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ON THE INFLUENCE OF THE CEILING PROFILE ON THE DISTRIBUTION OF THE ROOM ACOUSTICAL PARAMETERS AND THE REVERBERATION TIME

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ABSTRACT
Room acoustical parameters as the sound pressure level decay, the Deutlichkeit (distinctness), the EDT are influenced mainly by the longitudinal section of an auditorium, especially its ceiling profile. But does also the reverberation time (with same volume and absorption area) depend on the ceiling profile? Has a (conical) tent-shaped hall as the 'Philharmonie' in Berlin or the new 'Elbphilharmonie' in Hamburg a smaller reverberation time than a shoe-box, or is always Sabine right? How does this depend on the 'roughness' respectively diffusivity of the surfaces? This mainly 2-dimensional problem has been investigated by a sound particle simulation (ray tracing) programme. It turns out that, if the surfaces are not totally diffusely scattering, there is a considerable influence of the ceiling profile on the reverberation time.

INTRODUCTION AND APPROACH
Many room acoustical parameters are in use, however only a few, or only 3 groups are independently from each other meaningful: 1) the total level, strength measures etc. 2) parameters related to reverberation time (RT) and especially the early reflections as the Clarity C or Deutlichkeit D or the Early Decay Time (EDT), 3) the lateral efficiency (LEF) correlated to the 'spatial' impression, all being energetic measures, evaluating the energetic impulse response ('echogram')[1,2,3]. The definitions of the parameters investigated here are:

- RT= time for a level decay of 60dB, evaluated usually in the range of -5…-35dB;
- EDT= time for the first level decay by 10dB;
- D= E50/Etot where E50= energy received in the first 50ms, Etot = total energy received (where in practice Etot has to be extrapolated from an energy Eend received in the maximum tracing time of the rays by assuming a further exponential decay; the 'clarity', responsible merely for musical perception, which is defined respectively as C= E80/Etot should be, but is not investigated here.)

The lateral efficiency (important mainly for the perception of music) is, as well known, mainly dependent on the position of the side walls, hence on the ground plan of the room. As most rooms are much wider than high, the very first reflections, however, come mainly from the ceiling (if the ground is as usual occupied by the absorbing audience). So, for the architect's important early phase of drafting, one can (for teaching purposes) simplify: the ceiling profile influences mainly the Deutlichkeit, the ground plan the spatial impression. Therefore, for both separately, two-dimensional considerations are sufficient.

Ray tracing as an efficient tool for room acoustical optimization of auditoria is common today. But, in spite of all progress these methods remain trial- and error- methods, however: it is still up to the user to get the idea what to change in geometry and surface properties to reach an optimum distribution of the room acoustical parameters. Architects rather want to know how to design a hall for a given purpose, given the wanted room acoustical and some other parameters. But it seems no systematic investigation on that inverse question exists. However, there are some empirical ones on existing halls investigating the correlation between typical geometrical and room acoustical parameters, for ex. by Gade [2] stating high correlations between RT and EDT, rather low between C (or D) and RT resp. their expectation values from the exponential decay, but no statements on ceiling profiles.

'Tent- shaped' halls as the new 'Elbphilharmonie' in Hamburg
But also the ceiling profile is an important questions for architects, especially when – as it is a modern trend – centralistic auditoria with the stage more or less in the middle are in mind and, hence, rather a 'tent-shaped' hall as the famous 'Berlin Philharmonie'. An example - and occasion - for this paper is the draft for the new 'Elbphilharmonie' in Hamburg whose main concert hall is designed for 2150 persons. The draft [4], similar to the Berlin hall, reveals maximum dimensions of 60m * 40m (with a polygonal, roughly elliptical/conical ground plan) and a maximum height in the middle of 30m ('tent shaped' with a large reflector

hanging over the stage in the middle). From that a volume of at least 30000m³, hence a specific volume of ca. V/N= 15m³/seat can be estimated. As well known, for symphony halls 8-10m³ are recommended for RT=2s. This rule origins from the Sabine formula and the estimation that the absorption area is about A=N*0.7m² where one person occupies 2/3m² with an absorption degree (AG) of $\alpha_p = 0.8$ typically for audience at 1kHz and other almost hard surfaces have typically about 5 times the audience area with AGs of $\alpha_r = 0.05$. (From that in the following it is concluded that the AG of the total ground plan is typically about $\alpha_b = 0.58$.) The world wide average of good concert halls is 8.9m³ (Beranek [5]). Also the Berlin Philharmonie has 9m³ (average height 12.8m, maximum about 20m). So, these 15m³/seat sound critical. But the acoustical consultant, Y. Toyota states that, due to the tent-shape and the more omni-directional sound incidence, a higher volume would be necessary [6] (with same absorption area and volume). Is he right?

So, this paper concentrates on the ceiling shape, i.e. the longitudinal cross section and its influence on the RT and the EDT, compared with the Eyring and Sabine values, and on the Deutlichkeit. It is aimed at a restricted but systematic investigation on the influence of the roof inclination angle and the diffusivity of the surfaces on the spatial average values of RT, EDT and D (only in one middle frequency band).

THE COMPUTATIONAL METHOD

It is used a self-developed 2D- ray tracing program, in the most efficient version of sound particle simulation [7,8]. m_0 'sound particles' (SP), emitted omni-directionally from a point source, are traced over many (l_0) reflections up to a maximum travelling distance. (This is here restricted to that corresponding to 3/4 of the pre-computed Eyring RT, i.e. -45dB decay). Only 2 concepts may be explained here: a) the technique of computing the immissions and b) the diffusivity coefficients.

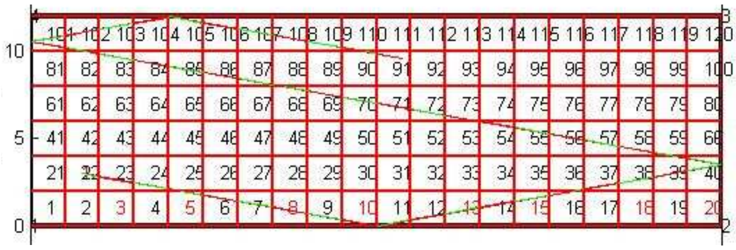

Fig.1: Ray-Tracing in a 2D-room=polygon. The rectangular type of the 'concert hall' investigated here is 40m long and 12m high; the source point is at the position x=3 from the left and at a height of 3m (speaker on a stage); there are 120 (20*6) quadratic 2m*2m-detectors. One ray is emitted here to the right downwards, crossing the detectors; 8 of the detectors serve as special receivers to compute the local EDT and RT values: here with the numbers 3,5,8,13...20 (marked red) at the bottom with middle coordinates x=5, 9, 15,19….39, y= 1; the computed inner crossing distances are marked alternating red and green.

a) To compute the local and temporal sound energy densities (in 2D: energies/surface), and from that the echograms, the SPs are detected in small quadratic detectors (fig.1) simulating the audience (here spread over the whole 'room' i.e. the polygon, but only the lowest row of them is evaluated). The SP's contribution is proportional to their relative energies e_i weighted with their inner crossing distances w_i (by that there is no directivity of the detectors although they are not spheres!). The formula for the 'intensity' (energy/width/time) then reads:

$$I' = \frac{P}{S_d \cdot m_0} \cdot \sum_{n=1}^{n_0} w_n \cdot e_n \qquad (1)$$

where P is the fictive sound power of the source, n_0 the number of the crossing SPs and S_d is the detector ground area. For $n_0 \rightarrow \infty$ this is converging to $I' = P/(2\pi r)$ the 1/r-law as expected for 2D propagation. With the sound particle method, the correct distance is reproduced in a statistical way – which is nevertheless more efficient as the use of the deterministic mirror image source method – provided the number of SP is high enough to re-solve ('sample') the smallest objects of the room. This is achieved here by choosing m_0 so high (the angle between 2 SP so low) that even at highest reflection order on average as well the smallest surfaces are hit as also all detectors are crossed.

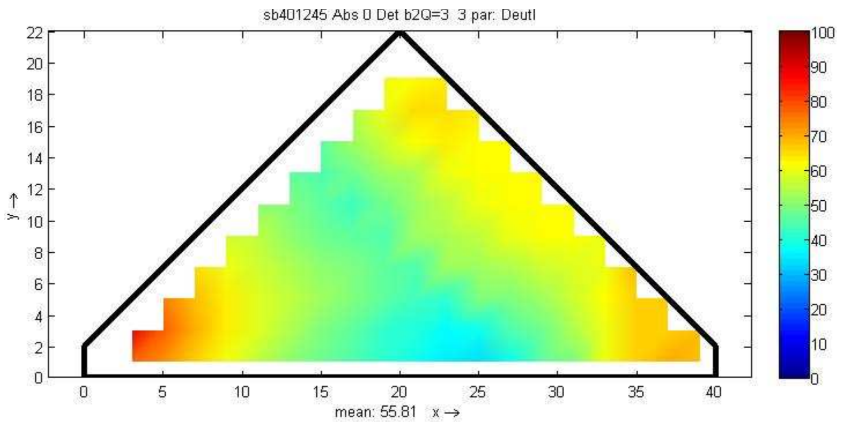

Fig.2: Deutlichkeit distribution in the ‚tent-shaped' version of the room, with maximum height of 12+10=22m at a roof inclination angle of $\alpha = 45°$ (2 types in between with $\alpha = 15°$ and $\alpha = 30°$ with turning points a quarter length from the side not shown here, rest side wall height 12-10=2m); the results are valid for total geometrical reflections (DG=0); to the right the colour legend: the red high values are near the source (bottom left), the lowest (green) typically in the middle of the room; the average D value of the 'tent' of 56% is quite high compared with that of the 'shoe box' (fig.1.) with only 39% (compare tab.1); the colours are interpolated over the quadratic detector lattice.

This 1/r- distance –law means that either source, or receivers are lines extended in the third direction or the assumption the **side walls were in close distance and reflecting.**

For estimation and comparison purposes, the **Eyring RT is pre-computed analytically**, i.e. assuming the diffuse sound field and the 'fate of a representative SP' travelling mean free path lengths of $\Lambda = \pi \cdot S / U$ (U=polygon circumference, S= polygon area) seeing an 'average absorption degree' $\bar{\alpha} = \sum \alpha_j \cdot b_j / U$ (edge length- b_j - instead of surface-weighted) or a mean absorption exponent $\bar{\alpha}' = -\ln\left(1 - \bar{\alpha}\right)$. So, in 2D, the

Eyring RT is $T_{60Ey} = 6 \cdot \ln(10) / c \cdot \Lambda / \bar{\alpha}' \approx 0.128_{s/m} \cdot S / \left(U \cdot \bar{\alpha}' \right)$, for the Sabine value $\bar{\alpha}' \approx \bar{\alpha}$ (2).

It should be stated, that also in 2D an exponential decay is expected – by the same reason as in 3D: the intensity from single (mirror iamge) sources is (without absorption) decreasing with 1/r, compensated by the fact that their number at higher order reflections increasing with r. The difference to the known value 0.161 in 3D instead of 0.128 in 2D is due to the factor $\Lambda = \pi \cdot S / U$ instead of $\Lambda = 4V / S$ in 3D .

From the echogram energies (fig.3,4), the D values (fig.2.) can easily be computed. The local EDT and RT values have to be computed from a linear regression of the level decays within the echograms. The EDT is computed from the decay within the delay time range as estimated for the decay of 0..-10dB from the pre-computed Eyring RT. A RT could in the same way be computed directly from the echogram over the respective times for the level decay -5..-35dB (times 2). Usually, with 'reverberation' is meant the decay after a switched-off-noise rather than from an impulse. So, a regression after backward-integration is performed. However, the rest-reverberation energy (after -35dB) has to be taken into account. This is estimated by a linear regression and extrapolation from the later decay -20…-35dB. (But the results are seldom different from the direct regression.) The EDTs and RTs are evaluated and averaged here only for 8 receiver places in the lower row (see fig.1).

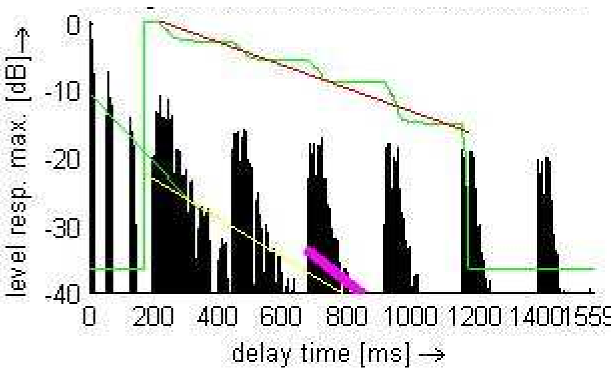

Fig. 3 A typical flutter-echo for the geometrically reflecting 'shoe-box' (side wall absorption only 5%): the straight decreasing lines are lines of linear regression; the steeper left line (green) for estimating the (shorter) EDT, the yellow one for the directly computed RT, the thick magenta line for the decay -20..-35dB used to estimated the rest reverberation energy; the red line above is due to the regression for the backward integrated and corrected decay (green curve). zero- energy values in the gaps are excluded from the regression analysis.

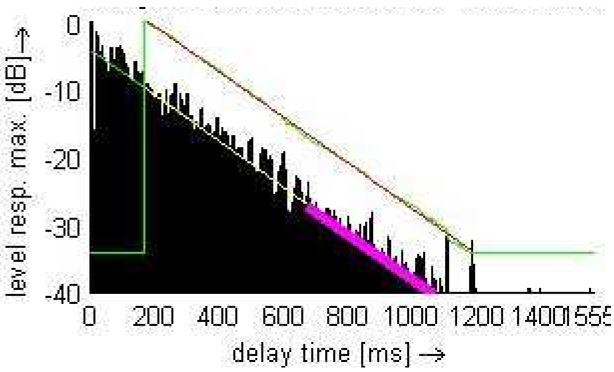

Fig. 4 A smooth echogram as typical for a diffuse sound field for the same 'shoe-box' as in fig. 3 but with total diffusely reflecting surfaces. All regression lines are parallel indicating same EDT as RTs in all ranges.

b) Geometrically reflecting surfaces (incident = reflection angle) do not exist, neither totally diffusely reflecting. So, the well known concept of 'diffusivity coefficients' (DG) was utilized [7,8]: first, due to Lambert's law, a reflection vector with an angle probability density proportional to the cos(incident angle) is computed by drawing a random number; if the wall is not perfectly diffusely scattering, the final reflection vector is interpolated linearly between the specular reflection vector and the scattered one by a linear interpolation according the (0< DG < 1).

It should be kept in mind that with 'diffusivity degree' is meant not only the effect by the 'roughness' or 'raggedness' of the walls, chairs, stairs etc. (often denoted as 'scattering coefficient') but also by the finite surface dimensions or by the edge-effect (leading to diffraction). In this sense, the DGs even for smooth walls are seldom lower than 5 or even 10% [7, 9], they are even (due to Fresnel's theory) increasing with running distance of the rays (and with frequency). Thus it can be found that in most rooms, at middle frequencies, from the 3.-6 order of reflection, almost all reflections are mainly diffuse [10].

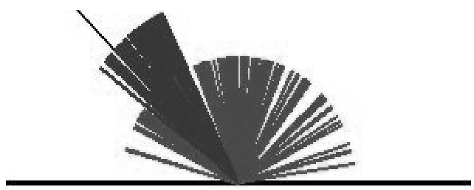

Fig.5: Scattered rays: left the single (long) specularly reflected ray, around that, for DG=25%, the scattered ray vectors (enlarged), the short rays are the cosine-type scattered rays of the first computation step.

DISCUSSION OF NEGLECTS

Concerning the computed room acoustical parameters as the Deutlichkeit, the systematic error due to the 2D- instead of the 3D- propagation will be low, generally depending on the proportions of an assumed real room, i.e. the height to length proportion and may hardly be estimated in advance. The especially high audience absorption at grazing incidence is neglected. This influences the Deutlichkeit at higher distances in praxis. Also the air absorption is neglected. But, as came out from earlier investigations [7], the angle dependency of absorption may often be neglected in the context of statistical room acoustics. Other artefacts as the neglecting of diffraction and other wave phenomena may be ignored here in convex rooms.

SPECIAL ASSUMPTIONS AND PARAMETERS

This investigation, as presented here in the first step, is restricted to only one type of auditorium typical for large concert halls: 40m long and 12m high starting with a 'shoe-box' (one may imagine a width of 25m hence a ground surface of 1000m² occupied by 2/3 by audience, hence about 1000 seats) and a reverberation time of 2s. The suitable absorption degrees AG, source and receiver positions were mentioned in figure 1. (One might object: too restricted, but only the prolongation factor for the RTs are to be considered.) **The main parameter is the roof inclination angle α** which varies from 0° (shoe box) to 45° in steps of 15° (see fig.2 such that the height in the middle varies between 12 and 22m, at the side from 12 to 2m and the cross section S and about the circumference U is constant, hence also the mean free path length (14.5…15m). Since the AGs are also constant, RT_{Eyring} is almost constant with 2.01..2.02s (RT_{Sabine}= ca. 2.3s). To ensure echograms longer than for 45dB-decay, the respective tracing distance for all rays is 532m, which means on average 36 reflections. To ensure a sufficient spatial resolution, 2100 ….2600 ($\alpha = 45°$) rays are emitted (the computation time with MATLAB on a 1.8GHz PC was about 90s). **The important second parameter is the diffusivity degree DG of all surfaces which varies according the series 0, 0.05, 0.1, 0.3 and 1.**

RESULTS

The main result sums up fig.6. It shows clearly as a significant effect: the RTs decrease with the roof angle, by a factor of 1.5 in the (theoretical) case of specularly reflecting walls, but even for a DG of 5…10% - realistic for large smooth walls, the decreasing factor is still 1.5. The effect vanishes for DG>0.3. Table 1 documents the numeric values, also for the other room acoustical parameters investigated.

Tab. 1 Relative prolongation factors (related to RT=2s according to Eyring) due to roof inclination angle alpha and diffusivity degrees for the EDT, the RT directly computed by linear regression from the 8 echograms, the RT by backwards integration and rest reverberation correction and the Deutlichkeit (average over the 20 places on the ground.)

Alpha Roof	Diff.degr.	rel. EDT	RTdir	RT60bic	Deutl
0	0.00	0.949	1.432	1.436	0.386
0	0.05	0.858	1.348	1.346	0.426
0	0.10	0.846	1.275	1.299	0.448
0	0.30	0.864	0.728	0.814	0.514
0	1.00	0.962	0.912	0.915	0.444
15	0.00	1.083	1.367	1.370	0.468
15	0.05	1.161	1.337	1.370	0.495
15	0.10	1.214	1.196	1.161	0.510
15	0.30	1.266	0.789	0.820	0.589
15	1.00	0.929	0.908	0.901	0.475
30	0.00	0.810	1.375	1.393	0.472
30	0.05	0.869	1.180	1.191	0.486
30	0.10	0.924	1.084	1.103	0.519
30	0.30	1.288	0.869	0.887	0.556
30	1.00	0.998	0.922	0.927	0.508
45	0.00	0.669	0.954	1.013	0.548
45	0.05	0.666	0.872	0.862	0.549
45	0.10	0.621	0.857	0.845	0.558
45	0.30	0.669	0.843	0.833	0.588
45	1.00	0.990	0.895	0.896	0.539

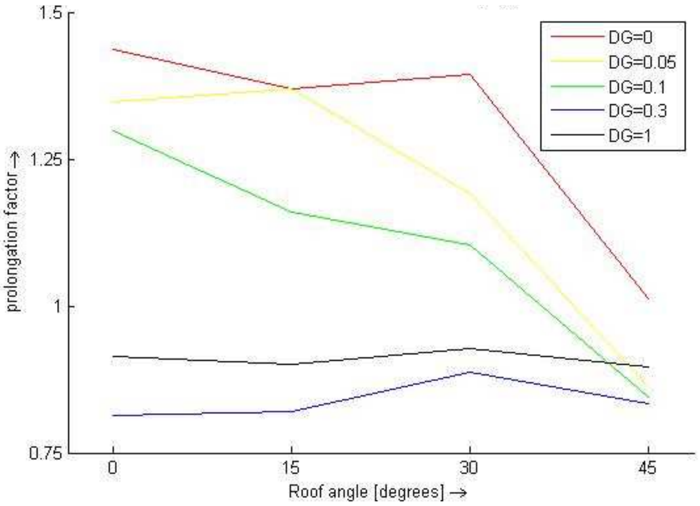

Fig. 6 Relative prolongation factors in relation to the Eyring reverberation time T_{Eyring} = 2s as a function of the roof inclination angle, the diffusivity degrees DG as a parameter. The prolongation factors relative to the more common Sabine RT=2.3s may be estimated from these table.

Fig.7 shows: The EDTs are for the 'shoe-box' near the Eyring RTs, increase for middle angles and are for the 'tent' with $\alpha = 45°$ much lower (the EDTs are highly sensitive on the geometrical situation, so this should not be generalized).

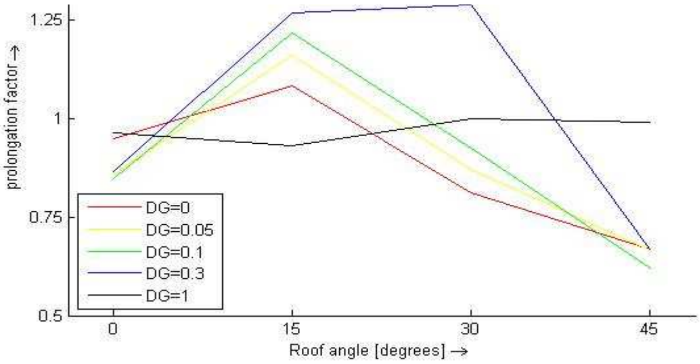

Fig. 7 The EDTs in relation to the Eyring reverberation time as a function of the roof inclination angle (else as fig. 7)

Fig. 8 shows: The Deutlichkeit is clearly increasing with the roof inclination (compare fig.2.). This confirms: in a 'tent' shaped hall early reflections become stronger (as the source is in a corner). The 'tent' shape is clearly favourable.

(Why always the case DG=0.3 plays an extra role is unclear.)

Finally, table 2 shows, as an example for the 'tent' with $\alpha = 45°$, some single results.

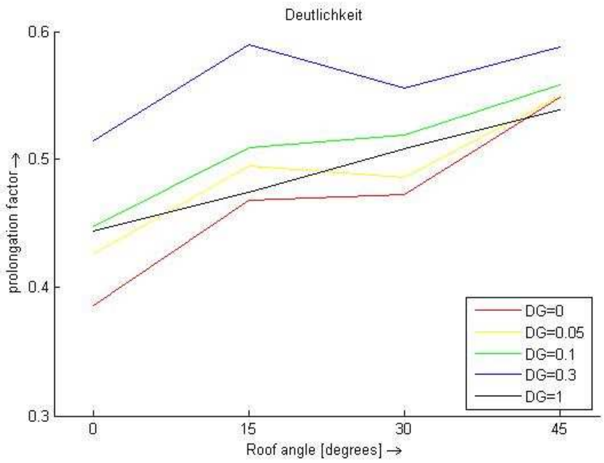

Fig. 8 The Deutlichkeit values as a function of the roof inclination angle (else as fig. 7)

Tab. 2. Special values of the 8 receivers with echograms in the tent shaped room with $\alpha = 45°$ and DG=0; here also the later RT for the decay of -20-35dB is displayed; this RT is largest in the middle of the room (position 3 and 4); the EDT is lowest (the decay is steepest) at the positions 1 and 8, i.e. near the corners – where also the Deutlichkeit is typically highest (positions see fig.1);.

no.	Pos x	y	EDT	T60direkt	T20-35	T60ric
1	5.000	1.000	1.02	1.91	1.85	2.06
2	9.000	1.000	1.24	1.96	2.09	2.20
3	15.000	1.000	1.36	2.09	2.59	2.31
4	19.000	1.000	1.40	2.04	2.33	2.20
5	25.000	1.000	1.49	1.96	1.98	2.06
6	29.000	1.000	1.79	1.93	1.79	1.98
7	35.000	1.000	1.33	1.83	1.47	1.81
8	39.000	1.000	1.16	1.67	1.34	1.73
average values			1.35	1.92	1.93	2.04

DISCUSSION ON THE CAUSE OF THE EFFECT

Of course, the non-diffuse sound field in the halls is the main cause of the deviations of the RTs from the Eyring values, especially for geometric reflections. In this case, the mean free path lengths (mfp) in the 'shoe-box' (statistically evaluated) turn out to be much longer as in the diffuse field: 17.2 instead of 14.5m. This would lead to an RT=2.4s. The hitting frequencies of the walls – a measure for diffusivity -, however, remain astonishingly constant, correspond almost perfectly to the surface (in 2D: lengths) proportions. So the RT enhancement effect is clearly due to the longitudinal flutter-echoes in the shoe-box (see fig. 3). In the 45°-tent, even specularly reflecting, this effect vanishes (the mean free path lengths remain at 15.4m). The cause for longer RTs is the non-mixing sound field: the longitudinal echoes 'survive'. The level decay is not linear but hanging'. This can also clearly be seen at the fact that only the RTs are higher in the 'shoe-box', not the EDTs (compare figures 6 and 7). With decreasing DG this effect vanishes also for the shoe-box. The effect that in the 'tent' the RT is lower than in the 'shoe-box' (even with low DGs) seems to be mainly due to the smaller real free path lengths. In the 'tent' the sound rays are more regularly re-directed towards the absorbing ground, the sound field is 'more mixing'.

CONCLUSIONS

It can be stated that the reverberation times in an auditorium (a large room with the sound absorption mainly by the audience on the ground surface, α_{ground}=60%, else 5%, RT_{Eyring}=2s, RT_{Sabine}=2.3s) considerably depend on the shape of the ceiling, vary in the order of +-20% for realistic diffusivity degrees of DG=0.1, plus 12% compared to the Sabine value for a flat ceiling ('shoe box') and minus 25% for a 'tent'-shaped hall with 45° roof inclination. For very 'ragged' ('diffusely scattering') walls and ceilings the effect vanishes; the reverberation time is then about 20% lower than according Sabine, or 10% lower than according Eyring. The EDT is much lower than the RT, by 15% for the 'shoe box', by 33% for the 'tent' (for DG=0.1), correspondingly, the 'Deutlichkeit' (already 15% higher than expected due to an exponential reverberation) is again about 25% higher for the 'tent'. The 'tent'-shape is clearly more favourable.

OUTLOOK

Many questions remain open: What is the correlation between ceiling profile and Deutlichkeit and level decrease with distance? What is the optimum shape of the ceiling for a wanted parameter distribution? Is an elliptical, parabolic or similar shape best? (A strict ellipse would concentrate reflections in the other focus, a parable on a rising surface, but both is not perfect.) What is an 'optimal parameter distribution' and an optimal mix and weighting of parameters? Can a self-optimizing procedure for the room ceiling shape be found? This is certainly the most challenging question. As the number of 'degrees of freedom' in a concert hall is extremely high the solution of this typical inverse problem remains a long-term goal.

References

1. Barron, M. & Lee, L.-J.; Energy relations in concert auditoriums, 1. JASA, 84 (1988), p. 618-628
2. Gade, C. Anders; The Influence of architectural Design on the Acoustics of Concert Halls; Applied Acoustics 31(1990), p.207-214
3. Lehmann, P.; Über die Ermittlung raumakustischer Kriterien und deren Zusammenhang mit subjektiven Beurteilungen; Thesis, TU Berlin (1976)
4. Article on the 'Elbphilharmonie' in the daily newspaper `Hamburger Abendblatt'; www.abendblatt.de, 7.4.2007; Architects : Herzog & deMeuron;
5. Beranek.; Leo; Concert and Opera Halls – how they sound; Am. Inst. of Physics for the Acoustical Society of America, 1996
6. interview with the acoustician Y. Toyota (Nagata Acoustics, Japan/USA) in the 'Abendblatt' 26.4.2007 titled ' Musik in der Mitte'
7. Stephenson, U.; Eine Schallteilchen-Computer-Simulation zur Berechnung der für die Hörsamkeit in Konzertsälen maßgebenden Parameter. *ACUSTICA 59 (1985), p. 1-20,*
8. Stephenson, U.: The Sound Particle Simulation Technique - An Efficient Prediction Method for Room Acoustical Parameters of Concert Halls. Reprint of the Audio Engineering Society, New York (1989), 86th AES Convention, Hamburg (1989).
9. Mommertz, E.; Vorländer, M.; in Applied Acoustics 60 (2000), p. 187-199
10. Kuttruff, H.; A Simple Iteration Scheme for the Computation of Decay Constants in Enclosures with Diffusely Reflecting Bondaries; J. Acoust.Soc. Am. 98 (1), 1995, 288-293