DIFFUSION IN CONCERT HALLS ANALYSED AS A FUNCTION OF TIME DURING THE DECAY PROCESS

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1 INTRODUCTION

Diffusion and scattering continue to be hot topics in room acoustics and in particular in auditorium acoustics. It is being heavily debated **how** scattering due to surface roughness and room geometry relates to the level of diffusivity in a room. We suggest the Dynamic Diffusion Curve (DDC) as a tool for evaluation of the level of diffusion in an impulse response. The idea is that a high degree of diffusion is connected with a low directional trend; theoretically an ideal diffuse sound field has equal probability of any direction of propagation and thus the intensity should be low, whereas a one-dimensional propagating sound wave has a high intensity level (equal to the sound pressure level). DDC is derived from the difference between the decay curve derived from the backwards integrated squared impulse response measured or simulated with an omni-directional microphone and the decay curve of the backwards integrated intensity impulse response, which can be measured or simulated by a combination of three intensity probes or three figure-of-eight microphones (x, y and z directions). So, DDC is a measure of the amount of non-directional energy as a function of the time during the decay process.

2 BACKGROUND

It is recognized that diffusivity in room acoustics is important. The well known formula $T_{60} = 0.16*V/A$, by Wallace Clement Sabine assumes diffuse sound field. Measures and tools have been developed to quantify the degree of diffusivity; in 1953 Thiele suggested a measure called *Directional diffusion* that compare total energy to intensity [2]. *Directional diffusion* ranges from 100% in a completely diffuse sound field to 0% in free field, which intuitively makes a lot of sense. There are however problems with *Directional diffusion*; it is a steady state value that can exhibit high levels while there are still echoes present in an impulse response.

To visualize diffusivity graphically, hedgehogs [1, page 96] showing directions of received energy in a receiver position has been suggested. Aligning these hedgehogs for discrete time intervals e.g. for every 10 or 50 milliseconds at a time axis will form a graphical squirrel tail which shows incoming energy at different incident direction and time intervals. Such a method present complicated data which is difficult to extract information from. This is a classic problem, to little data tells little whereas the full set of data makes it difficult to extract meaningful information.

3 STEADY STATE DIFFUSION

It is possible to measure energy as well as intensity in the three axis directions (X,Y and Z) using a sound field microphone and it is straight forward to simulate energy as well as intensity in room acoustics simulation software. Thus we define steady state diffusivity, as a measure for diffusion in dB[1]:

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[1] Besides *Directional Diffusion* in %, Thiele suggested a Clarity parameter in %, and just as for the Clarity parameter, today we may prefer to present a measure for diffusivity in dB.

$$D_{ss} = 10 \times \log_{10} E(t) - 10 \times \log_{10} \sqrt{I_{8x}^2 + I_{8y}^2 + I_{8z}^2} \quad (dB) \tag{1}$$

For free field conditions D_{ss} equals it minimum of zero decibels and for point responses with a high degree of diffusivity it can be more than 10 dB (one should not expect infinitely many dB corresponding to $I_{8x}^2 + I_{8y}^2 + I_{8z}^2$=0).

3.1 Let f be a function of....

If accepting the above definition for diffusivity then it is clear that diffusivity and intensity are closely related - measures that increase intensity will decrease diffusivity. Many aspects will influence the level of diffusivity in a room:

1. The geometry.
2. Source position versus receiver position.
3. Absorption.
4. Scattering.

1. The shape of rooms has a direct influence on where sound is reflected and thereby on intensity.
2. If the receiver is close to the source and if there is visible sight between source and receiver this will result in high intensity and less diffusivity.
3. Uneven distribution of absorption results in increased level of intensity compared to total energy. Because of absorption, only a reduced amount of the incoming sound is reflected, this can result in an increase of intensity and a decrease of D_{ss} if absorption is not evenly distributed - there is more sound moving towards an absorbing area than being reflected from it.
4. Scattering is often assumed that lead to a more diffuse sound field. While it may be true that some rooms get a more a diffuse sound field by adding scattering to its surfaces, it is not given that this is always the case.

4 DYNAMIC DIFFUSION CURVES

Although D_{ss} may give an good indication whether an impulse response contains little or much directional energy, a receiver position which has a high degree of steady state diffusivity can still include pronounced echoes as reflections arriving at different time in the impulse response can add to intensity with different directional signs and cancel out in the D_{ss} measure (e.g. a reflection coming from the plus X direction and another from the minus X direction at different times). To be able to access the dynamic behavior of the diffusion we define the Dynamic Diffusion Curve; DDC:

$$\begin{aligned} DDC(n) = {} & 10 \times \log_{10} \int_{t=\infty}^{t=t_n} E(t)\, dt \\ & - 10 \times \log_{10} \sqrt{\left(\int_{t=\infty}^{t=t_n} I(t)_{8x}\, dt\right)^2 + \left(\int_{t=\infty}^{t=t_n} I(t)_{8y}\, dt\right)^2 + \left(\int_{t=\infty}^{t=t_n} I(t)_{8z}\, dt\right)^2} \end{aligned} \tag{2}$$

DDC is a backwards integrated curve having its function values defined for each time step according to formula (2). The dynamic diffusion curve has a lot in common with the Schröder curve from which reverberation parameters such as EDT and T_{30} are derived. The Schröder curve is the backwards integrated[2] squared (filtered) impulse response and its initial value has a special meaning, this is the sound pressure level at the receiver position. DDC like the Schröder curve, is

[2] Using backwards integration corresponds to using terminated stationary noise as excitation signal rather than using an impulse and yields more reproducible results.

also a backwards integrated curve, but subtracted the intensity[3]. The initial value of the DDC is not unknown to us; indeed this is the Steady state diffusion, D_{ss}. DCC represent the (vertical) distance between the backwards integrated energy curve and the backwards integrate intensity curve given in dB. Unlike the energy curve, the intensity curve need not be monotonic.

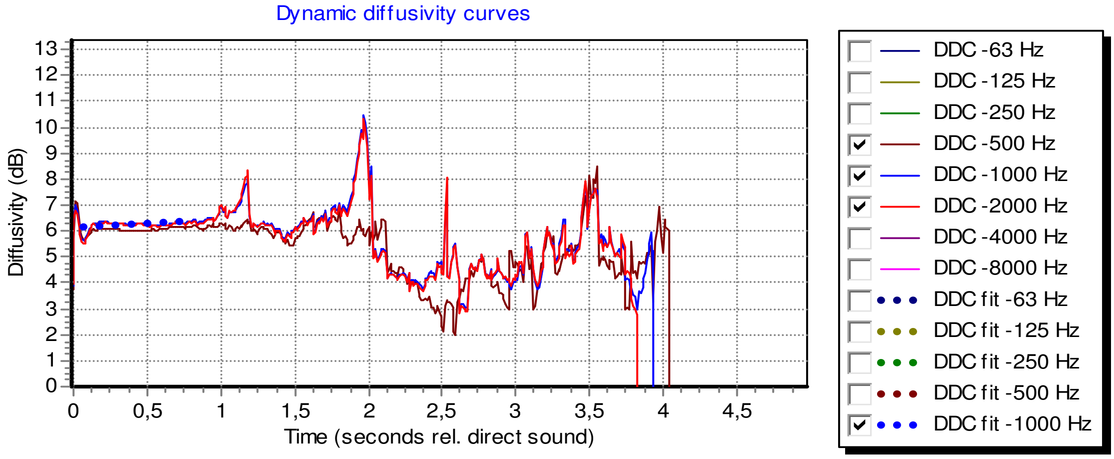

Figure 1. *A simulated DDC for a room with high scattering coefficients of 0.5 and uneven distribution of absorption (10% on walls and 80% on floor and ceiling).The abscissa is given in time (seconds). Fitted line (blue) shows the best fit for the DDC between -5 and – 35 dB at 1000 Hz.*

The example given in figure 1 is the DDC for a room simulated in ODEON version 11β [3] with the dimensions (w, l, h) = (12, 16, 14) metres. The floor and ceiling are 80% absorbing and all other surfaces are 10% absorbing. Scattering coefficients are set to 50% on all surfaces and additional scattering due to diffraction is taking into account in the simulation using ODEON's scattering method; *Reflection Based Scattering* [4]. The ordinate in the graph is *Diffusivity* in dB and the abscissa is time given in seconds.

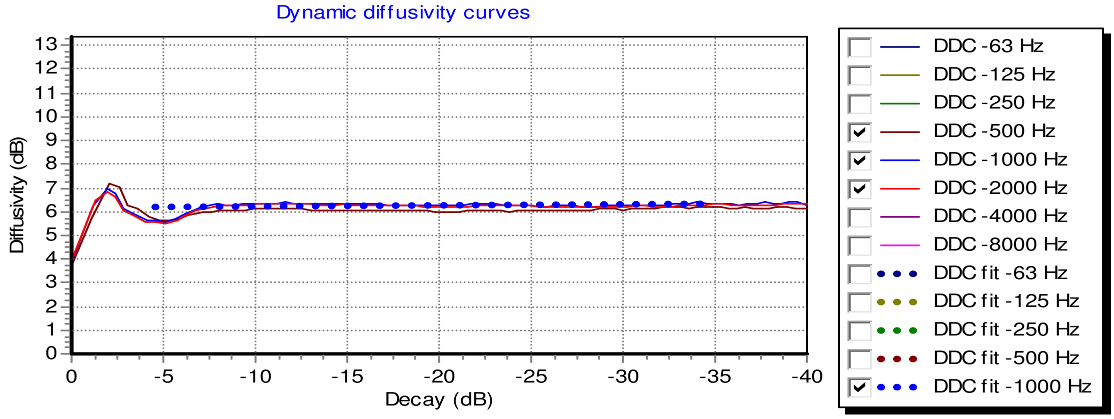

Figure 2. *DDC for a room with high scattering coefficients of 0.5 and uneven distribution of absorption (10% on walls anda 80% on ceiling). The abscissa is given in Decay (dB). Fitted line (blue) shows the best fit for the DDC between -5 and – 35 dB at 1000 Hz.*

The graph in figure 1 can be deceiving; it does not give any indication on energy level at which the diffusion takes place, indeed the impulse response yielding that DDC has a reverberation time of 1.54 seconds at 1000 Hz so most of the apparently interesting variations takes place at very low levels (and may be due to artefacts of the simulation, e.g. a limited ray number or in measurements due to a poor signal to noise ratio). Therefore it may be interesting to convert the abscissa into dB

[3]Note that intensity needs to be summed individually (formula 2) for each of the three axis directions before being squared – because it is intensity which has a directional sign.

decay, each time value being translated into its corresponding dB decay using the Schröder decay curve for the impulse response. For some impulse responses with an almost exponential decay there will be close to linear connection between the two, for non-exponential decays however, the transformation of the abscissa scale will be far from linear. In figure 2 the same DDC is depicted with its abscissa in *dB decay*. The DDC with abscissa in *dB decay* displays a flat **plateau** when limiting the view to the first most interesting 40 dB. The initial part where there are changes in the slope in the Schröder curve, displays a soft **peak** where it would display heavy fluctuations in the graph with abscissa in time (figure 1). In the following we will use an abscissa in dB decay for the DDC and we will refer to the **peak** level and to the **plateau** level which we calculate as the mid-point of the regression line of the DDC between -5 and -35 dB (the - 20 dB point).

5 DDC FOR ROOMS WITH DIFFERENT DISTRIBUTION OF ABSORPTION AND LEVEL OF SCATTERING

Using the example above we will investigate further the effect of scattering and distribution of absorption. The impulse response is simulated with **low** and **high** scattering (5% and 50% scattering on all surfaces respectively) and ***even*** distribution of absorption (10% absorption on all surfaces, ***unevenC*** distribution of absorption (80% on ceiling and 10% on all other surfaces) and ***unevenCF*** (80% on floor and ceiling and 10% on all other surfaces). This gives us 6 cases; ***even+low***, ***even+high***, ***unevenC+low, unevenC+high, unevenCF+low*** and ***unevenCF+high*** (the case in figure 1 and 2). If investigating the curves using an abscissa in time the curves are quite different (the cases have different reverberation times), but when using the abscissa in dB decay as in figure 2 the graphs are quite similar except for their levels of diffusion. In the table below is listed; D_{ss}, peak level and plateau level.

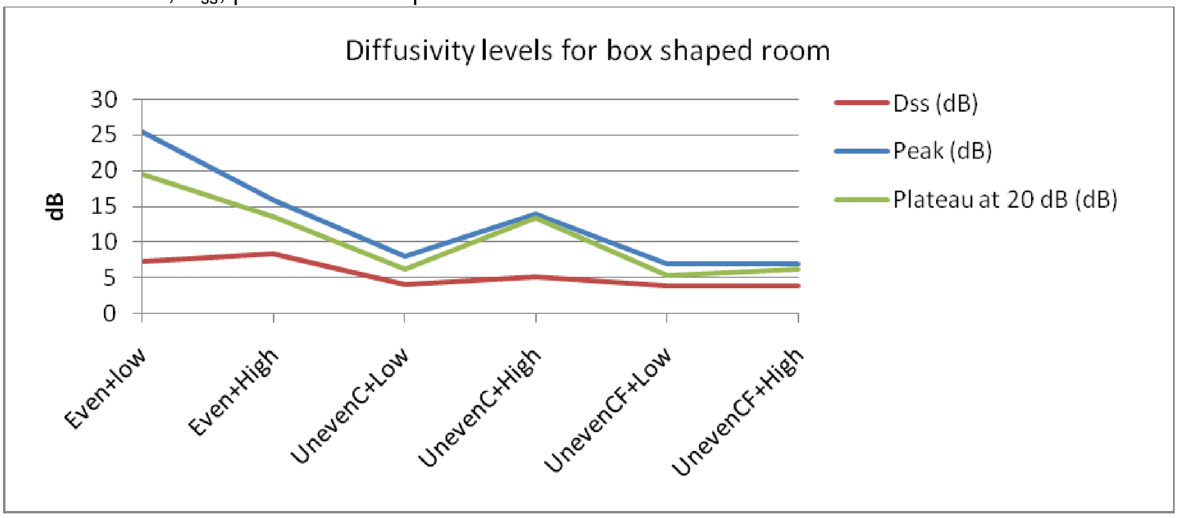

Figure 3. *Diffusivity levels extracted from DDC at 1000 Hz. Even/Uneven refer to the distribution of absorption (UnevenC with absorption on ceiling and UnevenCF with absorption on ceiling and floor) – low and high refer to the amount of scattering.*

In figure 3 it can be seen that the peak and plateau values are closely related whereas D_{ss} does not respond as strongly to changes in room conditions (absorption and scattering). This may be because D_{ss} is influenced by the direct sound. The results indicates that uneven distribution of absorption does indeed decrease diffusion as one may expect, on the other hand, there doesn't seem to be a strong trend that scattering will increase diffusivity as often assumed.

6 STUDYING A FLUTTER ECHO USING DDC

The example below shows the Queens Hall, the Royal Library in Copenhagen [5]. In the project phase a flutter echo was predicted between side reflectors for a source position at the front of the stage. Even though the position is at the first part of the stage it is critical. The hall is occasionally being used by the rhythmic conservatory, therefore the position can be occupied by percussionists.

We will study DCC where there is little scattering on the reflector panels and where scattering has been added to the panels.

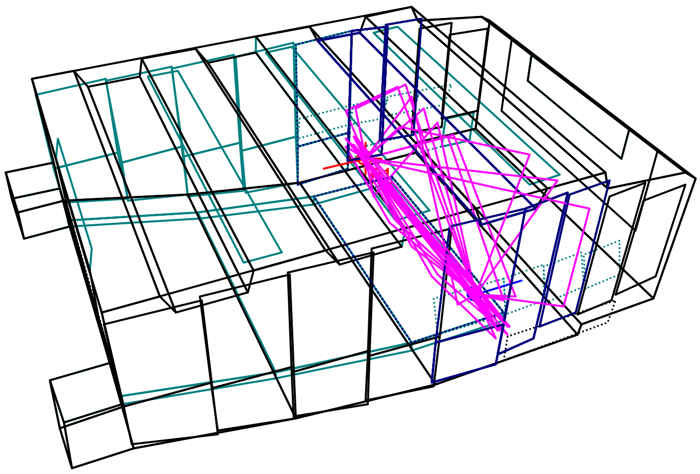

Figure 4. *ODEON model of* the Queens Hall, the Royal Library, Copenhagen*. Reflections repeats continuously between four reflector panels that is tilted slightly towards each other – creating a flutter echo when reflector panels are left without any scattering surface finish.*

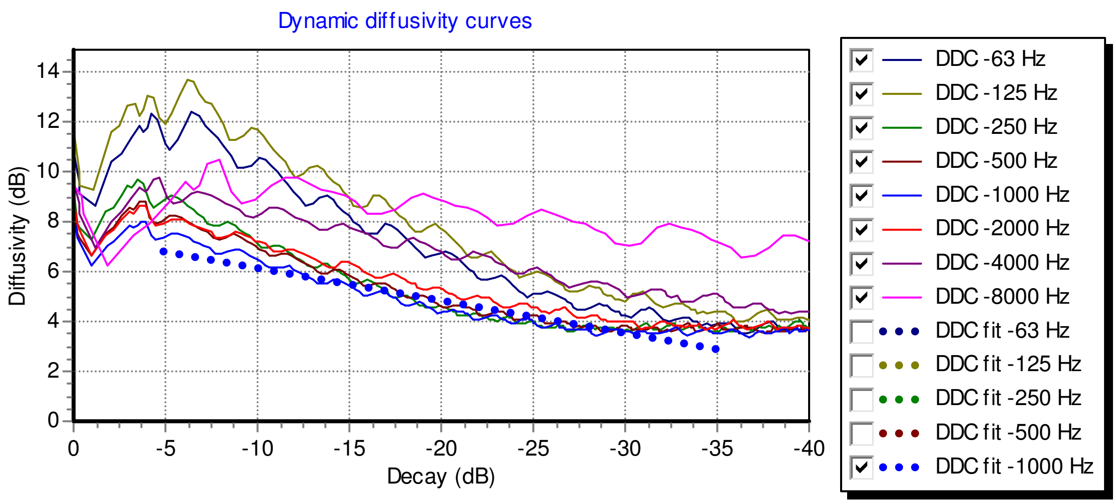

Figure 5. *DCC in model of the Black Diamond when side reflectors are without scattering surface finish. DDC has pronounced ripples in the range between -5 and -35 dB and the fitted slope is 0.13 dB/dB decay (drops 3.9 dB over 30 dB).* D_{ss}*= 8.3 dB. Initial peak= 8.0 dB and plateau level is 4.7 dB.*

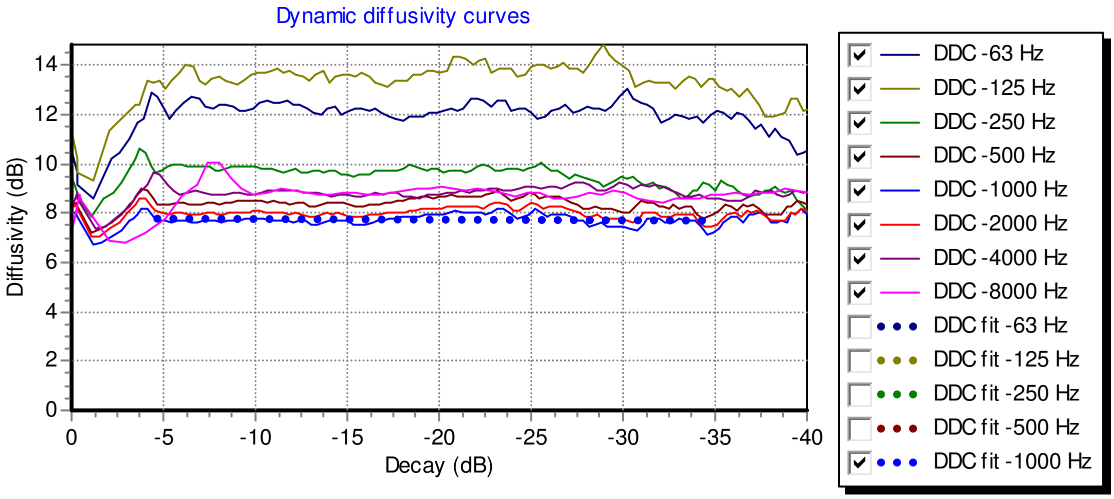

Figure 6. *DDC at 1000 Hz in the Black Diamond when scattering surface finish has been added to the side reflectors. DDC appears to be quite smooth in the range between -5 and -35 dB and the fitted slope is 0.001 dB/dB decay.* D_{ss}*= 8.2 Initial peak= 8.2 dB and the Plateau level is 7.7 dB.*

The changed reflector panels with scattering surface finish in figure 6 does indeed diminish the flutter echo, in the real hall as it was built and in the simulated model (when listening to it by means of auralisation). As can be seen D_{ss} and the peak level have only minor differences with and without diffusing reflector panel – however it is evident that the level of diffusion decreases as sound decays when the reflector panels does not diffuse reflections – this and the ripples seems to be indicators of the flutter echo (figure 5).

7 STUDYING ECHO IN FOCUSING POINT OF AN ELLIPTICAL ROOM

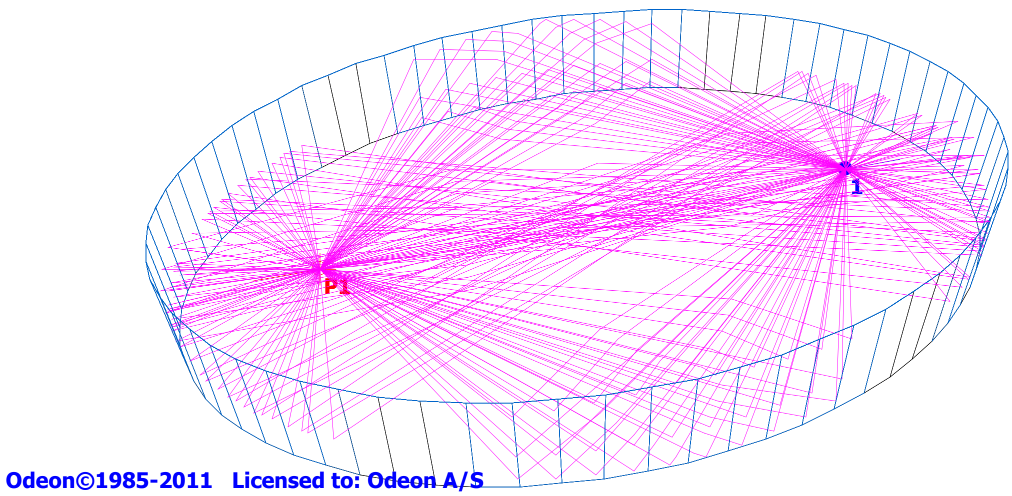

Figure 7. *Elliptical room with dimensions (l x b x h) = (30, 20, 4) metres. All surfaces are smooth with just 1% scattering. Ceiling and floor are 80% absorbing and walls consists of concrete. Direct sound path , first and second order reflections are displayed.*

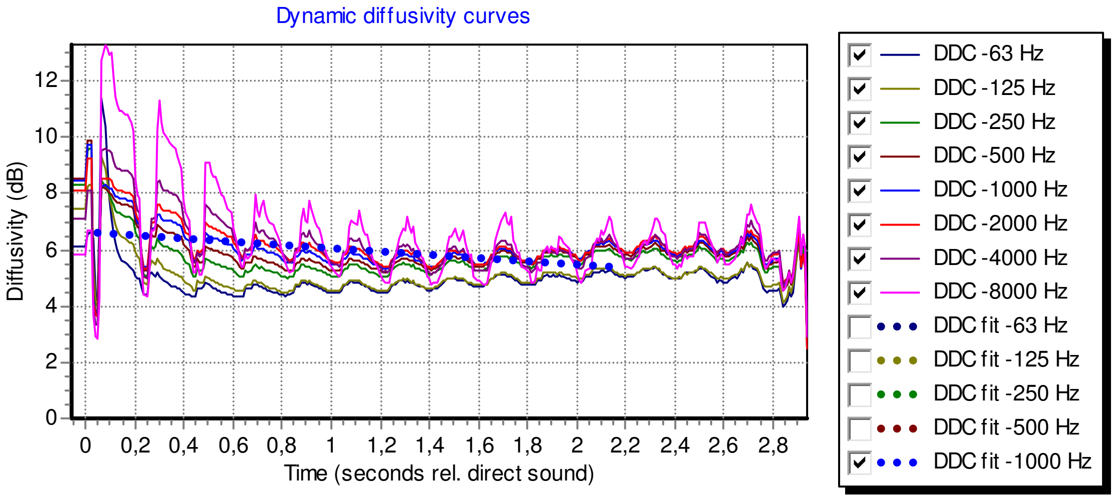

Figure 8. *DDC for impulse response in the focus point of the elliptical room displays strong ripples. D_{ss}=8.5, Initial peak = 9.7 dB, plateau level= 6.7 dB. Note that abscissa is in time (seconds), giving a clearer view of the echo (frequency bands are time aligned and time between strong reflections is equidistant.*

The impulse response related to the DDC in figure 8 does indeed contain strong repeated echoes. The average plateau level of the DCC is not particular low, clearly this is not the indicator of the echo. The height between top and bottom of the ripples on the other hand marks strong changes to the diffusivity caused by reflections making immediate change to the DDC. To use the DDC for investigation of echo problems, a measure for the height of the ripples may be useful.

8 EXAMPLES OF DIFFUSIVITY LEVELS IN CONCERT HALLS

Preliminary investigations has been carried out on models of 12 concert halls, 11 European concert halls [7] and the Boston Symphony. In models of all halls; the source was located on the front of the stage while the receiver positions was located at a central position "parterre". Diffusivity levels extracted from the calculated DDC are displayed below in figure 9. The DDC's calculated for the 12 halls have features common to the one shown in figure 2. An almost general trend is that the peak value is slightly higher that the plateau level - the steady state diffusion D_{ss} is with few exceptions lower than the peak as well as the plateau level and plateaus are almost flat and without any significant ripples. The predicted levels varies considerably; for example the plateau level varies from 5.6 dB in Royal festival hall to 11.2 dB in Gasteig. These examples indicates significant differences between halls. At this point it has not been examined how big differences can be observed within one hall, but indeed the diffusivity parameters should be expected to show large variations with positions and this might yield valuable information. Which values are optimal for a concert halls is unknown at this point - it is not given that a very high (nor a low) level is preferable.

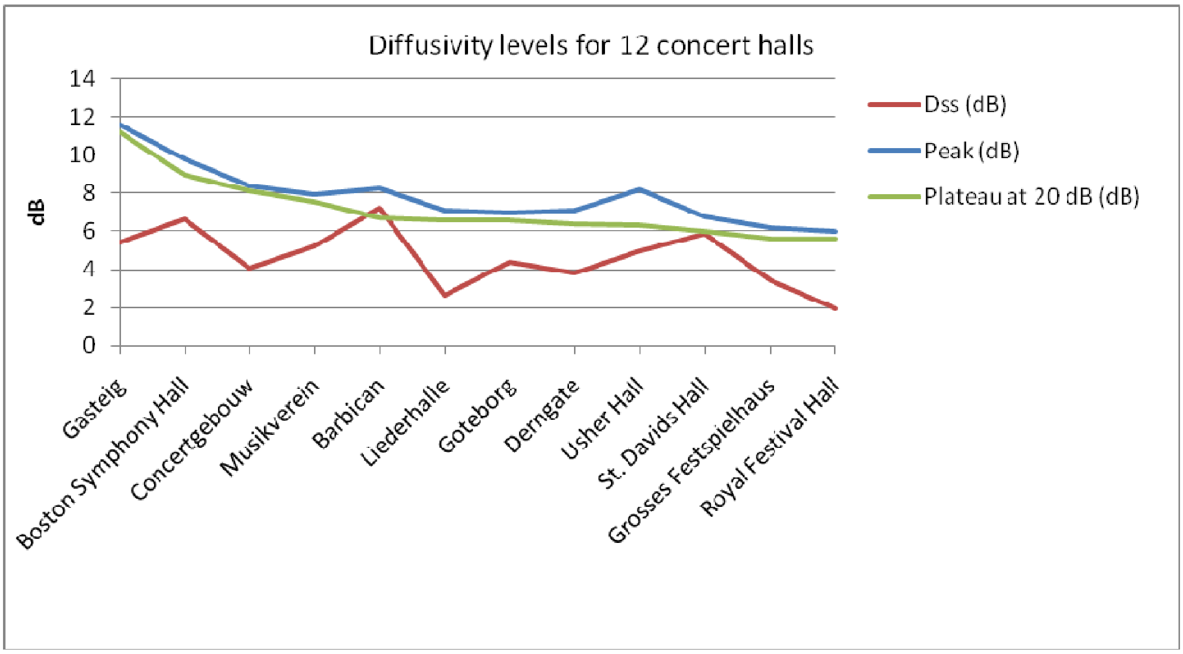

Figure 9. *Diffusion levels at 1000 Hz in 12 concert halls, for impulse responses where source is on stage and the receiver position parterre.*

9 CONCLUSION

The Dynamic Diffusion Curve; DDC has been suggested as a tool for investigation of diffusivity in decays of rooms such as auditoria. Preliminary investigations suggest impulse responses without echoes have a characteristic flat plateau on the DDC that can characterize the amount of diffusion present in the decay. The plateau level is higher than D_{ss} (steady state diffusivity). Study of the fluctuations in the DDC may be used for detection and investigation of echo problems including flutter echoes. Variations of DDC and derived parameters with respect to source and receiver positions should be investigated further on simulated as well as measured impulse responses. Not the least, for the DDC to be a useful design tool it should be investigated to which degree parameters derived from the DDC is audible e.g. in terms of just noticeable differences (JND's) and which levels are preferable.

10 REFERENCES

1. Willi Furrer, Room and Building Acoustics and Noise Abatement, (1956,1961).
2. R. Thiele, “Richtungsverteilung und Zeitfolge der Schallrückwurfe in Räumen,” Acustica 3, 291–302 (1953).
3. ODEON Room Acoustics Software, www.odeon.dk
4. Claus Lynge Christensen, Jens Holger Rindel, A new scattering method that combines roughness and diffraction effects. Forum Acousticum 2005. Budapest, Hungary.
5. Tutorial at the Odeon home page: Detecting flutter echo http://www.odeon.dk/detecting-flutter-echo
6. ISO 3382-2, Acoustics - Measurement of room acoustic parameters - Part 2: Reverberation time in ordinary rooms.
7. Gade, A. C., Acoustical survey of 11 European concert halls, Denmark, 1989.