DOI: 10.61782/fa.2023.0911

Sound Absorption Measurements - how to?

Christian Nocke
Akustikbüro Oldenburg
Sophienstr. 7, D-26121 Oldenburg

ABSTRACT

A brief historical review on measurement techniques of sound absorption or the acoustic surface impedance will be presented, starting from procedures in the 1930s. Many in-situ and laboratory methods have been described over the decades.

Some of these methods are based on the assumption of diffuse sound fields.

A clear definition and criterion for diffusivity is missing. But a commonly used measurement procedure of so-called diffuse sound absorption coefficients is described in the international standard ISO 354. A diffuse sound field is a theoretical approach. Within the procedure of ISO 354 the sound field itself is changed by introducing the sample to be testet. This reverberation room paradoxon is investigated with the help of measurements with measurements on samples placed not according to the procedures of ISO 354. The corresponding, non-standard measurements are presented and compared to computer simulations.

Keywords: sound absorption, absorption measurement, computer simulation, reverberation chamber, ISO 354

1. INTRODUCTION

For more than a century different approaches to measure the acoustic absorption or acoustic surface impedance of a material have been used. Due to different requirements and in different contexts the quantity to be measure can be the impedance or absorption coefficient. As Morse et al. [1] pointed out the complex quantity impedance is rather used in a scientific context whereas the real quantity absorption is found in practical applications. The impedance might be used to calculate some of the absorption coefficients quoted in the following.

Different measurement concepts and ideas lead to many different procedures. Aiming towards various applications each procedure has advantages and disadvantages. The following review of different procedures will be far from complete but has been chosen according with respect to the applicability to measure on spot or in-situ.

At least two procedures for the measurement of sound absorption are well known for a long time and are described in international standards. These two will be briefly summarized before some historical approaches in free-field conditions towards the measurement of the impedance or absorption will be quoted. In contrast the well-known reverberation chamber procedures rely on a certain sound field condition.

2. DEFINITIONS: IMPEDANC & ABSORPTION

Acoustic Impedance: According to DIN 1320 [2] the specific acoustic impedance of a material is defined as the quotient of "the complex amplitudes of sound pressure and particle velocity". Other authors [3][4] suggest to work with the specific acoustic admittance instead avoiding this mathematical problem of dividing by a vector quantity such as velocity. Relating this specific acoustic impedance to a plane wave will give the definition of the characteristic field impedance Z_0. It is well known that

$$Z_0 = \rho_0 \ c_0 \tag{1}$$

with the density ρ_0 of the fluid and the speed of sound c_0. For a spherical wave the characteristic impedance is given by the following expression

$$Z_{o,spherical} = \rho_0 c_0 \frac{ikr}{1+ikr} \tag{2}$$

---

[*] ***Corresponding author**: info@akustikbuero-ol.de.*

with the wave number k and the distance r between source and receiver. Only for large values of r compared to the wave length $\lambda = 2\,\pi\,/\,k$ (or kr >> 1) this characteristic impedance of a spherical wave will converge to the real and constant value of Z_0. For small values of kr this quantity is complex.

The acoustic behavior of a boundary between two materials can be described by the change of the characteristic impedances. For porous sound absorbers various models to describe the acoustic properties with wave number and characteristic impedance have been developed, see [4][5][6][7]. This leads to the definition of the normal specific acoustic impedance, see [3]. This quantity can be theoretically calculated for one or several layers of sound absorbing material [4][5][7]. From a practical point of view this quantity, the normal specific acoustic impedance of a surface, is sufficient to describe the acoustic behavior of a surface. Most of the impedance measurement procedures presented in the following will aim at the value of this quantity that will be referred to as impedance Z in the following.

Sound absorption coefficients: Since an early discussion on “the sound absorption problem” in 1939 [8] many different definitions of sound absorption coefficients have been introduced. Maybe this lead to a remark by Mechel about too many sound absorption coefficients (see [4], there p. 275). Quite generally the sound absorption coefficient α can be defined by

$$\alpha = \frac{absorbed\ energy}{incident\ energy} \tag{3}$$

Plane wave absorption coefficient For a plane wave at normal incidence the formula

$$\alpha_0 = 1 - \left|R_p(Z)\right|^2 \tag{4}$$

can easily be deduced, with the plane wave reflection factor Rp(Z) = (Z – 1) / (Z + 1), Z as defined above [4]. For oblique incidence at angle θ this absorption coefficient can be calculated according to

$$\alpha_0 = 1\text{-}\left|\mathrm{R_p}(\mathrm{Z})\right|^2 \tag{4}$$

with Rp(Z) = (Z sin θ – 1) / (Z sin θ + 1) [4]. For small angles of incidence, e.g. near grazing incidence this description with plane waves is not valid [9].

Statistical absorption coefficient: For statistical incidence of plane waves the absorption coefficient α_{st} can be calculated according to well known Paris formula

$$\alpha_{st} = \int_0^{\pi/2} \alpha(\theta)\ \sin 2\,\theta\ d\theta \tag{5}$$

For locally reacting absorbers this integral can be solved a corresponding formulae might be found in [4][11][12].

Sabine absorption coefficient: In room acoustics the so-called Sabine absorption coefficient is used very often describing the average absorption in a room. Some requirements have to be fulfilled to apply the formula of Sabine [10].

Other absorption coefficients: Apart from these absorption coefficients other definitions can be found in literature. EYRING [13], MILLINGTON [14], MORSE ET AL. [1], NOBILE [15], THOMASSON [16] and many others have defined sound absorption coefficients.

3. SOUND ABSORPTION MEASUREMENTS

Standard procedures: The traditional method to determine the sound absorption of a material is the standing wave tube. Details of different measurement procedures are described in internationals standards [11][17].

Geometrical or in-situ procedures Apart from this various free-field methods for the absorption coefficient and/or the impedance can be found in literature. Common to many of these approaches is the assumption of plane wave propagation or sound rays. Following this they might be named as geometrical procedures, see § 24 in [10].

One of the first suggestions for the measurement of the acoustical properties of a material in free-field conditions has been given by SPANDÖCK [22] in 1934. Short pure tones with 800 Hz and 4000 Hz and a duration of 1/200 s have been applied to record the direct and reflected signal before and after reflection at a surface. The result is the sound absorption of the surface. A similar technique has been described one year earlier by CREMER [23].

An experimental set-up from ENRSTHAUSEN/VON WITTERN for outdoor applications is depicted in Fig. 1, taken from [24].

INGARD/BOLT [25] described in 1951 a procedure using a standing wave in front of the sample under investigation. In analogy to the standing wave tube the amplitude and phase of the sound pressure has been measured. A comparison between a acoustically hard surface and the sample yields the complex reflection factor R_p. These authors clearly indicate a low frequency limit of this procedure as the assumption of plane waves is not valid at the short distances used for the measurement. For small angles of incidence the sphericity of the wave should also be taken into consideration [26]. ANDO [27] describes a “interference pattern method” similar to this approach.

YUZAWA [27] developed a subtraction technique using two microphones with exactly the same distance to the source. One microphone is positioned close the surface, the other further away. Subtraction of both signals delivers the magnitude of the reflection factor R_p.

DAVIES/MULHOLLAND [29] describe a method to determine the impedance from measurements of the complex reflection factor. A comparison of two measurements, one in free-field and the second close to the surface, is carried out. A similar approach has been applied by KINTSL [30]. Instead of a loudspeaker a spark source has been applied. The required size of the sample is estimated by a formula also used later in [31][32].

A method to measure the impedance also using two microphones is presented by ALLARD [33][34]. Both microphones are positioned close to the surface. This method is very similar to a procedure only theoretically proposed by KURZE [4][35]. The measured quantity is the transfer function between both microphones. Form this the impedance is deduced using a full wave description of the sound field in front of an impedance plane as given by NOBILE/HAYEK [36].

WILMS/HEINZ [37] demonstrate the application of maximum length sequences (MLS-) based measuring techniques to obtain the reflection factor in-situ. The basis of this procedure is the recording of impulse responses between a speaker and microphone at normal incidence of sound. The microphone is positioned half the distance between sample surface and speaker. Applying time windowing to the impulse responses extracts the direct and reflected sound. This method is very similar to SPANDÖCKS [22] pulse method. Measured results are shown for a range of 100 Hz to 15000 Hz. No hints are given about sample size and validity of the results at low frequencies.

A very similar method also applying MLS-technique is presented by GARAI [31]. Especially restrictions of the frequency range and the size of the sample are investigated. At low frequencies GARAI shows that there are restrictions of the method. These restrictions are explained because the assumption of plane wave propagation is not valid at low frequencies.

MOMMERTZ [38] finally refines the last two methods and introduces a subtraction technique to deduce the complex reflection factor R_p. Again MLS measuring technique is applied avoiding any special requirements for the measurement environment. Instead of using a fixed positioning of source and receiver as proposed by YUZAWA [27] also time windowing is applied to the recorded impulse responses. Two measurements have to be carried out, one serves as reference and is subtracted from the reflection measurement. For normal incidence of sound a frequency range between 250 Hz and 8000 Hz is employed. For oblique incidence of sound no range of validity is proposed. For small angles of incidence results for the plane wave reflection factor Rp greater than 1 in magnitude are shown. Especially at low frequencies MOMMERTZ proposes that these results should be explained by spherical wave reflection.

An improvement of ALLARD`s [33][34] two microphone technique also using MLS technique is presented by LI/HODGSON [39]. Here results with reflections factors R_p above 1 in magnitude are presented below 500 Hz. No further discussion of this result is included.

Abb. 4. Meßanordnung im Freien

Figure 1. Experimental set-up for outdoor measurements of sound absorption by refeflection measurements from 1939 [24].

A transfer function method based on spherical waves is described and applied in [40][41]. A survey on different procedures can be found in [42][44].

4. ISO 354 SOUND ABSORPTION

Another procedure to measure the sound absorption is based on Sabine`s well-known reverberation formula and has been standardized in ISO 354 [18]. Various inter-laboratory comparisons have been carried out for this method [19][20][21]. ISO 354 (2003) [18] describes a procedure based on Sabine's formula, as given by

$$T = 0{,}16\,\frac{V}{A} \tag{6}$$

with reverberation time T, volume of room V and equivalent sound absorption area A. In ISO 354 the equivalent absorption with and without sample, A_1/A_2, is derived by

$$A_{1/2} = \frac{55{,}3}{c\,T_{1/2}} - 4Vm_{1/2} \qquad (7)$$

with T1/2 reverberation time in empty room and room with sample, c is speed of sound and $m_{1/2}$ attenuation coefficient in both room conditions correspondingly.

This formula can be derived theoretically from a statistical approach of sound rays in a room. It is obvious that this formula shows several approximations such as:

- position of sample is neglected
- size of sample is neglected
- difference between sound fields in empty room room with sample is neglected
- "diffusity" of sound field is not considered, especially important at low frequencies

There are other topics related to the validity and range of application of these formulae (6) and (7), see §12 and §25 in CREMER [43].

Despite these deficits the procedure of ISO 354 is widely used and accepted. ISO 354 in its present version allows some interpretations, but at the same time tries to avoid some errors by describing suggestions and recommendations on sample size, microphone and sample positioning, room conditions etc. Attempts to "correct" the deficits described above need to consider the sound field in the room as well as other aspects.

In the following some measurements in a reverberation chamber according to ISO 354 are presented with set-ups of the sample

5. RESULTS FOR NON-STANDARD SETUPS

5.1 Measurements

In figure 2 and 3 two set-ups used for an investigation are shown. The sample was made out of blocks with 1.2 m x 0.6 m x 0.2 m in size. The material is an open pore melamine foam. In the first setup (setup 1) the floor of the reverberation chamber has been nearly fully covered with a highly absorptive material (56 blocks = 40.3 m²). The second setup (setup 2) covers 10.8 m² (15 blocks). For this the blocks were laid 200 mm distance in each direction. Both setups are non in agreement with the requirements of ISO 354. This is why this is called a non-standard measurement. All other requirements of ISO 354 such as measurement equipment, microphone positions, loudspeaker positions etc. have been strictly followed. The only deviation from ISO 354 requirements is the setup of the sample (size and positioning).

The results of the measurements for the Sabine absorption coefficient according to ISO 354 are shown on the following section 5.2. together and in comparison with results from computer simulations from a 3D-model.

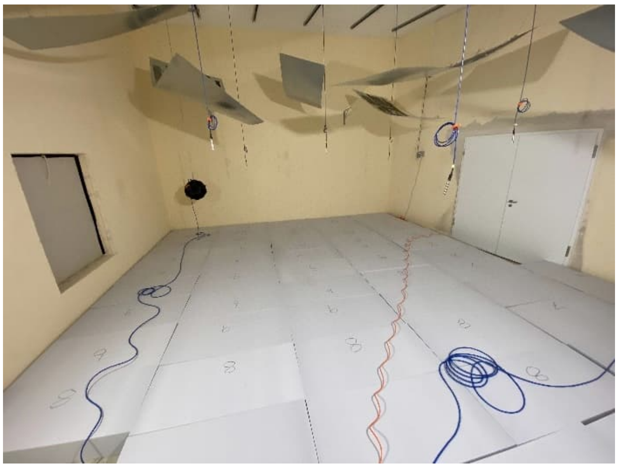

Figure 2. Setup 1 - reverberation chamber fully covered with sample of a highly absorptive material.

Figure 3. Setup 2 – reverberation chamber covered with a sample consisting of single modules/block of a highly absorptive material.

5.2 3D simulations – ray tracing

The room or better reverberation chamber used for the measurements is modelled in a commercially available 3D room acoustics simulations software (CadnaR from DataKustik, Gilching). In this software basically a raytracing algorithm is applied to model sound propagation; this is based on the geometrical acoustics approximation. Scattering and diffraction can be included by different approaches. Every surface in the room is assigned an absorption coefficient as well as a scattering coefficient. Both quantities are frequency dependent.

Geometrical acoustics fails to describe wave phenomena in acoustics such as modal effects, interferences and others. In general, it is assumed that geometrical acoustics is valid above Schroeder frequency.

Two different approaches have been chosen to design the 3D model, called simple and extended model in the following. For both cases the walls, floor and ceiling of the room have been used. Two doors, another closed opening and other small objects like loudspeakers, microphones, humidity/temperature sensors have been neglected in both models. The main difference between the two approaches is the inclusion of scattering.

- Simple model
  A scattering coefficient of 1.0 in all frequency bands has been applied. Scattering objects (reflective sails) are omitted. The sound absorption coefficients of all surfaces (walls, ceiling, floor) have the same value and were adjusted to reproduce the reverberation time in the empty room.
- Extended model
  Scattering elements (sails) modeled as in room, but with flat reflective surfaces. Sound absorption coefficients of the room boundary surfaces were adjusted in such a way that the reverberation time of the empty space was reproduced. Scattering coefficients of the room surfaces were adjusted in an iterative process in such a way that the best possible match was achieved.

In figure 6 the two models with a “standard” sample set-up according to ISO 354 are shown.

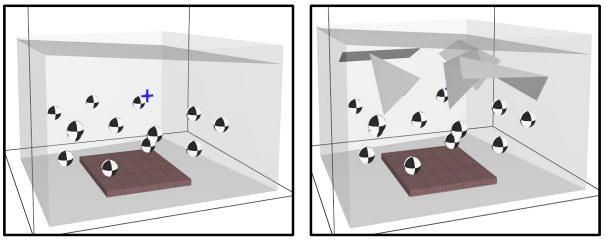

Figure 4. Sketch of simple model (left) and extended model (right).

In the following results from simulations for the two experimental setups described as described under 5.1. are shown and discussed. The frequency dependent absorption coefficient used for the simulations is taken from measurements carried out strictly according ISO 354, but: values larger than 1.0 can not be taken into account and have been cut to 1.0 for the simulation. Figure 5 and 6 show the 3D models as used for the simulation. The only change in the computer model is the geometry of the sample. A small change in volume occurs as well as the surface area is slightly changed by adding the sample to the corresponding empty room of the simple or extended model respectively. The simulations calculate the reverberation time in the empty room and in the room with the sample. The absorption coefficient is then derived from these simulation results exactly as described by the procedure of ISO 354. The 63 Hz octave band has been added for information purposes.

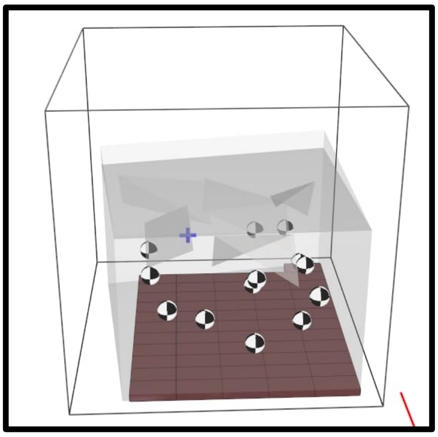

Figure 5. Sketch of setup 1 from figure 2 as modeled in 3D software.

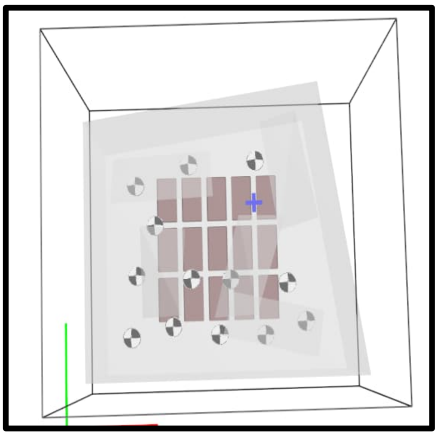

Figure 6. Sketch of setup 2 from figure 3 as modeled in 3D software.

The figures 7 and 8 show each four sound absorption curves. In blue curve (▬) refers to the values as measured in the real reverberation chamber, see figure 2 and 3. The grey curve (▬) shows the input data in the virtual reverberation room for the surfaces of the sample. In red (▬) the result from the simulation in the simple model and in green (▬) the result from the extended model is shown.

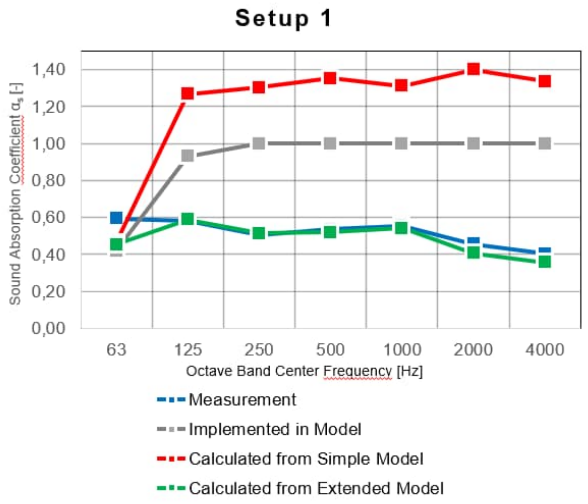

Figure 7. Results of the absorption coefficient for setup 1 from figure 2 and 5 in comparison with implemented, measured and simulated values.

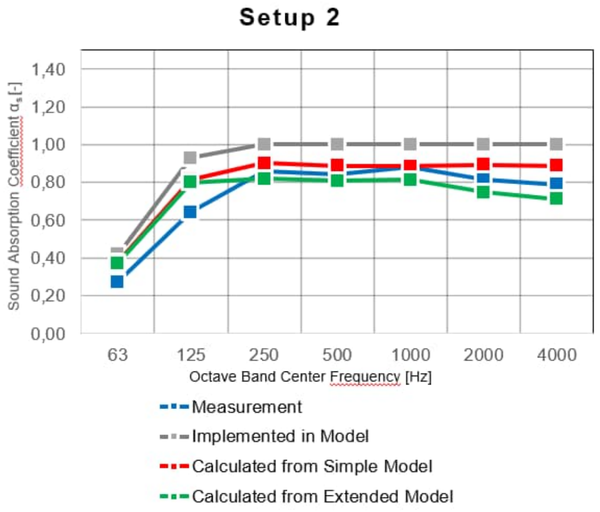

Figure 8. Results of the absorption coefficient for setup 2 from figure 3 and 6 in comparison with implemented, measured and simulated values.

In general, it can be observed that the extended model approach leads to a better agreement between the measured absorption curve and the result from simulation. For the setup 1 with a non-diffuse sound field in the room with the sample the agreement between simulated and measured values is very close, especially between 125 Hz and 400 Hz. The 63 Hz shows a deviation as expected. This deviation can be observed for the setup2 already at 125 Hz; also the deviation between the simple model simulations and the extended model simulation compared to the measured values is slightly larger.

A comparison between the measured results and the values from a standard measurement according to ISO 354 (implemented values for model) show large deviations especially for setup 1. Also, the measured results for setup 2 show smaller values than the standard values. This type of modular mounting as in setup 2 has become more popular over the last years. And covering a ceiling fully with an highly absorptive ceiling might also not be adequate in real life rooms. Further implications can be discussed elsewhere and are widely know in room acoustic design.

6. SUMMARY & OUTLOOK

In this paper a brief review of measurements procedures for so-called "sound absorption" values is given. From a physical point of view not only the energetic quantity "sound absorption coefficient" might be used, but reflection of sound waves is better described with the magnitude and phase, e.g. using impedance/admittances. Procedures for this exists.

Approximative approaches as given by Sabine also yield a decrease of energy in a sound field when absorptive surfaces are exposed to the sound field. The paradoxon [46] in the reverberation chamber measurements is based on the two different sound field conditions. This has been described in early papers already by different authors [47][48][49].

For a future revision of ISO 354 several topics need to be solved. Hereby, the question of uncertainty [50] can remain open as most of the results are used in room acoustic applications. It is suggested to concentrate on practical issues that need answers, e.g. modular sound absorbers, absorption of objects, absorption of structured setups, large objects. In conjunction with the present revision of ISO 3382 on the measurement of impulse responses also the questions of modern measuring equipment needs to be observed.

Finally, the question of "A war of coefficients or a meaningless wrangle over practical unessentials?" [45] might hopefully be answered until 2039 after one century on "The absorption coefficient problem" [8].

7. ACKNOWLEDGMENTS

Great Thanks to Tiedo Meyer of Akustikbüro Oldenburg für his longtime support on computer simulations and much more.

8. REFERENCES

[1] Morse, P. M., R. H. Bolt und R. L. Brown: Aousti impedance and sound absorption. J. Acoust. Soc. Am., 12(2):217-227, 1940

[2] DIN 1320 –Akustik - Begriffe (Acoustics - Terminology), Beuth, 2009

[3] Beranek, L. L. und I. L. Vér: Noise and vibration ontrol engineering - priniples and appliations. J. Wiley and Sons In., New York, 1992

[4] Mechel, F. P.: Schallabsorber, Bd. I - Äußere Schallfelder, Wechselwirkungen. S. Hirzel Verlag, 1989

[5] Allard, J.: Propagation of sound in porous media - modelling sound absorbing materials. Elsevier sciene publishers LTD, 1993.

[6] Zwikker, C. und C. W. Kosten: Sound absorbing materials. Elsevier, 1946.

[7] Attenborough, K.: Models for the acoustial properties of air-saturated granular media. Acta acustica, 1:213-226, 1993.

[8] Hunt, F. V.: The absorption coefficient problem. J. Aoust. Soc. Am., 11:38-40, 1939

[9] Morse, P. M.: Vibration and sound. ASA, 1981

[10] Cremer, L. und H. A. Müller: Die wissenschaftlichen Grundlagen der Raumakustik, Bd. II. S. Hirzel Verlag, Stuttgart, 1976

[11] ISO 10534 – 1: Acoustics – Determination of sound absorption coefficient an impedance in impedance tubes – part 1: Method using standing wave ratio, 1996

[12] Mechel, F. P.: Design harts for sound absorber layers. J. Aoust. Soc. Am., 83(3):1002-1012, 1988

[13] Eyring, C. F.: Reverberation time in "dead" rooms. J. Aoust. Soc. Am., 1(1):217 - 241, 1930

[14] Millington, G.: A modified formula for reverberation. J. Aoust. Soc. Am., 4(1):69 - 82, 1932.

[15] Nobile, M. A.: Measurement of the spherical wave absorption coefficient at oblique incidence using the two-microphone transfer function method. In: Proc. of Internoise 89 , S. 1067-1072, 1989

[16] Thomasson, S.-I.: On the absorption coefficient. Acustica, 44(4):265 -273, 1980

[17] Acoustics - Determination of sound absorption coefficient and impedance in impedances tubes - Part 1: Method using standing wave ratio, 2001

[18] ISO 354 Acoustics - Measurement of sound absorption in a reverberation room, 2003

[19] Kath, U.: Ein Hallraum-Ringversuch zur Bestimmung des Absorptionsgrades. Acustica, 52(4):211-215, 1983

[20] Kosten, C. W.: International comparison measurements in the reverberation room. Acustica, 10(5/6):400-411, 1960

[21] Kuhl, W.: Ursachen und Verhinderung systematischer Abweichungen vom „wahren" Absorptionsgrad bei der Absorptionsgradmessung im Hallraum. Acustica, 52(4):197-210, 1983.

[22] Spandöck, F.: Experimentelle Untersuchung der akustischen Eigenschaften von Baustoffen durch die Kurztonmethode. Annalen der Physik, 5(20):328-344, 1934

[23] Cremer, L.: Bestimmung des Schluckgrades bei schrägem Schalleinfall mit Hilfe stehender Wellen. Elektr. techn. Nachrichten, 10(7):302-315, 1933

[24] Ernsthausen, W. und W. v. Wittern: Eine Methode zur Bestimmung des akustischen Reflexionsvermögens von Bodeflähen. Akustische Zeitschrift, 4(6):353-359, 1939

[25] Ingard, U. und R. H. Bolt: A free field method of measuring the absorption coefficient of acoustic materials. J. Aoust. Soc. Am., 23(5):509-516, 1951

[26] Ingard, U.: On the reflection of a spherical sound wave from an infinite plane. J. Aoust. So. Am., 23(3):329-335, 1951

[27] Ando, Y.: The "interference pattern method" of measuring the complex reflection coefficient of

acoustic materials at oblique incidence. In: Proc. of ICA 68 , S. E33-E36, 1968

[28] Yuzawa, M.: A method of obtaining the oblique incident sound absorption coefficient through an on-the-spot measurement. Applied Acoustics, 8(1):27-41, 1975

[29] Davies, J. C. und K. A. Mulholland: An impulse method of measuring normal impedance at oblique incidence. J. Sound Vib., 67(1):135-149, 1979

[30] Kintsl, Z.: Investigation of the sound absorption of a wall section by a impulse technique. Sov. Phys. Acoust., 21(1):30-32, 1975

[31] Garai, M.: Measurement of the sound-absorption coefficient in situ: the reflection method using periodic pseudo-random sequences of maximum length. Applied Acoustis, 39(1/2):119-139, 1993

[32] Norme francaise: ode d'essai pour la détermination de charatéristiques acoustiques d'érans installés en champ libre. afnor, 1990

[33] Allard, J. F. und Y. Champoux: In situ two-mirophone technique for the measurement of the acoustic surface impedance of materials. Noise Contr. Eng. Journ., 32(1):15-23, 1989

[34] Allard, J. F. und B. Sieben: Measurements of acoustic impedance in a free field with two microphones and a spectrum analyzer. J. Aoust. So. Am., 77(4):1617-1618, 1985

[35] Kurze, U.: Zur Entwicklung eines Gerätes für komplexe Schallfeldmessungen. Acustica, 20(5):308-310, 1968

[36] Nobile, M. A. und S. I. Hayek: Acoustic propagation over an impedance plane. J. Acoust. Soc. Am., 78(4):1325-1336, 1985

[37] Wilms, U. und R. Heinz: In-situ Messung komplexer Reflexionsfaktoren von Wandflächen. Acustica, 75(1):28-39, 1991

[38] Mommertz, E.: Untersuchung akustischer Wandeigenschaften und Modellierung der Schallrückwürfe in der binauralen Raumsimulation. Dissertation, RWTH Aachen, 1995.

[39] Li, J.-F. und M. Hodgson: Use of pseudo-random sequenes and a single microphone to measure surface impedance at oblique incidence. J. Acoust. Soc. Am., 102(4):2200-2210, 1997.

[40] Nocke, C.: Improved impedance deduction from measurements near grazing incidence. Acustica/acta acustica, 85(4):586-590, 1999

[41] Nocke, C.: In-situ acoustic impedance measurement using a free-field transfer function method. Applied Acoustics, 59(3):253-264, 2000

[42] Nocke, C. In-situ Messung der akustischen (Wand-)Impedanz, Dissertation, Universität Oldenburg, Shaker, Aachen, 2000

[43] L. Cremer "Statistische Raumakustik", Bd. II, Hirzel, Stuttgart, 1961

[44] C. Nocke, V. Mellert, "Brief Review on in-situ measurement techniques of impedance or absorption", *Proceedings Forum Acusticum*, Sevilla, 2002

[45] Jamilla Balint, Michael Vorländer; A war of coefficients or a meaningless wrangle over practical unessentials?. J Acoust Soc Am 1 September 2021; 150 (3)

[46] M. Vorländer, Geometrische Akustik in kleinen Räumen?, 28. Deutschen Jahrestagung für Akustik , Bochum , Germany , DAGA 2002

[47] D. Y. Maa , "Distribution of eigentones in a rectangular chamber at low frequency range ," J. Acoust. Soc. Am. 10 , 235(1939)

[48] F. V. Hunt, L. L. Beranek, and D. Y. Maa, "Analysis of Sound Decay in Rectangular Rooms," J. Acoust. Soc. Am. 11, 80(1939)

[49] H. Kuttruff, "Eigenschaften und Auswertung von Nachhallkurven (Characteristics and analysis of decay curves)," Acustica 8(4), 273–280(1958)

[50] M. Vercammen, "Improving the accuracy of sound absorption measurements according to ISO 354," in Proceedings of the International Symposium on Room Acoustics, Amsterdam, the Netherlands(2019)