Parameter of metallic hollow spheres - a porous sound absorbing material

Joern Huebelt*, *Andreas Zeibig**, *Cris Kostmann***, *Guenther Stephani***

* Institut fuer Akustik und Sprachkommunikation
Technische Universitaet Dresden, Germany
Joern.Huebelt@mailbox.tu-dresden.de

** Fraunhofer-Institut fuer Fertigungstechnik und Angewandte Materialforschung,
Teilinstitut Dresden, Germany
Cris.Kostmann@epw.ifam.fhg.de

Abstract

Recently structures of metallic hollow spheres (MHS) were applied as sound absorbers for the reduction of noise, e.g. silencer. An effective design requires the description of the acoustical behavior of this structures by an absorber model. For that purpose the characteristic values of the structure, the characteristic impedance and wave number and the absorber parameter, the flow resistivity, the open porosity and the tortuosity have been measured. In this work the range of this parameter will be demonstrated. Moreover the influence of the characteristic values and the absorber parameter on the acoustical behavior will be discussed. After that an optimal structure will be presented.

1. Introduction

Metallic hollow spheres (MHS) can be applied for the absorption of sound. One of the advantageous properties of this material is the high temperature resistance and the high mechanical strength. Among others this leads to a wider range of application of this structures compared to the classical porous absorber materials, e.g. mineral wool or open porous foam.

Important for the absorption process of porous media is the dissipation close to the interface of the structure and air. Moreover for absorber structures which are located in front of a nearly full reflecting wall the ratio of absorber thickness to wavelength of sound is important. The MHS show a low attenuation compared to classical porous absorbing material.

2. Determination of characteristic values and parameters

2.1. Characteristic impedance and wave number

There are different methods for the estimation of the absorption of porous materials. For instance the measurement using ”Kundts Tube” or the determination in the ”reverberation chamber”. The results measured by use of these methods are valid for the certain examined configuration of the absorber, e.g thickness of the absorber, or number of layer, only . This can be disadvantageous in the case of the optimization of an existing material.

The surface impedance $\underline{Z}_{w\,i}$ of a layered absorber can be calculated by the recursive formula [1]:

$$\underline{Z}_{w_i} = \underline{Z}_{A_i} \frac{\underline{Z}_{w_{i+1}} + j\frac{\underline{Z}_i}{\cos\underline{\varphi}_i}\tan\underline{\varphi}_i}{\frac{\underline{Z}_i}{\cos\underline{\varphi}_i} + j\underline{Z}_{w_{i+1}}\tan\underline{\varphi}_i}, \qquad (1)$$

with

$$\underline{\varphi}_i = \underline{k}_{A\,i} d_{A_i} \cos\underline{\vartheta}_i.$$

Here $\underline{Z}_{w\,i+1}$ is the ”input” surface impedance of the adjacent layer $(i+1)$, $\underline{Z}_{A_i}$ is the characteristic impedance, $\underline{k}_{A\,i}$ the characteristic wave number and d_{A_i} the thickness of the i-th layer. So for a known pair of characteristic values, $\underline{k}_A$ and $\underline{Z}_A$, the acoustical properties, e.g surface impedance or absorption coefficient, can be calculated by use of Eq. (1). It should be noted, that this formula can be applied for a layered absorber with various thickness d_A.

In [2] a method for measuring the pairs of characteristic values is proposed. The method offers a sufficient accuracy. This has been proofen by the comparison with the accuracy of other methods [3].

The complex characteristic wave number $\underline{k}_A$ is defined as

$$\underline{k}_A = k_A^{'} + jk_A^{''} = \omega\left(\frac{1}{c_A^{'}} + j\frac{1}{c_A^{''}}\right). \qquad (2)$$

In this definition $\underline{c}_A$ is the sound speed in the porous material and $\omega = 2\pi f$ is the angular frequency. For the time dependents of $+j\omega t$ the components of the komplex wave number are:

$$k_A^{'} > 0 \qquad k_A^{''} < 0. \qquad (3)$$

Where the real part $\underline{k}_A$ is indirect proportional to the sound speed and the imaginary part ist proportional to the attenuation of the propagating wave.

According to the method described aforementioned the characteristic values can be determined by measurement of the acoustical transfer function of the homogeneous absorbing material. Thus the absorber is mounted in a tube and the sound pressure has to be measured on four points, two in front and two behind of the specimen. The transfer matrix of the absorber material can be expressed as:

$$\begin{pmatrix} \underline{T}_{11} & \underline{T}_{12} \\ \underline{T}_{21} & \underline{T}_{22} \end{pmatrix} = \begin{pmatrix} \cos \underline{k}_a d_A & j\underline{Z}_A \sin \underline{k}_A d_A \\ \frac{j}{\underline{Z}_A} \sin \underline{k}_A d_A & \cos \underline{k}_a d_A . \end{pmatrix} \quad (4)$$

Therefore the characteristic impedance and the wave number can be written as

$$\underline{Z}_A = \left(\frac{\underline{T}_{12}}{\underline{T}_{21}} \right)^{\frac{1}{2}}, \quad (5)$$

$$\underline{k}_A = \frac{1}{d_A} \arccos(\underline{T}_{11}). \quad (6)$$

2.2. Absorber parameter

The absorber parameter porosity σ and the inner surface of the structure A_i have been determined by geometrical calculation and tomographic examination. The flow resistivity Ξ has been measured by use of the technique of Stinson [4]. Furthermore the tortuosity τ has been estimated by measurement of time delay of ultra sonic sound. Here an inaccuracy for specimen with higher attenuation has to be mentioned. This measurements have been carried out on a pool of approximately 100 specimen.

In this work the absorption coefficient have been determined for specimen with various thickness d_A in the "Kundts" tube. For clarity in Figure 1 the the absorption coefficient is shown as a function of the parameter $d_a/(f \cdot c_A)$. Thus the maximum of the absorption coefficient for all specimen measured can be found at

$$d_a/(f \cdot c_A^{'}) = 0.25 \quad (7)$$

and the minimum at

$$d_a/(f \cdot c_A^{'}) = 0.5. \quad (8)$$

Thereby the propagation speed $c_A^{'}$ was determined by Eq.(6).

Furthermore the absorber parameter have been predicted using the geometrical information of the structure, e.g. diameter of spheres, given in the overview of Sarradj [5].

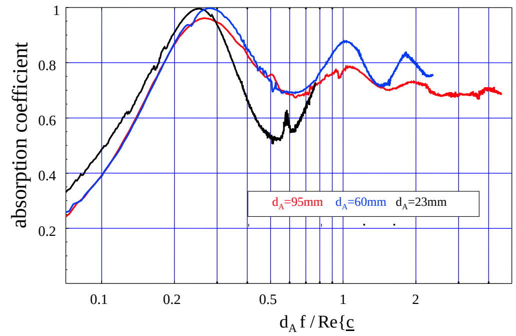

Figure 1: *Absorption coefficient as function of the variable $d_a/(f \cdot c_A^{'})$ for MHS specimen of various thickness d_A.*

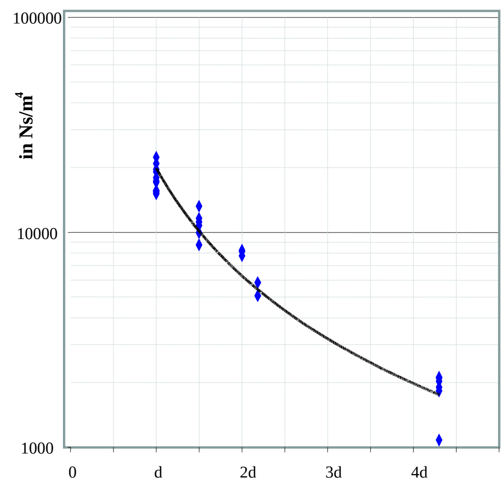

Figure 2: *Flow resistivity versus diameter of sphere.*

3. Discussion

Wave number: In the upper diagram of Fig.3 the mean value of the propagation speed $c_a^{'}$ of a wave propagating in MHS as a function of the frequency is shown. Here the parameter of the curves is the mean value of sphere diameter of the structures. It can be seen, that for a smaller diameter of the spheres the propagation speed decreases.

On the other hand the attenuation $k_A^{''}$ of the structure increases for smaller diameters. Compare the lower diagram in Fig. 3. That means, for a high dissipation inside of the MHS the diameter of the spheres should be small. This is in accordance with Fig. 2. Here the flow resistivity, a value which is proportional to the attenuation, is indirect proportional to the diameter. Moreover for small values of $c_a^{'}$ the first maximum of the absorption coefficient as a function of frequency can be found at lower frequency (see Eq. (7) and compare Fig. 1).

Characteristic impedance: Important for the absorption is the transfer of the sound energy into the MHS. The reflection coefficient of the interface between two media

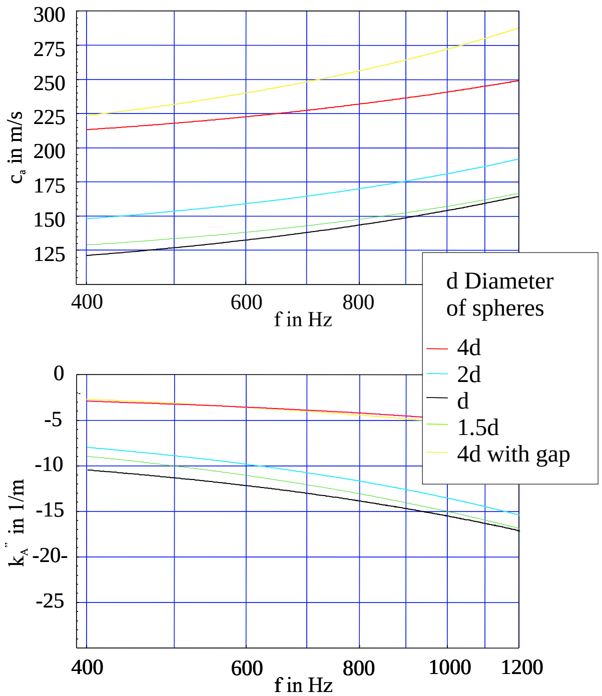

Figure 3: *The characteristic wave number. Upper diagram: propagation speed $c_a^{'}$, lower diagram: attenuation $k_a^{''}$.*

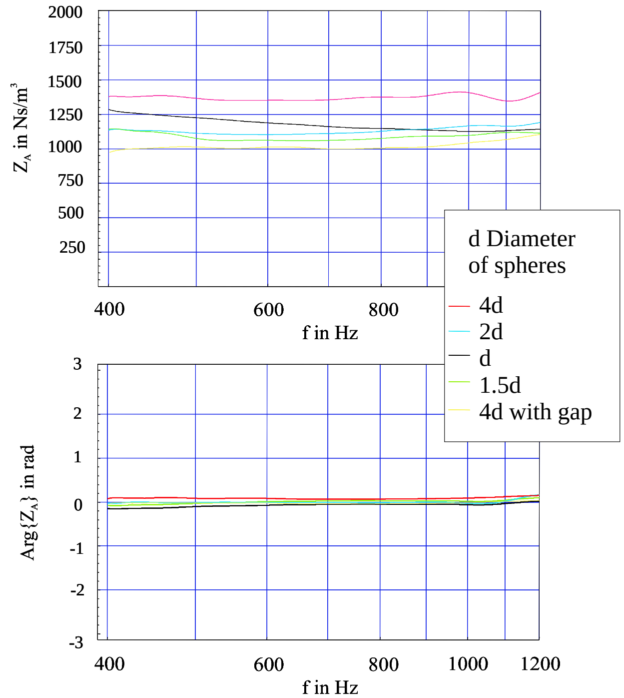

Figure 4: *The characteristic impedance $\underline{Z}_A$. Upper diagram: Magnitude of $\underline{Z}_A$, lower diagram: Phase of $\underline{Z}_A$.*

can be expressed as

$$\underline{R}_p(\vartheta_0) = \frac{\underline{Z}_w - Z_0/\cos(\vartheta_0)}{\underline{Z}_w + Z_0/\cos(\vartheta_0)} = \frac{\underline{Z}_A/Z_0\,\underline{n}_1\cos(\vartheta_0) - \sqrt{\underline{n}_1^2 - \sin^2\vartheta_0}}{\underline{Z}_A/Z_0\,\underline{n}_1\cos(\vartheta_0) + \sqrt{\underline{n}_1^2 - \sin^2\vartheta_0}}. \quad (9)$$

From that it can be seen that the transfer of sound energy into a semi infinite MHS depends on the refraction index $\underline{n}_1 = \underline{k}_A/k_0$, the angle of incidence ϑ_0 and the surface impedance Z_w. Thus for a perpendicular sound incidence ($\vartheta_0 = 0$) the transferred sound energy into a semi infinite structure depends only on the value of the characteristic impedance $\underline{Z}_A = \underline{Z}_w$. So the well known condition $\underline{Z}_A = Z_0$ for the maximum of transmitted sound energy can be found.

In Figure 4 the mean value of the characteristic impedance $\underline{Z}_A$ as a function of frequency is shown. Except large diameter of spheres, there is no strong deviation between the mean values of the characteristic impedance for structures with different sphere diameter. But it was figured out that the absolute value of characteristic impedance can be adjusted by the chosen sinter temperature (see Fig 5). Moreover due to the insertion of caps into the structure the characteristic impedance $\underline{Z}_A$ can be adjusted to match the characteristic impedance in air Z_0.

Absorption coefficient: The first maximum of the absorption coefficient α_{max} at $d_a/(f \cdot c_A) = 0.25$ as a function of flow resistivity is shown in Fig. 6. In this graph high values of α_{max} occurring at small values of flow resistivity. This is because of a destructive interference at the surface of the MHS. This interference occurs due the superposition of the incident wave and the backward travelling wave, reflected on the backside of the absorber. For a higher attenuating structure, that means for higher values of flow resistivity, the backward travelling wave shows a smaller amplitude. So the attenuation of the wave due to interference on the surface of the structure decreased.

In Fig. 7 the first minimum of the absorption coefficient α_{min} at $d_a/(f \cdot c_A) = 0.5$ is shown. Here for high values of flow resistivity the value of α_{min} is small. The decrease of the flow resistivity leads to an increase of α_{min}. The curve reaches a maximum at $1.5d$ and decreases after that for smaller values of flow resistivity. At $d_a/(f \cdot c_A) = 0.5$ a positive interference of the incident and the back travelling wave occurs. Therefore the absorption coefficient for small values of flow resistivity is small. Concluding, to produce a nearly broad band absorbing material a structure with $1.5d$ should be used.

Permeability of skin of the spheres: The permeability of the skin of the spheres is about $5 - 20\%$. However some of the specimen have been manufactured with a higher permeability. So the inner volume of spheres and the hole can be understood as a "Helmholtz" resonator with a resonance frequency at approximately 6000Hz.

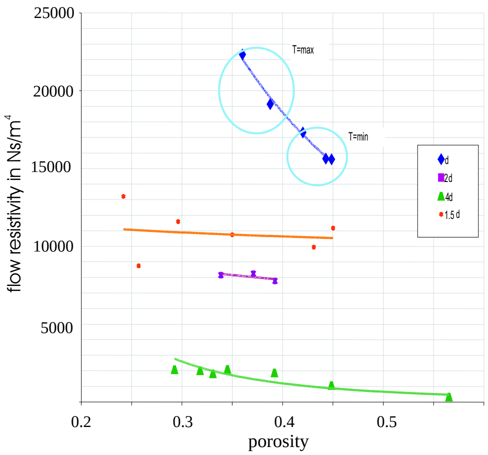

Figure 5: *Flow resistivity as a function of the open porosity for classes of sphere diameter. Parameter: Sinter temperature.*

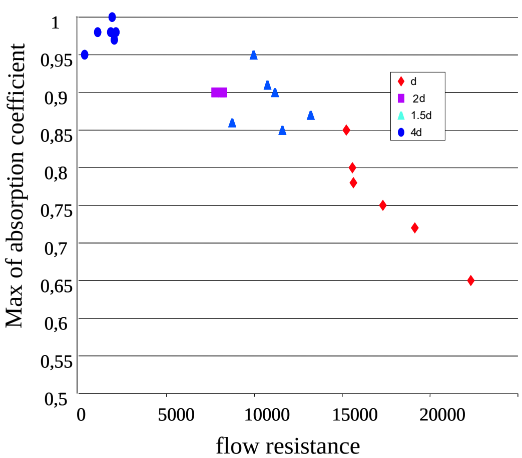

Figure 6: *The maximum of absorption coefficient at* $d_a/(f \cdot c_A) = 0.25$ *versus flow resistivity.*

4. Conclusions

It was pointed out that an important factor for the acoustical performance of the MHS is the diameter of the spheres (optimum at 1.5d) and the sinter temperature. Moreover the use of higher permeability of the sphere skin leads to an increase of absorption at higher frequency.

5. Acknowledgments

This work was supported by the "Stiftung Industrieforschung", Marktstrasse 8, 50968 Koeln, Germany.

6. References

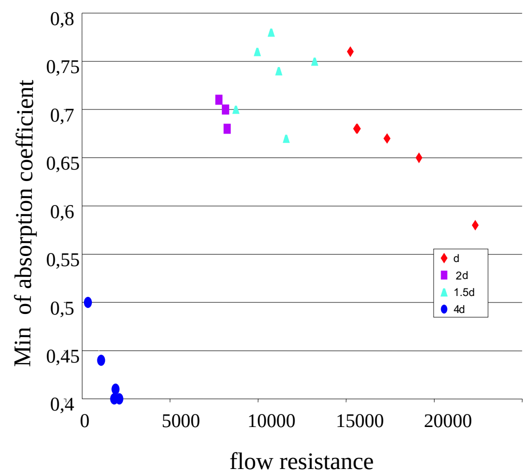

Figure 7: *The minimum of absorption coefficient at* $d_a/(f \cdot c_A) = 0.5$ *versus flow resistivity..*

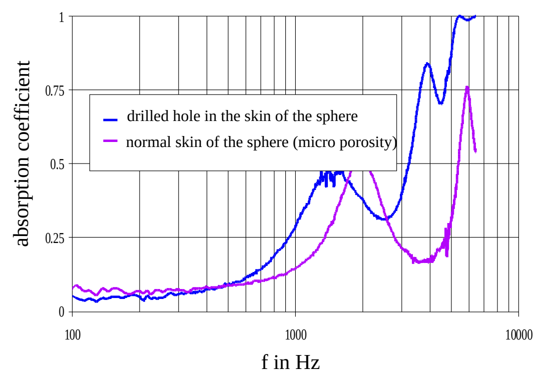

Figure 8: *MHS with higher permeability of the sphere skin.*

[1] L. M. Brekhovskikh, *Waves in layered media*, 2nd ed., A. Mathematics and mechanics, Eds. New York [u.a.] : Acad. Press, 1980, no. ISBN 0-12-130560-0.

[2] B. Song and J. S. Bolton, "A transfer-matrix approach for estimating the characteristic impedance and wave numbers of limp and rigid porous materials," *Journal of the Acoustical Society of America*, vol. 107, no. 3, pp. 1131–1152, 2000.

[3] E. Elsaghir, "Messverfahren zur Bestimmung von Absorberparametern," Master's thesis, Intitut fr Akustik und Sprachkommunikation, TU Dresden, Germany, 2003.

[4] M. Stinson and G. Daigle, "Electronic system for the measurement of flow resistance," *Journal of the Acoustical Society of America*, vol. 83, no. 6, pp. 2422–2428, 1988.

[5] E. Sarradj, T. Lerch, and J. Huebelt, "Input parameters for the prediction of acoustical properties of open porous asphalt," *Acta Acustica united with Acustica*, submitted 2003.