRI and it can also affect the weighted SRI between the rooms, R'_{w}.

The application of the intensity method for determining the flanking sound power in rooms has been discussed in many connections. A measurement method has been proposed in a Nordic Nordtest project[143] and an ISO standard is under preparation.[144] Hopkins and Immanuel[145] found that the values of F_{pI} were reasonably large in field conditions because of the large surfaces to be scanned. The reliability of sound intensity measurements was assumed to be poor in most cases because the limit F_{pI}=10 dB was exceeded. More similar research is needed to find the limits of application of the intensity method *in situ*.

2.2.6 Sound leakages

Sound transmission through holes and slits is the third contributory factor, after direct and flanking transmission, affecting the sound transmission between rooms. Leak transmission can be considered one of the most important sound transmitters between spaces, which are divided using moving walls, doors or windows. Slits can occur also in walls due to poor sealing of wall seams or breaks in wall structures. Building elements comprise sound leaks either by design or by mistake in the workmanship. The most common building element, where both kinds of leaks can occur, is the door.

The simplest model for sound leaks in walls was introduced by Jones.[146] It is based on a simple hypothesis that the transmission coefficient is unity for leakages at every frequency. The total SRI of the element was calculated by weighting the sound reduction indices of both the leakage and the structure with area. This model was found reasonable for practical purposes where the exact frequency dependence of the SRI is not needed.

A thorough theoretical insight into the sound transmission properties of slit-shaped apertures was given by Gomperts,[147] and Gomperts and Kihlman.[148] Circular apertures were studied by Wilson and Soroka,[149] and Sauter and Soroka.[150] These classical models take into account the dimensions of the aperture to model the wave behaviour inside the slit. According to these models, the SRI of apertures depends strongly on frequency. An open aperture corresponds acoustically to an open pipe. At low frequencies, the SRI is usually positive, i.e. an open aperture acts as a sound-insulating device. At resonance frequencies, the SRI drops, while at antiresonances, the SRI is high. The lowest resonance occurs approximately when the depth of the aperture is equal to the half wavelength of sound. The variation in the apparent SRI is very strong, e.g. between –10 and +10 dB in the resonance region. Negative values of SRI occurred because only a single isolated slit was considered. At resonance, incident sound energy will be gathered into the slit from a larger area than the cross-sectional area of the slit. It should be noted that higher order resonances can be observed only by using narrow-band analysis. Typical third-octave band analysis will reveal only low order resonances.

Previous theories were reviewed and experimentally validated by Oldham and Zhao.[151] Very good agreement was found between measurements and theory for ideal apertures.

In most practical cases, the slits are not free but sealants are used. The effect of sealing materials on the behaviour of slits was investigated by Mechel.[152] It was found that the performance of apertures containing porous and/or plastic sealants could not be approximated by the theories of open apertures presented above. Design charts were presented for practical applications including the impedance and the propagation factor of the sealant as design parameters.

Even though there are verified models for predicting the sound insulation of sound leakages, there is no experimental evidence of their validity for practical and less ideal apertures, like door seams.

2.2.7 Development of wall structures at low frequencies

The SRI of double panels is, on average, considerably better than that of single walls having the same mass. An exception to this occurs at the lowest frequencies around the mass-air-mass resonance frequency, which is typically situated within 50…300 Hz. The SRI collapses locally in this frequency region. Conventional means to improve the sound insulation of double walls are to increase mass of the panels, increase the thickness of the interpanel distance and increase the absorption inside the cavity. These methods are usually quite ineffective because large improvements require considerable changes in the structure. In the following, two alternative approaches to improve the sound insulation of double walls at low frequencies will be presented.

The use of Helmholtz resonators in the cavity as a means to improve the SRI has been studied by Enger and Vigran[153] and Mason and Fahy.[154] Both investigations showed that an improvement of 10 dB could be achieved in the frequency range 300...400 Hz in SRI, provided that airborne transmission through the cavity was the main transmission path between the panels. Enger and Vigran proved that the use of resonators was more effective than using porous cavity absorbents at low frequencies. Porous absorbents were effective only at middle and high frequencies. In both investigations, the minimum total volume of resonators was found to be approximately 10…15 % of the cavity volume to obtain good results. On the contrary, Narang's[155] efforts to apply the same principle, but using slit resonators placed on the studs, were not so successful. Only a 1-2 dB increase in SRI could be achieved. A much higher improvement in SRI could be obtained by adding thin strips of porous material to the faces of the studs. This finding disagrees with Enger and Vigran. The reason may be that Narang operated at 800 Hz where even small amounts of porous absorbents can yield large improvements in SRI. Thus, it is possible that Narang's results can not be generalized at lower frequencies.

The application of active noise control methods as a means to improve the SRI of double walls at low frequencies is one of the most interesting issues in building acoustical research at the moment. Active noise control in double panels has been studied, e.g. by Jo and Elliot,[156] Thomas *et al*.[157] and Bao and Pan.[158] There are three main approaches to the placement of secondary sources: cavity control using loudspeakers in the air cavity, panel control using inertia shakers directly on the walls and room control using loudspeakers in the receiving room.

Typically, active noise control works better when the noise contains strong tonal components and is stable. The improvement in the SRI due to active noise control has been, at its best, in the range 10…40 dB when sinusoidal excitation has been used. When the primary sound is completely random the attenuation is smaller. It can be suggested that walls comprizing active systems give the best results when the sound source to be attenuated is stationary like an engine. Speech or music is probably much more difficult to deal with because they contain rapid fluctuations, to which electronic systems have not enough time to adapt.

Recently, Nykänen *et al*.[159] introduced an interesting new approach to cavity control whereby new kinds of extensive film actuators can be used as anti-noise sources instead of conventional loudspeakers. The new material can be a big step towards real actual products. Shortcomings in the quality of secondary sound sources is still one of the main reasons why active applications have not become commercially available.[160]

3 THE PURPOSE OF THIS THESIS

The purpose of this thesis was to study the application of the sound intensity technique to the measurement of sound insulation and to study physical prediction models for predicting the sound insulation of double wall and door structures.

This work deals mainly with the following sub-problems:

1. The application of the sound intensity method in laboratory and field conditions, especially in the presence of strong flanking sound.
2. Theoretical modelling of leak and structural sound transmission through doors and experimental validation of the models.
3. Comparison of different prediction models of double wall structures.
4. Investigation of flanking transmission through double structures.
5. Improvement of the sound insulation of wall structures.

The development of the kind of knowledge that is applicable to real structures and real development problems was the underlying objective of this study.

4 MATERIALS AND METHODS

The original Publications [I]…[VI] give precise descriptions of the materials and equipments used at a given time. This chapter gives an overview of the materials and methods used.

The experimental materials comprised several timber doors and steel doors, different door seals and multilayer walls. All the measured and modelled structures were commercial products except those used in Publication [VI].

All measurement methods used in this study are standardized. They were all established in the Laboratory of Ventilation and Acoustics during this study. The sound insulation measurements in the laboratory were done, mainly, using the two-microphone intensity method using discrete points and airborne diffuse-field stimulus. A robot device was developed to facilitate discrete point measurements. The measurements were done in third-octave bands. The frequency range of greatest concern was 100…3150 Hz. The problematic low-frequency range 50 … 80 Hz was not investigated. In addition, narrow band phenomena, like panel modes, were beyond the scope of this study. The pressure method was applied in Publication [IV] in the laboratory. Field measurements of sound insulation were done in Publication [V], using both the pressure method and the intensity method. The dynamic stiffness of two flexible cavity materials was determined in laboratory conditions in Publication [V]. The absorption coefficient of one hard wall material was determined using the standing wave method in Publication [IV].

The predictions of SRI in Publications [II], [III], [V] and [VI] were made with a custom-made software (SRICALC). The programming was done with Microsoft Visual Basic 3.0 Pro. All programming codes were verified by the structures presented in the original articles.

5 RESULTS

This chapter summarizes the main results of Publications [I]...[VI] and section 2.2.2. Because of the numerous separate results, none of the figures are repeated in this thesis. The reader is referred to the original Publications.

5.1 Intensity method [I, IV]

1. The reliability of sound intensity measurements is described by the value of the pressure-intensity indicator, F_{pI}. It was shown that the contribution of F_{pI}, determined by the properties of the sound field, could be predicted by [IV]

$$F'_{pI} = NF + 10\log_{10}\left[1 + 8\left(10^{\frac{R_I - R'_T}{10}} + 1\right)\frac{S}{A_2}\right] \quad \text{dB} \qquad (11)$$

where S is the specimen area, A_2 is the receiving room absorption area, R_I is the intensity sound reduction index of the specimen and NF corresponds to the geometric near field effects, which occur close to the specimen. R'_T is the maximum measurable sound reduction index between the rooms, when the transmission occurs only via other paths than the specimen (pure flanking situation). The difference between R'_T and R_I describes the amount of flanking.

Eq. (11) agreed well with measurements with different amounts of receiving room absorption (A_2 varying) and flanking (R_I varying). However, it represents only the physical part of F_{pI}. The residual intensity caused by the measurement equipment always leads to the overestimation of the true intensity, which will be estimated by measurements. Thus, the measured value of F_{pI} will be smaller than that of Eq. (11). The value of F_{pI} is calculated by

$$F_{pI} = -10\log_{10}\left[10^{\frac{-F'_{pI}}{10}} + 10^{\frac{-\sigma_{pI,0}}{10}}\right] \text{ dB} \qquad (12)$$

where $\sigma_{pI,0}$ is the pressure-residual intensity index.

NOTE: This equation was derived for the first time in Appendix. It was not used in Publication [IV].

2. A well-known formula, F_{pI}=9+10lg(S/A_2), presented by Fahy[33] was studied experimentally [IV]. This principle has been used by several authors and it has been referred to also in ISO 15186-1.[42] According to measurements, the formula was valid only when the receiving room was reverberant and the flanking ratio was negligible, i.e. $R_I < R'_T$ - 15 dB.

Because the influence of reverberation time is negligible in intensity measurements,[53] the main reason, why F_{pI} violates Eq. (7) is strong flanking. Therefore, the formula of Fahy has no practical importance. Instead, Eqs (11) and (12) agreed well with measurements in different acoustical conditions [IV]. This is shown also in the Appendix.

3. According to the literature and ISO 15186-1, the values of F_{pI} should be smaller than 10 dB during sound insulation measurements. This requirement was found to be too severe [IV]. It was proved experimentally that Eq. (7) could be used instead. Higher values than F_{pI}=10 dB were accepted also by Machimbarrena and Jacobsen[49] and Fahy.[33] This point needs some checking when the present standard ISO 15186-1 is revised. This principle is applied also in ISO 9614 series. For present commercial instrumentation, this condition allows such values as F_{pI}=15...20 dB. This enables accurate measurements in the presence of strong flanking.

4. The maximum measurable SRI using the intensity method, $R_{I,max}$, and the pressure method, R_{max}, was studied in laboratory conditions [IV]. These values have not been determined nor compared previously in the literature. Experiments were done for 8 very different specimens to obtain a large range of different values of F_{pI} and R_I. The value of $R_{I,max}$ was determined at the highest allowed value of F_{pI} given by Eq. (7). This point was determined by making a mathematical fitting to the measured data points using Eq. (11). It was found that $R_{I,max}$ was 4…15 dB higher than R_{max} when the receiving room was empty (T_2=1…5 s). When the receiving room absorption was strongly increased (T_2=0.5 … 0.9 s) $R_{I,max}$ increased further by 2…10 dB compared to $R_{I,max}$ in an empty room. As a result, it was possible to reliably measure wall structures with 9…22 dB higher SRI with the intensity method than with the pressure method.

The tendencies of this result can be generalized to all two-room test laboratories. The superiority of the intensity method is a direct consequence of the immunity of the intensity method to extraneous noise, which, in this case, is caused by flanking. Thus, the measurement of small and/or heavy specimens is easier with the intensity method in the presence of flanking. Expensive isolation structures between the test rooms are not as important as with the pressure method. The difference between the maximum measurable sound reduction indices, $R_{I,max}$ and R_{max}, increases with increasing dynamic capability index of the intensity measurement equipment and increasing receiving room absorption.

5. When wall specimens with uneven sound radiation distribution are measured, the number of discrete intensity measurement points should be sufficiently high. For example, when doors or windows with sound-leaking apertures are measured, the measured sound intensity level depends strongly on the position of the probe. The field-nonuniformity indicator F_4, introduced in ISO 9614-1,[38] was found to be a useful tool for estimating an adequate number of measurement points to avoid undersampling [I]. The mathematical meaning of F_4 resembles standard deviation. It was found that the measurement of specimens with a very uneven sound radiation pattern can lead to very long measurement times using the discrete point method.

5.2 Prediction of sound insulation [II, III, V, VI]

6. The validity of the prediction models of Sharp[73,96] and Cummings and Mulholland[82] for double panels was investigated for 13 real door structures [II, III]. Similar extensive and statistical investigations have not been presented previously except by Hongisto.[1] The model of Cummings and Mulholland was used for empty cavities and the model of Sharp for cavities filled with sound-absorbing materials. Sharp's model was used to take the

rigid interpanel connections into account. The door slits were sealed with fixed rubber sealants and the seams were tape-sealed on both sides. Thus, the leak transmission via slits was properly eliminated. The average difference between the predicted and measured SRI was small, when the single number presentation, R_w, was considered. The average difference between the predicted and measured values was +1.0±1.5 dB, and the range of variation -1…+3 dB. At single third-octave bands, the average difference between the predicted and measured SRI was less satisfactory. In the frequency range 100…500 Hz, the difference was ±3 dB, which is satisfactory. Above that, the difference increased monotonically with increasing frequency up to +12 dB.

7. As a consequence of the previous result, the comparison between existing prediction models for double panels was extended. More than 16 existing models for double panels were reviewed in section 2.2.2. Most models were restricted to special types of double panels. Typically, the presumptions of the models prevented their application to practical double wall structures. While some models considered the effect of cavity absorption, the other models allowed only empty or full cavities. The main parameter(s) used to model the cavity absorbent varied very much. Differences occurred also in the consideration of the loss factor, bending stiffness and normal modes of the panel(s). Only few models considered the effect of structure-borne transmission via rigid or flexible wall studs.

8. Thirteen prediction models were compared, in practice, with two simple double wall structures [VI]. Similar comparisons have not been presented in the literature. The scatter between models was unacceptably high, 20...40 dB depending on the frequency. At low frequencies, where the surface mass was the main explanatory parameter, the differences were smaller than at high frequencies. In general, the models overestimated the SRI at middle and high frequencies. Only few models could reasonably predict the measured value. The results of Publication [VI] are in complete disagreement with the general impression given by the original articles, where all models seemed to operate reasonably well. It should be noted that the models were compared as such. More work is needed to make a conclusive ranking of the models.

9. Attempts were also made to find simple models to predict the sound insulation of a symmetric sandwich structure. The model of Heckl[95] was applied to one special door structure comprizing two thin surface panels and a relatively stiff core material, which was bonded by glue to the surface panels [V]. This model presumes that the dynamic stiffness of the core material is known. The measured and predicted values of SRI were in relatively good agreement. In particular, the position of the dilatational

resonance could be predicted correctly because the dynamic stiffness could be measured in the laboratory.

5.3 Transmission of sound through doors [I, II, III,V]

10. The transmission of sound through doors was modelled in two separate parts: sound transmission through the door leaf (structural transmission) and sound transmission through the slits (leak transmission). A thorough investigation of sound transmission through doors has not been presented previously in the literature. The model presupposes that two tests are made; normal mounting, which gives the total SRI, and sealed mounting, which gives the structural SRI [II, III]. It was shown that the development of the structure is ineffective if the difference between these two tests is larger than 3 dB. According to the model, and the experiments, which conformed to the theory, the development of doors was efficient only when both transmission paths were considered simultaneously. Typically, efforts are wasted on the development of structural SRI, whereas the leak transmission is the main transmission path.

11. Jones' simple model[146] and the frequency-dependent model of Gomperts and Kihlman[148] were applied to predict the SRI of sound leaks of typical sound-insulating doors [II, III]. According to the experiments, Jones' model did not work very well because the sound leaks clearly indicated a certain frequency dependency. The predictions according to the model of Gomperts and Kihlman conformed well with the experimental results when the slits were open, i.e. without rubber seals. The predicted slit resonance frequency agreed with the measurements. When the rubber seals were installed in the slits, the predicted resonance behaviour was not so evident. This was thought to be due to the SRI of the rubber seal itself. When the seal obstructs the free propagation of sound in the slit, slit resonances disappeared. In the case of sealed door, both Jones' model and the model of Gomperts and Kihlman can be used with reasonable accuracy.

12. The total SRI of typical doors could be predicted with sufficient accuracy by using the area-weighted transmission coefficients of the door leaf (see section 5.2) and open slits [III].

13. It was shown experimentally for one specific door that the weighted sound reduction index, R_w, could vary in the range 24…46 dB depending on the degree of sealing [III]. At the highest frequency bands, the largest differences were even 40 dB, while at the lowest frequency bands, they were below 10 dB. The influence of sound leaks was stronger at high frequencies than at low frequencies. There are two explanations for this behaviour. Firstly, the structural SRI is higher at high frequencies. Therefore even small sound leaks lead to strong reductions in the SRI. Secondly, the model of

Gomperts and Kihlman predicts small values of SRI at high frequencies at the slit resonances. At low frequencies, the predicted SRI of slits was usually 10 dB.

5.4 Applications *in situ* in a rowhouse [V]

14. A field study was done in two dwellings of a rowhouse where poor sound insulation bothered the inhabitants. Between the living rooms of the two adjacent dwellings, flanking occurred via the common floor slab. The common partition between the dwellings was not in the living rooms so that direct transmission was not present. The flanking path could be localized using the intensity method. The problematic frequency range was 500 Hz. The floor covering, which was separated from the slab by a 2 mm thick flexible blanket, caused a mass-spring-mass resonance at 500 Hz. This could be proved also in the laboratory by measuring the dynamic stiffness of the blanket. The floor covering was identical in both dwellings and a strong overlapping resonance occurred, leading to the collapse of the SRI between the dwellings. Flanking in the resonance region could be attenuated by 8 dB by changing the resonance frequency of the floor covering in one dwelling to 150 Hz. The effect of overlapping resonance on flanking transmission has not been discussed previously in the literature.

15. Between the entries of the same dwellings, flanking occurred via an external airborne path via two similar street doors. The problematic frequency range was 1600 Hz. The doors were manufactured in the form of a sandwich panel. The dilatational resonance of the door was very strong at 1600 Hz according to the measurement for a single door. The resonance phenomenon could be predicted by the model of Heckl (result 9). The flanking occurred because of the strong overlapping resonances of both doors, leading to collapse in the SRI at 1600 Hz. Flanking could be attenuated by 8 dB by increasing the door mass.

16. Sound intensity measurements were performed before and after the structural repairs to the floor, which caused the flanking transmission in result 1. Before structural changes, the value of the pressure-intensity indicator, F_{pI}, was approximately 9 dB for the floor around the resonance region 500 Hz. For other room surfaces, F_{pI} was larger than 15 dB or negative, which violated Eq. (7). Thus, it could be estimated that the floor was the main flanking path. The flanking path could be localized purely on the basis of acceptable values of F_{pI}, not on the basis of the intensity data. After the structural changes to the floor in the receiving room, the measurements were repeated. The distribution of the radiated intensity on room surfaces was more uniform. The value of F_{pI} at the floor surface no longer fulfilled Eq. (7). Thus, the determination of partial sound powers of

room surfaces was impossible after the structural improvement of the floor at 500 Hz.

It seems that the intensity method can be used as a tool for localizing the flanking paths. However, accurate values of partial sound powers can be determined only for surfaces radiating sound considerably more than other surfaces. In most cases, this means that reliable data are obtained at most for one room surface, which is usually the partition wall.

5.5 Product development cases [I, III]

In the following, practical results are presented where the developed methods have been applied successfully in practical research and development projects. They prove that the developed methods are of practical value. The improvements in the floor and door structures in results 15 and 16 are also related to this category.

17. The laboratory performance of a timber door could be improved from 36/33 dB to 40/39 dB [III]. The performance was defined as the ratio of R_w obtained for a tape-sealed door and a normally mounted door. The structural improvement of 4 dB was obtained by modifying the original sandwich structure closer to an ideal uncoupled double structure. The number of wooden laths was reduced and the mineral wool, which was bonded with glue to both panels, was detached from the second panel by using a tiny air cavity.

18. The laboratory performance of a steel door could be improved from 43/40 dB to 47/44 dB [III]. The structural improvement of 3 dB was attained by reducing the interpanel connections and by slightly increasing the mass of the door by 30 %.

19. The structural improvements of results 17 and 18 would have been ineffective without simultaneous development of door sealing. The improvement of sealing was 6 dB for the timber door and 4 dB for the steel door. Different seal types were studied and general properties of optimal door seals were described [III].

20. According to several comparative experiments, the SRI of sandwich-type double structures was even 5…8 dB lower than that of optimal double structures with the same mass [III]. The reason for the smaller SRI was usually the dilatational resonance, which caused a collapse of SRI. For 50 mm thick doors, this occurred typically at 1000…2000 Hz. Above the resonance, the SRI increased quite slowly. The avoidance of such sandwich structures is necessary if good sound insulation is desired.

21. The sound leaks in a steel door could be localized to the lock device using intensity measurements at discrete points [I]. The two-dimensional moving device (robot) was built to obtain accurate intensity maps. The number of measurement points easily exceeds the bearable limits of a manual system even though small specimens are studied. The sound leak could be eliminated easily by adding sound-absorbing material inside the lock. The improvement of R_w was 3 dB, which is significant. The benefits of the intensity method have been obvious in several similar cases, as well.[1]

6 DISCUSSION

6.1 Intensity method

According to Publication [IV], it was possible to reliably measure wall structures with a 9…22 dB higher SRI with the intensity method than with the pressure method. The trends of this result can be generalized to any two-room test laboratory. It was shown that the difference between the maximum measurable sound reduction index, abbreviated to $\Delta=R_{I,max}-R_{max}$, increases with the increasing dynamic capability index of the intensity measurement equipment and increasing receiving room absorption. The former means that when intensity measurement equipment with very small phase mismatch is used, Δ is even larger.

In this study, the value of L_d was 6...16 dB, depending on the frequency. For example, Machimbarrena and Jacobsen[49] reported that their probe resulted in L_d=10...25 dB in the same frequency range. If their probe had been used in this study, approximately 5...10 dB higher values of Δ would have been obtained.

The lowest values of Δ in Publication [IV] were obtained below 200 Hz. This happened because only a 12 mm spacer was used. It is well known that this leads to inherently smaller values of L_d. If a 50 mm spacer had been used, the values of Δ would have been 6.2 dB higher below 200 Hz. This estimation is a direct consequence of Eq. (5).[37]

Thus, there are two arguments to show that the results in Publication [IV] did not entirely show the superiority of the intensity method over the pressure method in flanking conditions. If an intensity probe were used with a very small phase mismatch and adequate microphone spacing, wall structures with Δ=10...20 dB higher SRI could be measured than with the pressure method in an undamped receiving room. The range in Publication [IV] was 4...15 dB. When the receiving room absorption was strongly increased, on average by a factor of 7, the values of $R_{I,max}$ and Δ could be increased by 2...10 dB. Thus, when both adequate intensity probes are used and receiving room absorption is strong, the estimated value is Δ=15...25 dB.

The result of Δ in Publication [IV] can be generalized to any two-room laboratory if the same intensity probe is used. The influence of adding receiving room absorption can differ slightly but when the reverberation time of the receiving room is below 0.8 seconds, it is assumed that the previous results will be obtained in all typical reverberation rooms.

It is a basic assumption of the intensity method that the sound absorption inside the measurement surface causes underestimation of intensity if extraneous noise or reverberation is present. This occurs because the intensity probe measures the new intensity, which is the sum of radiated and absorbed intensity. During sound insulation measurements, overestimation of SRI will take place, if the specimen is sound-absorbing. This error was calculated in practice for one hard-walled specimen [I]. The calculation of the intensity measurement error required the determination of three parameters: the absorption area of the specimen, the absorption area of the receiving room and the flanking ratio, i.e. the ratio of sound energies radiated by flanking surfaces and specimen, respectively. This finding was not presented in the results because only one specimen was measured in Publication [I]. No experimental tendencies could be presented about the effect of the three parameters.

So far, only few reports have been published where measurements with sound-absorbing test specimen in reverberant test rooms have been made.[44,49] In future, experiments are needed to find the capability of the intensity method to measure the SRI of sound-absorbing specimens in a strongly damped receiving room. In this case, the sound incident from the receiving room would be negligible and the underestimation of sound intensity might be small except when the flanking ratio is high.

The influence of the flanking ratio and the receiving room absorption on F_{pI} was studied experimentally for several specimens [IV]. The measurements conformed reasonably well to the theory of Van Zyl and Erasmus[47] when a new parameter, called nearfield correction, was introduced. In this context, nearfield effects comprise mainly geometric nearfield effects in front of a large planar sound source. According to experiments, the contribution of nearfield on F_{pI} was approximately 2 dB when the receiving room absorption was large and flanking was small, that is, in such a situation when the masking effects of reverberation and flanking on F_{pI} were negligible. The measurement distance was between 10 and 30 cm where hydrodynamic near fields are weak.[33,53]

The theoretical background of geometric nearfield effects during sound insulation measurements should be further investigated. They should not have any influence on the accuracy of sound intensity measurements, unlike hydrodynamic nearfield effects.[33] Instead, they may have a small influence, probably smaller than 1 dB, on the sound pressure level in the middle of the receiving room, where the measurements using the pressure method are performed. The basic diffuse field theory of Eq. (3) is based on the presumption that the sound source is small and that the measurements are performed in a reverberant field. Because the middle point of a typical receiving room is certainly not in the geometric farfield of a large wall specimen, geometric nearfield effects may lead to the overestimation of the energy. As a result, the SRI obtained with the pressure method will be slightly underestimated.

In previous studies, the intensity method has given, on average, 1...2 dB higher values of SRI than pressure method.[51,53] As a counterpart to this, Machimbarrena and Jacobsen[49] showed that the difference between the pressure and the intensity method was negligible when a sufficiently large receiving room was used. This also agrees with the above presumption about geometric nearfield effects because the geometric nearfield effect decreases with increasing distance from the specimen. This point needs further research.

6.2 Prediction of sound insulation

The validity of double panel prediction models introduced in 2.2.2 have not been investigated extensively before except by Hongisto.[1] The second approach was taken in Publications [II] and [III], where the models of Sharp[96] and Cummings and Mulholland[82] were applied to 13 double door structures. The statistics of the difference between the predicted and measured results were calculated. It was found that Sharp's model works reasonably well for practical structures because it takes the mechanical connections into account. The major drawback of Sharp's model is that it does not permit empty cavities. Sharp's model presupposes that the cavity is "sound-absorbing" in the sense that there are no reflections from the cavity boundaries. It should not be a difficult task to extend Sharp's model to empty cavities because his model is based on London's model, using the assumption that no cavity resonances occur.[73,78] London's model did not take into account cavity absorbents. Another drawback of Sharp's model is that it does not consider the attenuation of sound while propagating in the absorbent. Thus, the model of Sharp, as such, is adequate for double structures where light cavity absorbents are used to prevent the reverberation of sound inside the cavity. Heavy and thick cavity absorbents with high flow resistivity will probably lead to underestimated predictions.

Sharp's model for predicting the structural SRI of doors was successful concerning the single number value R_w, but the model failed at high frequencies. This agrees with a previous study.[1] Several reasons can be suggested to explain this. The presumption that the transmission through tape and rubber seal(s) would be negligible could not be verified experimentally. It is possible that the SRI of sealed seams was not sufficient, thus leading to the reduction in measured SRI. However, this did not seem very probable because very high values of the SRI could be measured for certain doors.

On the other hand, approximately half of the double panel specimens in Publication [III] were manufactured of steel with a thin mineral wool layer bonded to the surface panel by glue. The other side of the mineral wool was free of bonding. It is likely that the mineral wool changed the bending stiffness of the steel panel to such an extent that Sharp's model did not work. It is known that the bending stiffness of such components is considerably larger than that of a single panel.[76]

Nor was the radiation of the narrow built-in frame considered in the calculations. The reasons were that the materials of the built-in frame were usually thicker than the materials of the door, and the frame constituted only 5 % of the door area. This assumption is well justified when the leak transmission is strong but in the opposite case it is not as evident. The modelling of the built-in frame is difficult because it resembles a beam, which behaves differently from thin panels.

It should also be noted, as the final comment on this issue, that it has been a general feature of all prediction models that they overestimate the SRI in general, and especially at high frequencies. In this light, the overestimations of the predictions in Publication [III] were not exceptional.

Five door specimens in Publication [III] were sandwich structures, i.e. the mineral wool inside the cavity was bonded to both surface panels. Their SRI was 5...8 dB lower than that of double panels of the same mass because a strong dilatational resonance frequency occurred, where the SRI collapsed locally. The exact position of the frequency varied between 500...4000 Hz, depending on the structure. Therefore, these doors were not considered in the statistical evaluation of Sharp's model (result 6). These doors were modelled as single panels. On the basis of result 9, where a sandwich door could be predicted, it seems that the model of Heckl could be appropriate for the sandwich door structures of Publication [III] as well. The validity of Heckl's model should be investigated further with sandwich structures.

A preliminary comparative study of different double panel models was presented in Publication [VI] and section 2.2.2. This work should be extended. Critical investigations are needed into all double panel models before they can be reliably applied to a practical design. The original articles usually give a too ideal impression about the applicability of the model. The number of investigated double panel models has to be increased and different double panel structures are needed before general conclusions can be drawn about the validity of the models.

The wall structures and the laboratory arrangements were reported inadequately in several original articles of Section 2.2.2. In such cases, the verification of the prediction model was difficult. In general, the theoretical derivations were carefully presented in the original articles, but the experimental parts were often inadequate. The proper documentation of the experimental structures and the calculation parameters is one of the key points that shall be borne in mind in future work.

It was noted during this study that the textbooks give very little data for the physical properties of building materials. The measurement method for the most usual physical parameters, e.g. loss factor, impedance, bending stiffness, dynamic stiffness, flow resistivity etc., should be developed and extensive material databases should be established to facilitate practical modelling when measurements are seldom possible.

Natural resonances (normal modes) of panels should be considered in prediction models of double panels. According to Section 2.2.2, natural resonances are omitted in most prediction models because they usually occur below 100 Hz for large ideal double walls. This is not the case for walls that have dense stud density or panels with high stiffness. It was shown in 2.2.3 that if the division between the studs is small, e.g. smaller than 400 mm for typical wall panels of 10...15 kg/m^2, resonances of the panels can occur above 100 Hz. For stiffer panels, even a 600 mm division, which is the most usual division in practical double walls, can lead to normal modes above 100 Hz.

In practical product development of wall structures, prediction models are necessary to get a deep and quantitative understanding of the sound transmission. If the measurements and predictions agree, one can be quite sure that the transmission phenomenon has been understood correctly. If they disagree, either the model or data are incorrect. In the present situation, the influence of physical parameters like dimensions, flow resistivity and dynamic stiffness of cavity absorbent, spacing of cavity studs, stiffness of cavity studs, and loss factor and bending stiffness of the panels can not be investigated using a single original model. There is an obvious need to develop a hybrid model that could consider all the physical factors affecting the sound insulation of double panels.

6.3 Sound transmission through doors

The model of Gomperts and Kihlman was mainly used to predict the sound transmission through the door slits. There were major problems in using the model when the slits were sealed. The main problem was the determination of the slit area. If the original area of the slits had been used, the total SRI of the door would have been strongly underestimated. In Publication [III], the area of the sealed slits was estimated on the basis of best fit between the measurement and prediction result. The area was usually considerably smaller than that of the physical area of the slit.

It was assumed that better results would have been obtained if the model of Mechel had been used.[152] This model takes the impedance of the sealant into account. The transmission coefficient of the slit and the sealant is larger for the free slit. The main advantage of the model of Mechel is that the area of the slit is based on the area of the slit. The disadvantage is that the measurement of the impedance of the sealant is needed, which makes the model less practicable.

6.4 Application *in situ* in a rowhouse

A case study of flanking transmission through double structures was presented in Publication [V]. The results showed clearly that identical double structures in adjacent dwellings can lead to a collapse in the SRI between the rooms at the double panel resonance frequency. This was shown for two separate transmission paths between the dwellings. It was also shown that the modification of one dwelling could be a sufficient solution to prevent strong flanking at the resonance, that is, modifications are not necessary in both dwellings.

The value of R'_w between the dwellings was 9 dB higher when the measurements were carried out between rooms in which ceramic tiles were used as the floor covering. In this case, no double panel resonance occurred. Thus, the mass of the concrete slab connecting the dwellings was sufficient to guarantee proper sound insulation between the dwellings. However, when a double structure was installed, the SRI considerably decreased.

It is very likely that flanking at double panel resonance is a general problem in new dwellings because a light floating floor (parquet or laminate) above a concrete slab is the most popular solution in modern dwellings. However, no generalization of this result could be made because only one site was studied. More similar research is needed in sites where symmetrical double structures are used.

7 CONCLUSIONS

This thesis clarifies the possibilities and the applicability of the intensity method, especially in sound insulation measurements, and the applicability and restrictions of the existing prediction models for sound insulation.

This section summarizes the most important new findings of this study and their scientific importance. In addition, needs for future research will be described, if shortcomings of this study or gaps in the literature were found.

<u>*The intensity method*</u>

1. When the two-microphone technique is used, the minimization of the pressure-intensity indicator, F_{pI}, is important to minimize the influence of the residual intensity and to improve the quality of intensity data. According to this study, the value of F_{pI} can be predicted using the physical parameters of the sound field and the measurement equipment, i.e. specimen area, receiving room absorption area, flanking ratio, geometric nearfield effects and pressure-residual intensity index. The theory agreed well with the experiments. This finding facilitates the minimization of F_{pI} in practical measurements.
2. Using the intensity method and strong receiving room absorption, wall structures with a 9...22 dB higher sound reduction index (SRI) could be measured than when using the pressure method. This trend can be applied to any laboratory when intensity measurement equipment with the same phase mismatch characteristics is used as in this study. However, if equipment with better phase matching is used, the above figures will be 15...25 dB or even larger. The advantage of the intensity method are obvious. In the presence of strong flanking, the intensity method enables the accurate measurement of heavy multilayer specimens or small specimens, while the pressure method can give only an underestimate. Thus, the range of measurable sound reduction indices can be enlarged with the intensity method.
3. If the specimen is sound-absorbing on the receiving room side, the intensity method will result in overestimated SRI. According to the literature, this is the most important drawback of the intensity method compared to the pressure method. However, the effect of a sound-absorbing specimen on the validity of intensity measurements has not been experimentally investigated. Such conditions should be defined theoretically and experimentally, where the error caused by the sound-absorbing specimen is negligible.
4. The intensity method could be used for the localization of flanking paths *in situ*. However, when the radiation was uniformly distributed between

the room surfaces, reliable intensity data could not be obtained from any room surface. Thus, the only important benefit of the intensity method *in situ* is the source localization ability. Partial sound powers of all room surfaces can not be determined.

Prediction of sound insulation

5. Structural transmission through the door leaf could be predicted by the model of Sharp[96] when the cavity was sound-absorbing, or by the model of Cummings and Mulholland,[82] when the cavity was empty. The model of Sharp was found to be, in general, the most appropriate model for double panels because it takes the transmission via interpanel connections into account. The predictions agreed with the measurements at middle and low frequencies, but at high frequencies the predictions overestimated the SRI.
6. The leak transmission coefficient through free slit-shaped apertures in doors could be predicted by the model of Gomperts and Kihlman.[148] This model takes the slit resonances at high frequencies into account. Their predicted positions agreed well with measurement results. When the slits were sealed with rubber sealants, the predictions did not work. It was assumed that the model of Mechel[152] should be used. This model presupposes the knowledge of the impedance and the propagation factor of the seals.
7. The SRI of doors could be predicted with reasonable accuracy when structural and leak transmission were considered separately. These transmission paths were predicted as explained above in conclusions 5 and 6. The total SRI of the door could be calculated by the area-weighted transmission coefficients of the door leaf and the slits. This prediction model is directly applicable in practice, where the improvement in the sound insulation of doors requires simultaneous consideration of sound leaks and structure. According to one example, the range of R_w of a door was 24 ... 46 dB depending on the degree of sealing. This shows the practical significance of sealing.
8. As a continuation of conclusion 5, thirteen existing models for predicting the SRI of double panels were compared. The results obtained with different models were in poor agreement even for the simplest double wall structures. The variations were between 20 ... 40 dB and they were largest at high frequencies. Most of the models overestimated the SRI at high frequencies. This comparison showed that different types of double panels could not be modelled using a single existing model. The selection of the model should depend on the physical parameter under study. Further work is needed to rank different models according to their range of application and general reliability. In future work, the

predictions and measurements should be repeated on several different double wall structures. The verifying measurements should be carried out in standard conditions and the physical parameters of the wall should be carefully determined and documented.

9. According to the above conclusion, none of the existing double panel prediction models was applicable to all types of double wall structures. Therefore, a hybrid model should be developed as a combination of existing prediction models. This model should consider the surface mass, loss factor, lowest normal modes, critical frequency and dimensions of the wall. The cavity absorbent should be modelled by using its impedance and propagation factor, which is based either on measured data or derived data, e.g. on the basis of the flow resistivity, dynamic stiffness and density. Empty cavities should also be considered. The interpanel connections, or studs, should be characterized by their density and stiffness. The existence of the normal modes of the subpanels formed between the studs should also be considered. Finally, the use of the Paris equation for calculating the field-incidence sound transmission coefficient should be reconsidered. It was proposed by Kang *et al*.[120] that the Paris equation should be weighted by Gaussian distribution.

10. In general, the most typical design fault of double walls were mechanical connections, either in the form of sandwich structure or rigid studs. The influence of studs in double structures could be modelled by Sharp's model. In the case of sandwich door structures, R_w was 5…8 dB lower than that of optimal uncoupled double panel doors, if the dilatational resonance occurred in the important frequency range. The validity of simple[95] and complex[76] prediction models should be investigated to be able to predict simple sandwich structures similar to those shown in this thesis.

11. It was shown that identical double structures in adjacent dwellings can cause strong flanking transmission at the resonance frequency of double structures. The most usual example was the floating floor (parquet), which was mounted on top of a thin foam blanket. This construction produced a mass-spring-mass resonance frequency of around 500 Hz. When the resonances were equal in adjacent dwellings, a collapse in the SRI occurred. The floor between the dwellings was uniform, which is very usual. The resonance decreased the total SRI between the dwellings to such an extent that the regulations were not fulfilled. This would not happen with a bare concrete slab because it is not burdened with similar strong resonances. To develop structures that fulfil present building regulations in buildings, more such investigations are needed.

Appendix - The influence of residual intensity on the pressure-intensity indicator

The purpose of this appendix is to determine a mathematical expression for predicting the measured pressure-intensity indicator, F_{pI}. In Publication [IV], an equation for the true pressure-intensity indicator was derived. It described the situation where no phase mismatching between the microphone channels occurred, that is, the pressure-intensity indicator caused by the properties of the sound field. It is denoted in this thesis by F'_{pI}

$$F'_{pI} = L_p - L'_I \tag{A1}$$

The measured intensity level, L_I, depends on the true sound intensity level, L'_I, and the residual intensity level, $L_{I,R}$. The residual intensity is a consequence of the phase mismatch of the intensity measurement equipment. The residual intensity is determined in the intensity calibration where both intensity microphones are exposed to the same pressure and phase. Such a situation can be easily arranged in a very small chamber, where the diameter is considerably smaller than the smallest wavelength of interest. In such a situation, the true intensity is assumed to be zero. Thus, the measured intensity is caused by the residual intensity.

The pressure-residual intensity index, $\sigma_{pI,0}$, is determined as

$$\sigma_{pI,0} = L_p - L_{I,R} \tag{A2}$$

In practical field measurements, this equation is always valid. The interpretation of Eq. (A1) is that the residual intensity level is always present at a constant distance from the measured sound pressure level, L_p. A typical intensity measurement result is presented in Figure A1.

Because the residual intensity acts like "background noise" to the true intensity, L'_I, the true sound intensity can be calculated by the conventional formula

$$L'_I = 10\log\left[10^{\frac{L_I}{10}} - 10^{\frac{L_{I,R}}{10}}\right] \tag{A3}$$

If the term L'_I is subtracted from the term L_p, we get

$$L_p - L'_I = L_p - 10\log\left[10^{\frac{L_I}{10}} - 10^{\frac{L_{I,R}}{10}}\right] \tag{A4}$$

which equals F'_{pI}. Because the following relations hold

$$L_I = L_p - F_{pI}$$
$$L_{I,} = L_p - \sigma_{pI,0} \tag{A5}$$

after some algebraic steps, we get

$$F_{pI} = L_p - 10\log\left[10^{\frac{L_p - F'_{pI}}{10}} + 10^{\frac{L_p - \sigma_{pI,0}}{10}}\right] \tag{A6}$$

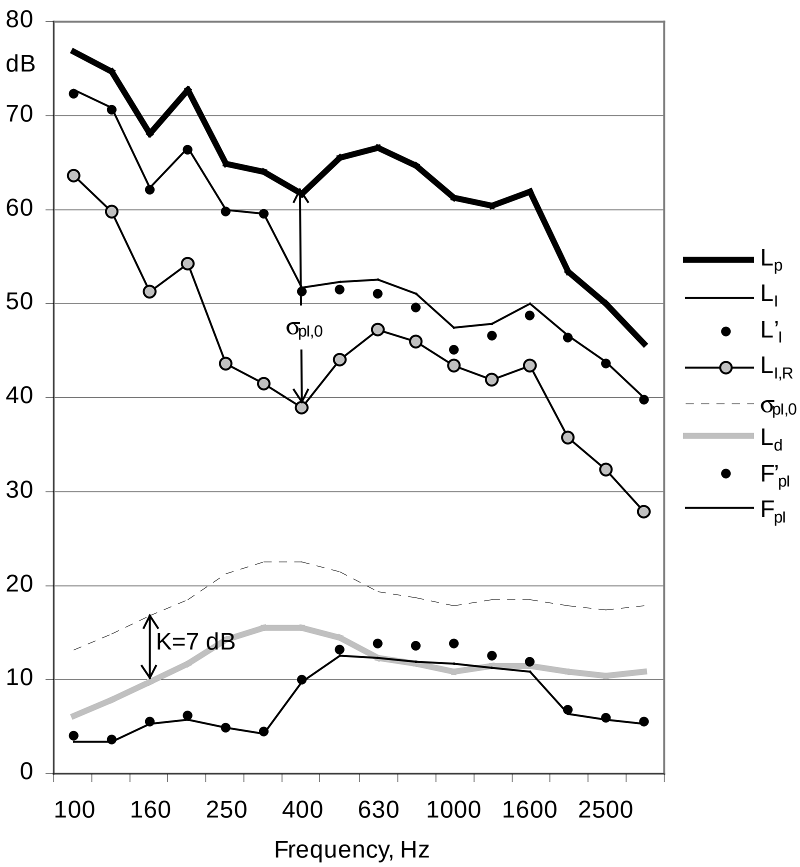

Figure A1 *- A typical example of the intensity parameters during sound intensity measurements. The point is to elucidate that the difference between the measured intensity,* L_I*, and the true intensity,* L'_I*, is larger than 1 dB, when* $F_{pI} > L_d$.

Because this equation is independent of L_p, we finally get

$$F_{pI} = -10\log\left[10^{\frac{-F'_{pI}}{10}} + 10^{\frac{-\sigma_{pI,0}}{10}}\right] \qquad \text{(A7)}$$

An example of the relation between F'_{pI} and F_{pI} is presented in Figure A2. The measured pressure-intensity indicator, F_{pI}, is always a little smaller than F'_{pI} because of the influence of the residual intensity. The difference is below 1 dB, when Eq. (7) holds.

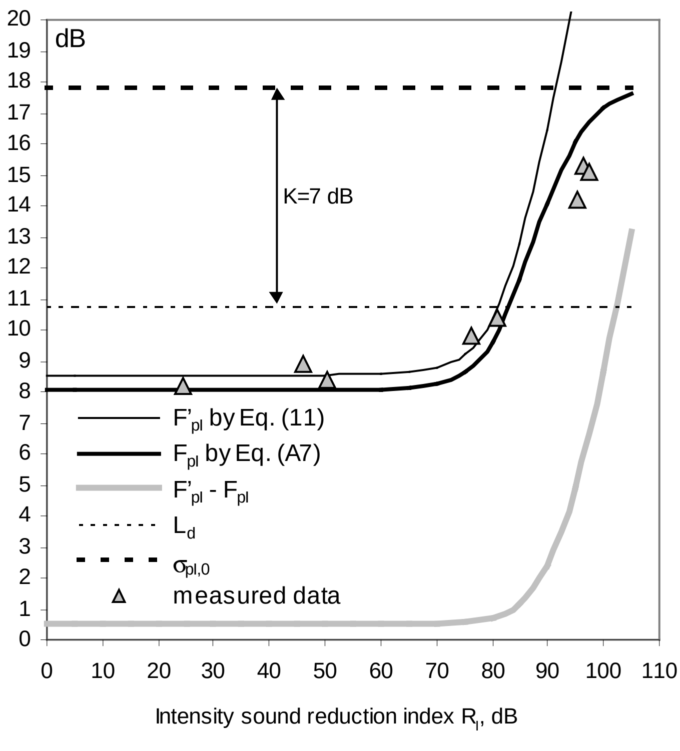

***Figure A2** - The difference between the true and measured pressure-intensity indicator at different values of R_I. The measured data are from Publication [IV] (case A0: 1000 Hz).*

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