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LOW FREQUENCY LIMITS OF REFLECTOR ARRAYS

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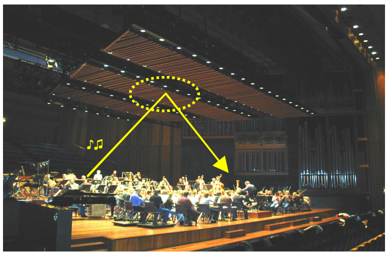
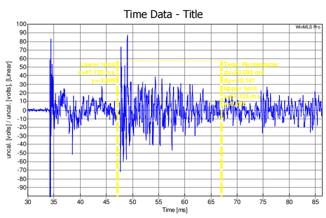
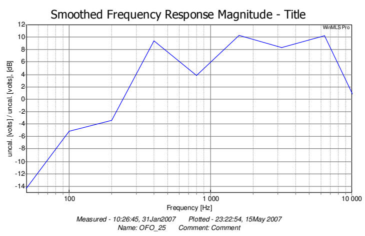
ABSTRACT

Reflector arrays have two independent low frequency limits. One is due to attenuation of wavelengths large compared to the size of the elements in the array, as established by Leonard, Delsasso, Knudsen (1964). The other is due to attenuation from diffraction, as established by Rindel (1991). In the latter case, the whole array is small compared to the Fresnel-Zone needed to transmit low frequency sound. These two attenuation effects may be described as two serial high pass filters in the transmission path via the reflector array. The arrays used as orchestra canopies are often so large that there is no practical low frequency attenuation due to array size. However, the size of the elements may be critical, since smaller elements improve the high frequency response while low frequency response suffer and vice versa. There are also many practical and architectural concerns when designing a reflector array, making the size and shape of elements an important acoustical issue. Some shapes are hard to decide whether they are large or small compared to the wavelength. This author has suggested the panel edge density as a geometrical predictor of the low frequency limit of an array. Theory and measurement results are presented.







INTRODUCTION

In concert halls, reflector arrays are often used to add sound reflections of proper delay and strength to listeners on stage or in the auditorium. A famous early reflector array was the canopy from late 1950's in the Tanglewood Shed. It extended from above stage and into the audience to control the initial time delay gap – IDTG. From being a means to provide short IDTG in the stalls in wide and/or fan-shaped halls, canopies and reflector arrays in particular have since the 80's tended to be more motivated by stage acoustics. Among the advantages of forming a canopy from an array of elements, is the large freedom in design and the inherent sound transparency often is required for the early-to-late sound balance [1]. This paper deals with the low frequency limits of plane panel arrays. Plane panel arrays are studied by this author because of theoretical and practical simplicity, and because arrays in many concert halls are variants of, or modifications of basically plane arrays.

BASIC THEORY AND PREVIOUS WORK

Reflector arrays have two independent low frequency limits [2]. One is due to attenuation of wavelengths large compared to the size of the elements in the array, as established by Leonard, Delsasso, Knudsen (1964) [3]. The other is due to attenuation from diffraction, as established by Rindel (1991) [4]. These two attenuation effects may be described by two serial high pass filters in the transmission path via the reflector array (Figure 1).

We shall refer to the two filters[i] as 1) the Reflection Filter and 2) the Fresnel-Kirchhoff filter[ii] (hereafter the FK-filter), respectively. The two filters combine in series as follows: The Reflection Filter describes the ability of a surface to reflect sound pressure, while the FK-filter integrates the reflected pressure components at the receiver (Figure 1).

The Reflection Filter
In the pass band of the ideal Reflection Filter, the frequency response is equal to unity. Attenuation occurs below the cut off frequency due to insufficient obstacle size allowing waves to be diffracted around the reflector.

The FK-filter
The pass band level and the cut off frequency of the FK-filter are both expressed by Rindel's formulas [4][5]. The pass band value is $20 \cdot \log(\mu)$ where the panel density $\mu = S_{panel}/S_{total}$ is the ratio of the panel area to the total array area. Attenuation below the cut off frequency is due to the array becoming small compared to the cross section needed to transmit low frequency sound un-attenuated. For rectangular arrays as well as single rectangular elements, the cut off frequencies can be calculated from length, width, distance, and incidence angle by Rindel's F_1 and F_2.
For conceptual purpose we introduce the Critical Zone (CZ), which is similar to the first Fresnel-Zone (FZ), only smaller in cross section, so that $S_{FZ} = \pi \cdot S_{CZ}$. An ideal reflector just filling the CZ reflects sound with the same magnitude as a reflector of infinite size. We then may define the apparent panel density $\mu' = S_p'/S_{CZ}$, where S_p' is the panel area inside the CZ. The level expression $20 \cdot \log(\mu')$ is valid also below the cut off frequency of the FK-filter.
The high limit of the useful frequency range corresponds to a CZ so small that it can be contained by a reflector element (Figure 5). Above the limit, there are strong fluctuations in reflection levels, as the CZ falls on or between elements as source-receiver positions changes. For rectangular elements, the limit is equal to the highest of F_1 and F_2.

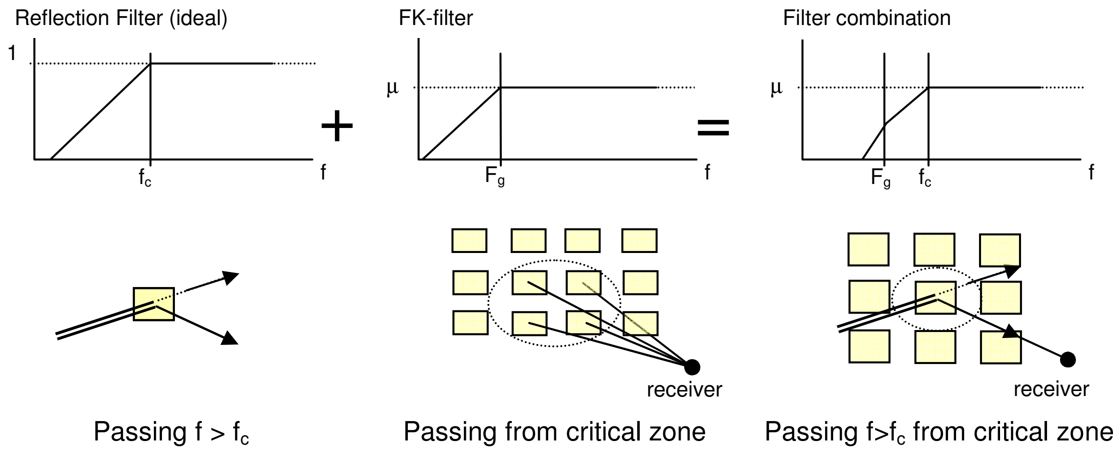
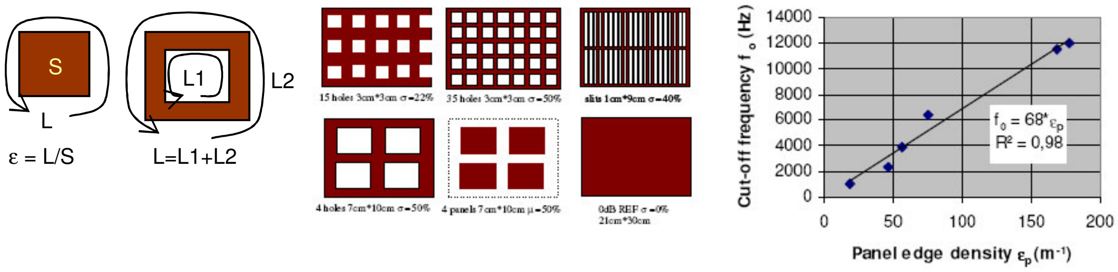


Figure 1. Serial combination of two filters

The Reflection Filter cut off frequency
For normal incidence on a simple circular disc of radius a, the cut-off frequency of the Reflection Filter can be deduced from scattering theory [6] by identifying the limit where scattered pressure

[i] In this context, filter is synonymous to transfer function
[ii] Denotation due to the Fresnel-Kirchhoff (FK) approximation theory applied.

approaches the pressure calculated by FK-theory. This occurs when ka=3π/4, corresponding to a cut off frequency of approximately F_c≈128/a.
Some shapes are hard to decide whether they are large or small compared to the wavelength, and their cut off frequencies is not straightforward to determine. This author has suggested the panel edge density as a geometrical predictor of the cut off frequency due to element size and shape, based on theory and measurements [2],[7]. Scale model arrays of varying geometries showed the trend F_c= 68* ε, where ε=L/S is the edge density when S is the surface area of panels with total edge length L (Figure 2). The size of ε is m^{-1}. In the above case of the disc of radius a, the edge density is ε=2/a, implying F_c≈64·ε (corrected since Copenhagen [2]). This closeness between theory and measured trend supports the possible validity of ε-predictor.



a. Edge density ε b. Scale models measured c. Measurement trend F_c = 68·ε

Figure 2. The edge-density predictor for the Reflection Filter cut off frequency

The *equivalent reflector radius* appears to be a convenient measure of non-circular elements, and is here defined as R_r=2/ε =2·S/L, since the edge density of a circular disc is 2/r, having P=2πr and S=πr^2. In the case of an A*B rectangle, the equivalent reflector radius approaches B when A>>B. In terms of equivalent reflector radius, the scale model measurement trend could be expressed as F_c=136/R_r, which is close to the 128/a deduced from circular disc scattering.

CURRENT INVESTIGATIONS [8] ON REFLECTION FILTER CUT OFF FREQUENCY

The trend of F_c= 68·ε was found from measurements on rectangular shapes and normal incidence. More scale model measurements have been carried out to test if the Reflection Filter cut off frequency can be predicted from edge density for many different element shapes and for varying incidence angles. Two student projects at NTNU, Trondheim, Norway, supervised by this author, have investigated this. Both projects identified the Reflection Filter effect.

Dependency on geometry at normal incidence

Bråthen [9] measured on scale model arrays of 40 different geometrical patterns, and concluded that the low cut off frequency could be predicted by F = 0.196·c·ε_p ± 10.8%, equivalent to 67·ε_p ± 10.8%, i.e. the interval 59·ε_p to 74·ε_p.

Dependency on angle of incidence

Thorød [10] measured 6 positions at 4 different incidence angles on 3 different scale model arrays, and observed a tendency towards rising low cut frequency limit as incidence angle increased through 15, 30, 45 and 60 degrees, with 0 degrees equal to normal incidence. This author has analyzed the measurement data in further detail, with the following conclusions: 1) The (Pearson) correlation between frequency responses and best fit high pass filters is on average 80% for the 72 measurements; 2) The variation in the set of cut off frequencies from the 72 high pass filters correlates 61% with variation in incidence angles, Figure 3.

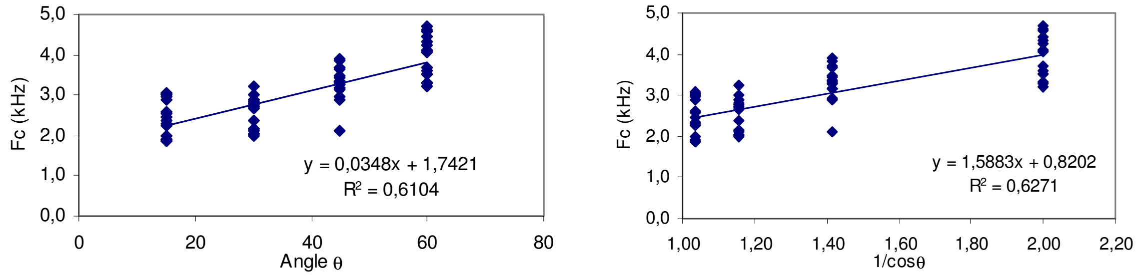
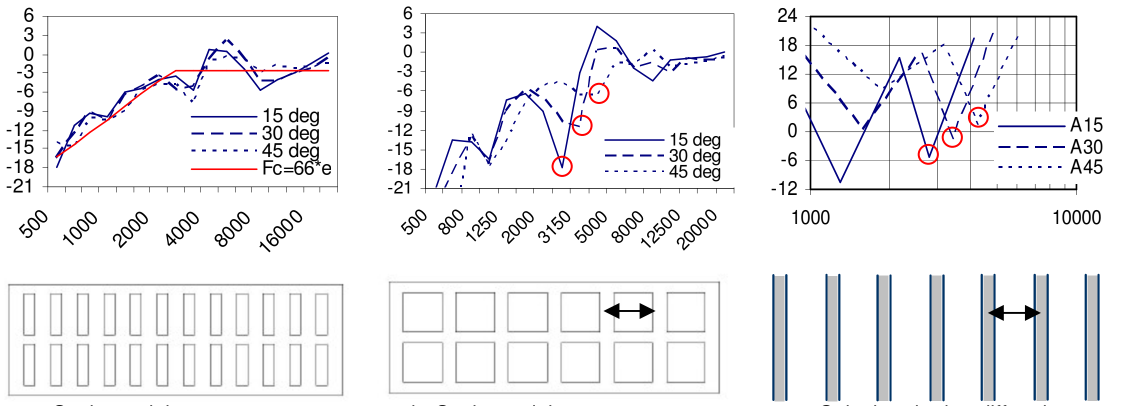


Figure 3. High pass filter cut off frequencies F_c plotted against incidence angles (left), and against projected element density $1/\cos\theta$, re 1 at normal incidence.

In terms of explanation degree: 1) The correlation values indicate that measured frequency responses can not be fully explained by ideal Reflection Filters; 2) Less than 63% of the variation in F_c's is due to variation in reflection angle. From this it is deduced that the angle-related variation in frequency response can not be explained by angle dependency in the reflection filters alone. Considerable explanation is found in angle dependent FK-filters, e.g. interference and effects from geometrical array-patterns. Spectral peaks and dips moving upwards in frequency as angle increases are to be expected, as illustrated in Figure 4c, and in Appendix, Figure 7. Therefore, *the hypothesis that the ideal reflection filter is independent of incidence of angle could not be rejected by this test.*



a. Scale model measurement, μ=70%, ε=37 m^{-1}

b. Scale model measurement, μ=51%, ε=41 m^{-1}

c. Calculated edge diffraction, μ=30%, ε=39 m^{-1}

Figure 4. (a) Measured and computed frequency responses at varying angles of incidence. All diagrams are dB vs Hz. 0dB corresponds to 100% dense reflector in (a) and (b), and to the first arrival component in (c), see also Figure 7 in Appendix.

Geometrical dependant deviations in Reflection Filter frequency response
The results is a reminder of the importance of choosing adequate array patterns to suppress peaks and dips in the FK-filter for two reasons: Primarily to provide good sound quality for the receiver, secondly to make it easier for the researcher to detect the cut off frequencies.

DESIGN ISSUES
There are many acoustical, practical and architectural concerns when designing a reflector array [1]. Many issues are about optimization or trade-offs. Frequency range, array size, element size and shape, surface density, array height, and array pattern are strongly interdependent, and one of them can not be chosen without considering the others.

Frequency range
What range of frequency response from a reflector do listeners require? This question is not to be answered in this paper, but we assume that the answer will differ from musicians to audience, and that the frequency response in the range of 500Hz to 4 kHz is important [14] in

stage acoustics due to the acoustic barriers inherent in a symphony orchestra being significant for frequencies > 500Hz. In this range, the spectrum should be flat (±3dB), and vary little from place to place.

Element size and shape

The size of the elements may be critical, since smaller elements improve the high frequency response while low frequency response suffer and vice versa. Rindel concluded that smaller elements are to be recommended for high frequency quality. However, we must keep in mind that small elements give poor low frequency response. For this reason one can not solve the low frequency issue without taking high frequency response into account. This requires precise knowledge about required frequency range, and how to achieve it through design.

Example: Applying $F_c=64\cdot\varepsilon$ as low limit and the Critical Zone criterion (Figure 5) for high limit of a 50% density array at 6m level above source-receiver, for 0.6*0.6m^2 square elements leads to the useful frequency range 0.4kHz to 2.8kHz. High limit can be calculated by Rindel's F_1 and F_2.

F=0.4-2.0kHz, $\mu' \approx \mu$ =50%, -6dB reflection   F=2.8kHz, μ'=100%, 0dB reflection. High limit.

Figure 5. Useful frequency range depends on element size and shape related to Critical Zone

Comment: While 0.4kHz low limit is assumed OK for stage acoustics, 2.8kHz high limit is assumed too low. Reducing element size to 0.5*0.5m^2 results in frequency range 0.5kHz to 4kHz, which may just be OK. This illustrates the problem of the inherent narrow frequency range of flat panel arrays. The high frequency range may be extended by applying curvature or surface diffusion to the panels, or by more adequate panel shapes. Ando [11] suggested that smoothness in frequency response could depend on element shape. Another approach is the two-way FK-filter system consisting of a narrow panel array with large panel array behind (above), like in the stage canopy in Oslo Concert Hall.

Array density

Panel density of the array affects the acoustic transparency and the early-to-late balance in the reflected sound energy, the strength of the reflections, as well as the air circulation in a concert hall. Air gaps of 0.6-0.8m are often required for lighting trusses. Size and geometrical pattern of the elements and the size of the array affect both coverage and quality of the reflected sound, and of course the architectural concept.

Array size

In practice, the arrays used as orchestra canopies are often so large that there is no low frequency attenuation due to array size, i.e. the FK-filter works in its band pass region. The array must not be too large, since this may separate sources and listeners from the reverberant space, especially if the array is dense and at low position.

Array height

The height position (source and receiver distance to the array) affects the FK-filter: The lower the array position is, the narrower can the bandwidth of even frequency response be, and vice versa. At higher positions, the Critical Zone will contain a larger amount of elements and air gaps, providing more even reflections at higher frequencies. On the other hand, too high array position may result in to much attenuation and delay.

Periodic effects, coloration and diffusivity

Array patterns with periodic edges can produce unwanted interference resulting in peaks and dips in the frequency response, or audible periodic pitch effects. To suppress coloration [12], and to provide even reflector coverage, the array should be diffusive [1]. The significance of diffusivity has been previously discussed [13].

Prediction models and calculation tools

There is a need to assist design by calculations. A brief discussion with some measurement results are presented in Appendix.

FURTHER WORK

An extended measurement program is planned with the aim to find array configurations with a frequency response with less than ±3dB deviation from an ideal 1. order high pass filter. The ε-predictor will be further tested for validity. Both angle dependency and shape dependency will be tested in further measurements on more ideal arrays.

CONCLUSIONS

The frequency response of a reflector array can be described by two serial filters – the Reflection Filter and the FK-filter. The useful frequency range of the array is in the pass bands of these filters. There are two low frequency limits, one for each filter. The FK-filter low limit is given by Rindel. Prediction of the Reflection Filter cut off frequency F_c is crucial in array design because of inherently narrow frequency range. It can be deduced from theory, and the panel edge density ε has been suggested as a predictor: $F_c = C \cdot \varepsilon$. Theory and measurements indicate C in the region of 64-68, and for design purposes the theoretical value of 64 is suggested. The dependency of incidence angle, element shape, and evenness vs fluctuations in frequency response is to be investigated further. In array design, several interrelated issues must be taken into account.

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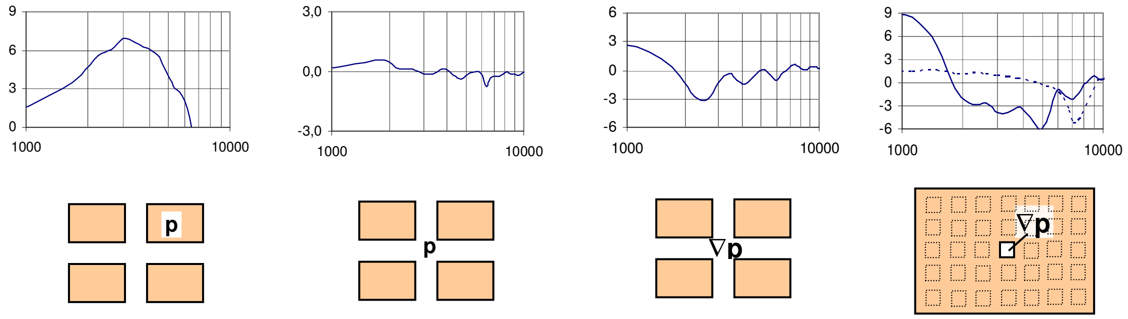
APPENDIX

Prediction models and calculation tools

There is a need to assist design by calculations. If we define the useful frequency region of the array to be above the cut off of the Reflection Filter, then FK-approximation is valid in the useful range. However, this requires that the cut off frequency is predicted by other methods than FK, e.g. a geometrical predictor like the edge-density predictor f >C·ε suggested by this author. BEM merge Reflection Filter and FK-filter into one. In the Helmholtz-Kirchhoff integral, geometry and source-receiver position are the FK-parameters, while the Reflection Filter parameters and simplifications are given in the table below.

	Reflection Filter parameters in H-K integral	Usual simplification
1	Pressure on the reflectors	Approximately twice the pressure of the incident wave
2	Pressure in the air gaps (apertures)	Unaffected by the presence of the array (free-field value)
3	Pressure-gradients on reflectors	Equal to zero on a rigid reflector surface
4	Pressure-gradients in the air gaps	Assumed unaffected by the proximity of the array (free-field value)

Simplifications 1) and 4) are bold assumptions, since the pressure reflection coefficient is weaker than unity, and because the reflectors introduce pressure gradients in the air gaps. Figure 6 shows measurements that illustrates the frequency dependency of the Reflection Filter parameters. Below the Reflection Filter cut off, 1) and 4) are complicated because



a. **p** re free field 64·ε =3.1kHz

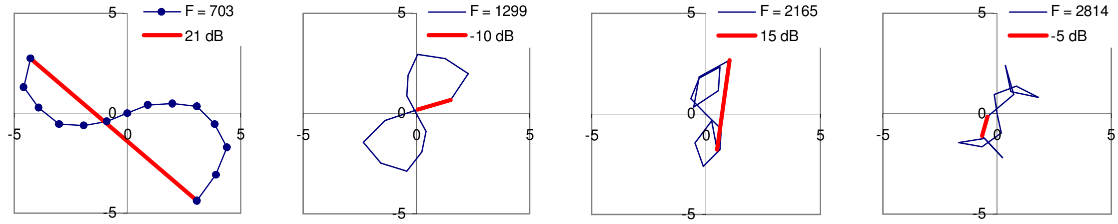
b. **p** re free field 64·ε =3.1kHz

c. ∇**p** re free field 64·ε =3.1kHz

d. ∇**p** re free field 64·ε =1.2kHz / 11kHz

Figure 6: Pressure **p** and pressure gradients ∇**p** measured on array surface, w normal incidence; (a),(b) and (c) 4 panels 7*10cm^2 ; (d) 1 (solid) and 35 (dotted) apertures 3*3cm^2 each in 21*30cm^2 panel. All diagrams are dB vs Hz; 0dB ref = measured free field values.

Appendix to Figure 4c



21dB peak at 703Hz

-10dB dip at 1299Hz

15dB peak at 2165Hz

-5dB dip at 2814Hz

Figure 7. Complex sum of diffraction components from 12 panel edges in Figure 4c. 0dB=single edge.