

CALCULATION OF THE SCATTERING COEFFICIENT OF A SINE-SHAPED SURFACE BY USING THE 3D BEM METHOD

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1 ABSTRACT

Scattering or diffusion coefficients may be measured or calculated from polar reflected pressure diagrams^{1,2}. It is common practice to evaluate these polar diagrams in the *far field* because the relative pressure magnitude as a function of reflection angle is independent of the distance to the reflector and so the scattering or diffusion coefficient becomes independent of the receiver distance. This makes it easier to compare different diffusers. The *first aim* of this paper is to study the influence of several parameters to the minimal far field distance: source distance, incidence angle, reflector size, reflection angle and frequency. This study will be restricted to the reflection of an omnidirectional point source, irradiating a perfectly rigid plane reflector. Once an estimation of this minimal far field distance is made, correct measurements and calculations are possible. In a *second part*, calculated random incidence scattering coefficients of a circular sine shaped sample will be compared to real scale measurements in the reverberation room.

2 INVESTIGATIONS OF NEAR AND FAR FIELD

When studying the reflected sound field of finite-size reflectors, a region may be observed where the reflected sound pressure level decreases monotonically at 6 dB per distance doubling. Closer to the surface, in the *near field*, interference effects produce an undulating reflected sound pressure field. The distance to the reflector where the far field begins is called the *minimal far field distance (MFFD)*. Under normal incidence, guidelines to calculate this distance can be found in literature^{2,3,4,5,6}. However, under oblique incidence, expressions are rarely found, e.g. in Ref. 7, p.108-110. To calculate the random incidence scattering coefficient, polar reflected pressure diagrams are necessary for every (!) incidence angle. Therefore, the maximum MFFD over all possible incidence angles needs to be found first.

2.1. The Sound Field Scattered by a Rigid, Plane Disc

Consider an infinitely thin rigid, plane disc S of radius a , which is irradiated by a point source at a distance r_1 (Figure 1). The incident sound pressure on the disc can be written (suppressing the $\exp(-j\omega t)$ time dependence):

$$p_i(\vec{s}) = \frac{A}{|\vec{s} - \vec{r}_1|} e^{jk|\vec{s} - \vec{r}_1|}, \quad (1)$$

in which A is an arbitrary complex constant [Pa.m], k the wave number [rad/m] and ω the pulsation [rad/s] of the incident spherical wave. The pressure field scattered by the disc will be denoted by $p_s(\vec{r}_2)$.

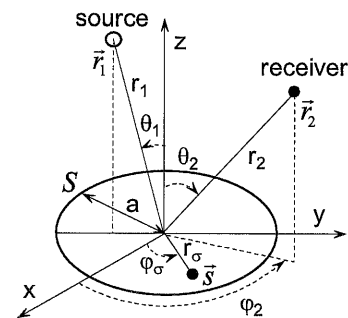


Figure 1: Geometry ($\phi_1 = 0^\circ$)

Since the disc is rigid, the resultant particle acceleration must have a zero component along the z-axis, normal to the disc:

$$\ddot{w}_{i,z}(\vec{s}) + \ddot{w}_{s,z}(\vec{s}) = 0, \quad \vec{s} \text{ on the disc } S \quad (2)$$

in which $\ddot{w}_{i,z}(\vec{s})$ is the normal particle acceleration [m/s²] that would be observed on the disc surface in the absence of the disc. This acceleration is given by^{8, eq. 10.6}:

$$\ddot{w}_{i,z} = -\frac{1}{\rho} \frac{\partial p_i}{\partial z} \Big|_{z=0} = -\frac{A}{\rho} \frac{(1 - jk|\vec{s} - \vec{r}_1|) r_1 \cos(\theta_1) e^{jk|\vec{s} - \vec{r}_1|}}{|\vec{s} - \vec{r}_1|^3}, \quad (3)$$

in which ρ is the fluid density [kg/m³]. Combining equations (2) and (3) gives us the virtual acceleration of the disc that generates the scattered pressure field as if the disc was only radiating sound waves⁹. The scattered pressure field can now be calculated by using a generalised form of *Rayleigh's formula* for radiation of a plane rigid body in an infinite baffle^{8, eq. 4.28}:

$$p_s(\vec{r}_2) = \frac{\rho}{2\pi} \int_S \frac{e^{jk|\vec{r}_2 - \vec{s}|}}{|\vec{r}_2 - \vec{s}|} \ddot{w}_{s,z}(\vec{s}) dS(\vec{s}), \quad (4)$$

which gives, after inserting $\ddot{w}_{s,z} = -\ddot{w}_{i,z}$ from expression (3):

$$p_s(\vec{r}_1, \vec{r}_2) = \frac{Ar_1 \cos(\theta_1)}{2\pi} \int_0^a \int_{\varphi_\sigma=0}^{2\pi} \frac{e^{jk|\vec{r}_2 - \vec{s}|}}{|\vec{r}_2 - \vec{s}|} \frac{(1 - jk|\vec{s} - \vec{r}_1|) e^{jk|\vec{s} - \vec{r}_1|}}{|\vec{s} - \vec{r}_1|^3} r_\sigma d\varphi_\sigma dr_\sigma, \quad (5)$$

in which

$$\begin{aligned} |\vec{s} - \vec{r}_1| &= \sqrt{r_\sigma^2 + r_1^2 + 2r_\sigma r_1 \sin \varphi_\sigma \sin \theta_1} \\ |\vec{r}_2 - \vec{s}| &= \sqrt{r_\sigma^2 + r_2^2 - 2r_\sigma r_2 \sin \theta_2 (\cos \varphi_\sigma \cos \varphi_2 + \sin \varphi_\sigma \sin \varphi_2)} \end{aligned} \quad (6)$$

with r_σ and φ_σ as defined in Figure 1. Assuming the source and the receiver on the z-axis (normal incidence) at heights z_1 and z_2 respectively, expression (5) can be simplified to a single integral:

$$p_s(z_1, z_2) = Az_1 \int_0^a \frac{e^{jk\sqrt{r_\sigma^2 + z_2^2}} (1 - jk\sqrt{r_\sigma^2 + z_1^2}) e^{(jk\sqrt{r_\sigma^2 + z_1^2})}}{\sqrt{r_\sigma^2 + z_2^2} (\sqrt{r_\sigma^2 + z_1^2})^3} r_\sigma dr_\sigma. \quad (7)$$

The influence of e.g. the source distance can be seen in Figure 2. When both source and receiver are located far away from the disc, the scattered sound pressure further simplifies to:

$$\lim_{\substack{z_1 \rightarrow \infty \\ z_2 \rightarrow \infty}} p_s(z_1, z_2) = \frac{A}{z_1 + z_2} \left[1 - e^{jk(\sqrt{a^2 + R^2} - R)} \right], \quad \begin{array}{l} z_1 ? a \\ kz_1 ? 1 \\ z_2 ? a \end{array} \quad (8)$$

in which R is half the harmonic mean of source and receiver distance:

$$R = \frac{\check{R}}{2} = \frac{1}{1/z_1 + 1/z_2} = \frac{z_1 z_2}{z_1 + z_2}. \quad (9)$$

The scattered pressure amplitude is the magnitude of expression (8)^{10, eq. 2.43}:

$$P_s(z_1, z_2) = \frac{2|A|}{z_1 + z_2} \left| \sin \left(\frac{k}{2} \left(\sqrt{a^2 + R^2} - R \right) \right) \right|, \quad R \gg a/2$$

$$\cong \frac{2|A|}{z_1 + z_2} \left| \sin \left(\frac{ka^2}{4R} \right) \right|, \quad R \gg a$$
(10)

The pressure maxima occur for values of R satisfying

$$R_m = \frac{a^2}{(2m-1)\lambda} - \frac{(2m-1)\lambda}{4} \quad m=1, 2, 3, \dots$$
(11)

The pressure maximum corresponding to the largest value of R is

$$R_1 = \frac{a^2}{\lambda} - \frac{\lambda}{4}, \quad \lambda \leq 2a.$$
(12)

For larger values of R or for $\lambda \geq 2a$, the scattered pressure amplitude is decaying monotonically.

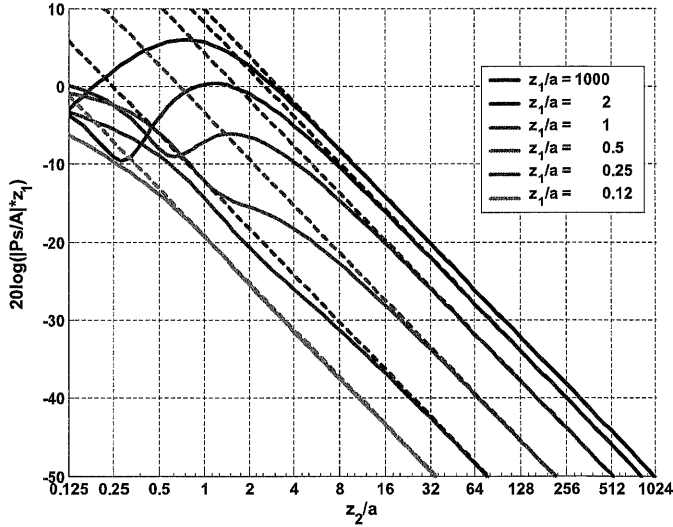


Figure 2: Reflected pressure amplitude for several source distances, according to equation (7) for the case of $\lambda/a = 1$. Source and receiver are on the disc axis. The far field approach is indicated by a dotted straight line (see equation (5) & (16)).

2.2. The Minimal Far Field Distance

2.2.1. The Kinsler Approach

We may take expression (12) as the MFFD for cases where $z_1 \gg a$ and $kz_1 \gg 1$. Mind that this expression does not necessarily assume a plane incident wave. However, it assumes normal incidence and gives us the MFFD in the specular direction only. How can we generalize expression (12) for oblique incidence, non-specular reflection and smaller source distances? In the following, we will look for an approach that might give us an answer in these cases as well.

If we assume the source at an infinite distance from the reflector, then R in expressions (10)-(12) can be replaced by z_2 (plane wave under normal incidence). The factor $\left(\sqrt{a^2 + z_2^2} - z_2 \right)$ may then be regarded as the pathway difference for a specularly reflected ray and a ray reflected by the edge of the disc. According to equation (12) the last maximum pressure amplitude then corresponds to a path length difference of $\Delta l = \lambda/2$ between both rays, apparently leading to a

constructive interference at a distance z_2 on the disc axis. In this case, the disc surface coincides with the first Fresnel-zone^{7, p. 22}. Cremer and Müller⁷ adopted the path length difference approach to the case of oblique *specular* reflection from an infinite strip of finite width and came to an analogous expression for equation (12) when replacing the reflector width by its projection, as seen by source and receiver. However, they limited Δl to $\lambda/4$, corresponding to a reflector size equal to the area of the first half-Fresnel-zone^{7, p. 109}. But how to extend this approach to *non-specular* reflection at oblique incidence?

We start from a more general approach adopted by Kinsler^{3, p.191}, who studied the sound field radiated by a flat rigid circular piston mounted on a flat rigid baffle of infinite extent. We may generalise his observation that, for a given source position, there exists a finite path length difference Δl_∞ between the longest possible and shortest possible ray path from the source via the reflector to an observer, situated on a line at a given reflection angle at an infinite distance r_2 from the receiver, which is by definition in the far field. In the two-dimensional example of Figure 3: $\Delta l_\infty = b + c' - d$. This path length difference will change when approaching the reflector along this line. When this change approximates $\lambda/2$, then the phases of the signals from the individual points on the reflector will have shifted sufficiently from those observed in the far field to alter the exact reflected pressure amplitude (e.g. equation (7)) sufficiently from his far field approach (e.g. equation (10)):

$$|\Delta l(r_2) - \Delta l_\infty| = \lambda/2 \quad (13)$$

In the example of Figure 3: $\Delta l(r_2) = b + c - (d + e)$. It is easy to verify that the distance r_2 obtained in this way corresponds to the last local maximum of the reflected pressure response in the case of normal incidence and specular reflection for $z_1 \gg a$ and $kz_1 \gg 1$ where $\Delta l_\infty \rightarrow 0$. This approach may thus be seen as a generalisation of the on-axis criterion $\Delta l = \lambda/2$.

We have applied this criterion (13) to an infinite reflector of finite width D (2D-case), hereby replacing the pathway difference to $\lambda/4$ ^{2,4,5,7 p.109,10 p.52} instead of $\lambda/2$, leading to a MFFD larger than the distance to the last constructive interference in the reflected pressure response. We have studied the influence of the source distance, incidence angle, reflection angle and reflector width. The conclusions from this study are:

1. For $r_1 \gg D$, the MFFD is largest at the specular reflection angle (Figure 4, left) and can be found by:

$$MFFD = (D \cos \theta_1)^2 / 2\lambda - \lambda/8 + D \sin \theta_1 / 2. \quad (14)$$

This does not hold for near grazing incidence, where the maximum MFFD may be found at other reflection angles. For normal incidence, this equation holds for every source distance.

2. For *other values of the source distance*, the reflection angles where the MFFD is largest seem to be bended towards the disc axis when comparing to their specular reflection angle (Figure 4, right). In this case a safe (overestimating) MFFD may be found by:

$$MFFD = D^2 / 2\lambda. \quad (15)$$

This MFFD is also recommended for random incidence simulations and measurements.

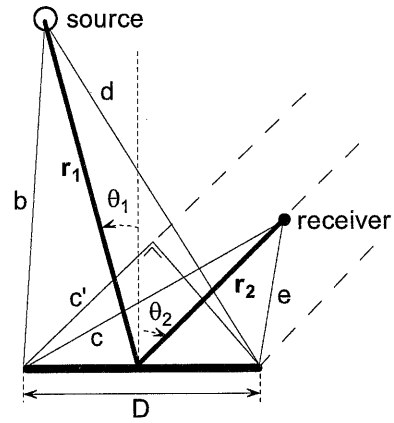


Figure 3: Kinsler approach example
(e.g. equation (7)) sufficiently from his far field approach (e.g. equation (10)):

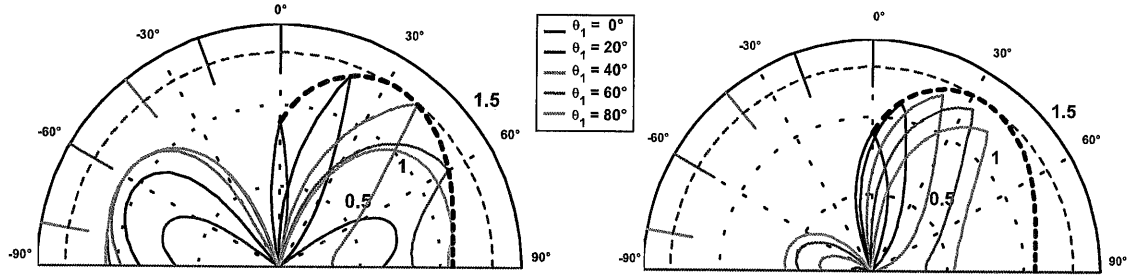


Figure 4: Calculated MFFD according to the Kinsler approach as a function of reflection angle for several incidence angles (marked at outer circle). Thick red line corresponds to the reflector cut. $\lambda = 3.4m$, $D = 3m$. Left: $r_1 = 100m$, Right: $r_1 = 1m$. (Expression (14) is drawn for $0^\circ \leq \theta_1 \leq 90^\circ$ at the specular angle in a thick dashed black line and expression (15) is drawn as a dashed red arc)

2.2.2. Far Field Deviation Approach

Another approach to set the MFFD might be based on the deviation of the true reflected pressure amplitude compared to its far field approximation. This far field approximation is simply a line in the $L_p \leftrightarrow \log r_2$ diagram with a slope of -6 dB per receiver distance doubling, which equals the true reflected pressure amplitude at infinity. When approaching the reflector from infinity along a line, this difference becomes larger until a maximum prescribed deviation is reached. We may take e.g. 0.5 dB for this deviation. This approach seems very straight and looks like the most justifiable one. However, an expression for the reflected sound pressure level and its far field approximation as a function of the receiver distance must be available in advance (in contrast to the Kinsler approach). In the simple case of the rigid plane disc, the reflected pressure is given by expression (5) and its far field approach by doing the following replacement in expression (5):

$$\frac{e^{jk|\vec{r}_2 - \vec{s}|}}{|\vec{r}_2 - \vec{s}|} \rightarrow \frac{e^{jk[r_2 - r_\sigma \sin \theta_2 (\cos \varphi_\sigma \cos \varphi_2 + \sin \varphi_\sigma \sin \varphi_2)]}}{r_2}, \quad r_2 \geq r_\sigma. \quad (16)$$

It is obvious that this method will give other MFFD values than with the Kinsler approach since they have a different way of defining the MFFD. An extensive study of the influence of previous parameters (source distance, incidence angle, reflection angle, wavelength and reflector size) using this MFFD definition and whether it corresponds with the Kinsler approach, still remains to be done.

3 3D BEM SIMULATIONS FOR CALCULATING THE SCATTERING COEFFICIENT OF A CIRCULAR PLATE WITH SINUSOIDAL PROFILE

In this second part, we study the sound field reflected by a rigid circular surface with a sinusoidal height profile. From the far field polar diagram, we can also calculate the scattering coefficient.

3.1. The Sound Field Scattered by a Rigid Sinusoidal Surface

Consider the case of a plane wave incident with wave vector $\vec{k}_1(\theta_1, \varphi_1)$ on an *infinite* surface (Figure 5):

$$\underline{p}_1(\vec{r}, t) = \underline{A} \exp(j\vec{k}_1 \cdot \vec{r} - j\omega t), \quad (17)$$

in which

$$\vec{k}_1 = (k_{1x}, k_{1y}, k_{1z}) = (k \sin \theta_1 \cos \varphi_1, k \sin \theta_1 \sin \varphi_1, -k \cos \theta_1)$$

and $\vec{r} = (x, y, z)$.

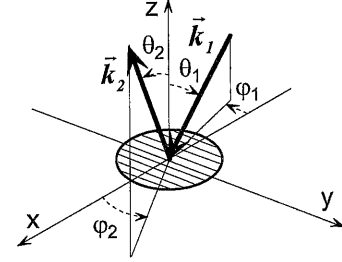


Figure 5: Geometry of incoming and reflected wave vectors.

The periodicity of the surface allows us to expand the reflected sound field above the corrugations into a Fourier series¹¹:

$$\underline{p}_2(\vec{r}, t) = \underline{A} \sum_{n=-\infty}^{\infty} \underline{R}_n \exp(j\vec{k}_{2,n} \cdot \vec{r} - j\omega t), \quad (18)$$

in which the components of $\vec{k}_{2,n}$ are:

$$\begin{cases} k_{2x,n} = k \sin \theta_{2,n} \cos \varphi_{2,n} = k_{1x} + n 2\pi / \Lambda \\ k_{2y,n} = k \sin \theta_{2,n} \sin \varphi_{2,n} = k_{1y} \\ k_{2z,n} = k \cos \theta_{2,n} = \sqrt{(k^2 - k_{1y}^2) - (k_{1x} + n 2\pi / \Lambda)^2} \end{cases} \quad (19)$$

The square root in $k_{2z,n}$ is chosen so that its real part or imaginary part is ≥ 0 . This way, the scattered field is a superposition of plane waves propagating away from the surface and evanescent waves propagating along the surface. The reflection angles of the propagating waves can be found from equation (19):

$$\begin{cases} \theta_{2,n} = \arcsin \sqrt{(\sin \theta_1 \cos \varphi_1 + n \lambda / \Lambda)^2 + (\sin \theta_1 \sin \varphi_1)^2}, & 0 \leq \theta_{2,n} \leq \pi/2 \\ \varphi_{2,n} = \arccos \frac{\sin \theta_1 \cos \varphi_1 + n \lambda / \Lambda}{\sqrt{(\sin \theta_1 \cos \varphi_1 + n \lambda / \Lambda)^2 + (\sin \theta_1 \sin \varphi_1)^2}}, & 0 \leq \varphi_{2,n} \leq \pi \end{cases} \quad (20)$$

The complex amplitudes $\underline{R}_n$ in equation (18) depend on the shape and the admittance of the sample. An exact method to calculate them was developed by Holford¹¹.

3.2. The Scattering Coefficient of a Rigid Finite Surface

To calculate the *directional* scattering coefficient of a *finite* rigid sinusoidal surface, the approach of Mommertz¹ is used, adapted to the case of rigid surfaces:

$$s(\theta_1, \varphi_1) = 1 - \frac{\left| \int_0^{2\pi} \int_0^{\pi/2} \underline{p}_1(\theta_1, \varphi_1, \theta_2, \varphi_2) \cdot \underline{p}_0^*(\theta_1, \varphi_1, \theta_2, \varphi_2) \sin \theta_2 d\theta_2 d\varphi_2 \right|^2}{\left[\int_0^{2\pi} \int_0^{\pi/2} \left| \underline{p}_0(\theta_1, \varphi_1, \theta_2, \varphi_2) \right|^2 \sin \theta_2 d\theta_2 d\varphi_2 \right]^2}, \quad (21)$$

in which $\underline{p}_1$ and $\underline{p}_0$ are the complex scattered pressure of the sinusoidal surface and a rigid flat equally sized reference surface respectively. This directional scattering coefficient can be averaged

over all incidence directions according to their probability in a diffuse field, to obtain the *random incidence* scattering coefficient:

$$s = \frac{1}{\pi} \int_0^{2\pi} \int_0^{\pi/2} s(\theta_1, \varphi_1) \cos(\theta_1) \sin(\theta_1) d\theta_1 d\varphi_1 \quad (22)$$

3.3. 3D BEM Calculations of the Scattered Pressure

To calculate the complex scattered pressures in equation (21), a 3D BEM model of a rigid circular surface with a sinusoidal height profile and a diameter $D = 2a = 3m$, a surface wavelength $\Lambda = 0.177m$ and amplitude $H = 0.0255m$ is made, together with a model of its rigid flat equally sized reference surface. For both models, the far field reflected energy pattern is calculated for incoming unit amplitude plane waves at elevation angles $\theta_1 = 10^\circ, 20^\circ, \dots, 80^\circ$ and azimuth angles $\varphi_1 = 0^\circ, 10^\circ, \dots, 90^\circ$ (see Figure 5) and frequencies from 500 Hz to 2000 Hz in steps of $1/6^{\text{th}}$ octave band. The receiver mesh is a hemisphere with an elevation and azimuth grid size of 2° and radius of 100m. The reader may verify that this is well above the MFFD for random incidence according to equation (15) (which strictly only holds for infinite rigid plane strips of finite width). The scattered pressure hemisphere for azimuth angles larger than 90° can easily be obtained from the calculated scattered pressure hemisphere using symmetry considerations. 2000 Hz was found to be the upper limit for reliable calculations, in relation to the element size of the surface mesh, which is made up of 18786 triangular elements. The calculations took about 11h per frequency on a 1,7 GHz pc with 1 Gb RAM memory.

3.3.1. Scattered Pressures

Figure 6 illustrates a case where a strongly backscattered wave ($n = -1$) is observed.

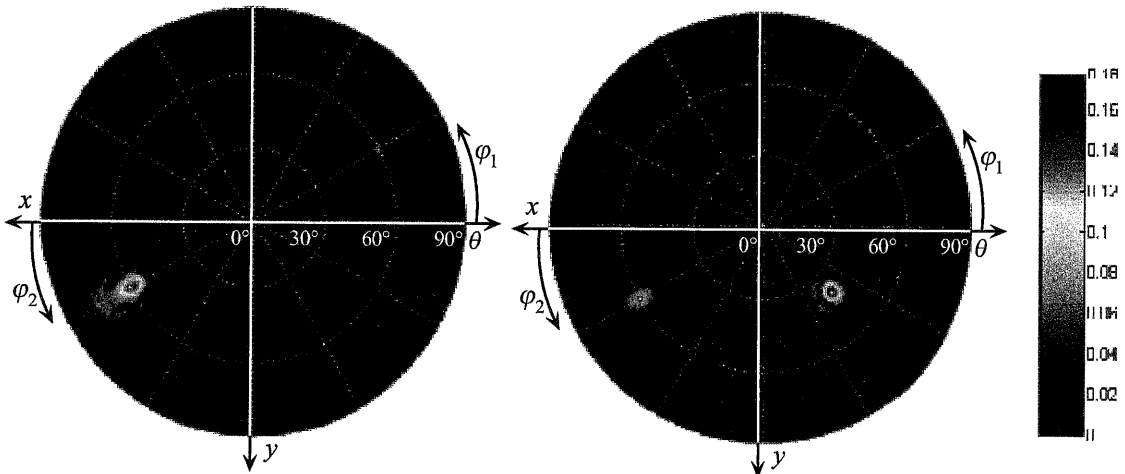


Figure 6: Far field scattered pressure amplitude diagrams [Pa] for flat disc (*left*) and sine profile (*right*) at 1587 Hz. The source direction is indicated by a red dot (elevation 60° , azimuth 30°). The reflection angles for propagating waves calculated by equation (20) are indicated by a small white dot.

From equation (20) it is clear that for an *infinite* periodic surface more propagating waves appear when

- λ/Λ is as small as possible
- φ_1 approaches 90° and θ_1 is as small as possible: forward ($n \geq 1$) and backscattered ($n \leq -1$) waves
- φ_1 approaches 0° and θ_1 is as large as possible: backscattered ($n \leq -1$) waves

These findings have been confirmed by the calculation results (*finite* surface). It has further been observed that, in cases where the only possible propagating wave is the specularly reflected one ($n = 0$), the reflection direction is bended upwards away from the surface in comparison with the geometrical reflection direction. This effect may be attributed to the finiteness of the surface, since it can be observed in the flat disc model as well. It is more pronounced for lower frequencies and more grazing incidence angles. In other cases, the reflection angles of all propagating reflected waves are predicted quite accurately ($\pm 1^\circ$), except for rather grazing reflected propagating waves.

3.3.2. Scattering Coefficients

From the far field scattered pressure diagrams directional scattering coefficients are calculated using a discretisation of equation (21). If these are averaged for each source elevation over all source azimuth angles, a scattering coefficient only depending on source elevation is obtained (Figure 7). Paris' formula finally gives us the random incidence scattering coefficient (eq. (22)).

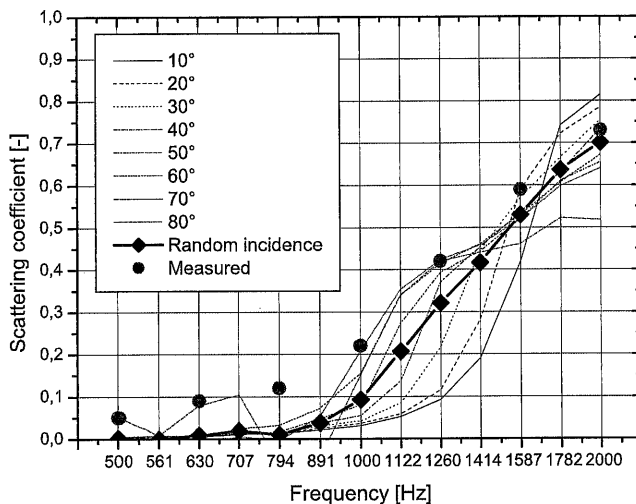


Figure 7: 3D BEM calculated and measured scattering coefficients for the sine profile. (Measured values are averaged values using the K.U.Leuven measurement technique¹²)

3.4. Comparison with Measured Scattering Coefficients

Real-scale measurements of the random incidence scattering coefficient of a sine shaped fibre cement circular plate have been performed^{12,13} according to the procedure described in ISO/DIS 17497-1¹⁴. The measured sample is equally shaped compared to the 3D BEM model. Obtained random incidence scattering coefficients are compared to the calculated values in Figure 7. If the test sample were *infinite* then, according to equation (20), no propagating scattered waves can occur (except for the specular reflection) for frequencies below 960 Hz. Consequently, in this region the scattering coefficient should be zero. In the case of the *finite* BEM model, this holds for frequencies up to about 840 Hz, as long as the incidence angle is not too grazing. The overall higher values measured (compared to the calculated values) may be attributed to small variations in the reverberation room condition (temperature, humidity) and the parasitic scattering effect of the supporting base plate.

4 CONCLUSION

In order to compare scattering properties from different finite diffusers, the far field polar reflected pressure diagram needs to be known. The minimal distance away from the diffuser to reach this far field depends strongly on the geometry and the frequency of the incident wave. In this paper, guidelines to find this minimal far field distance in the case of a rigid flat infinite strip have been developed using an approach originally adopted by Kinsler. Respecting these guidelines, the far field reflected pressure field from a rigid circular surface with a sinusoidal height profile has been studied using a 3D BEM model. Comparisons are made to the case of an infinite sinusoidal surface and an equally sized rigid plane reflector. Finally, random incidence scattering coefficients are calculated and compared to real scale measurements. A good agreement has been found.

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