REFLECTOR ARRAYS AND THEIR FREQUENCY LIMITS – A STATUS REPORT

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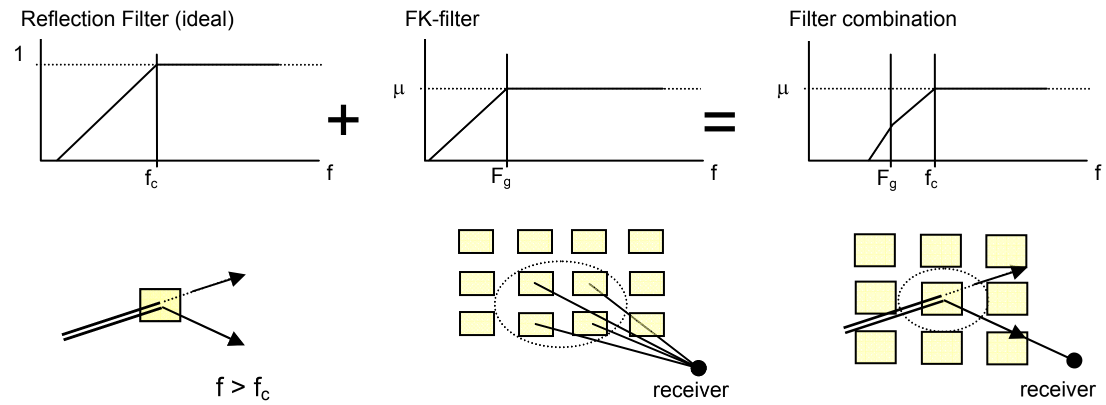
1 INTRODUCTION

Theory supported by several measurement projects on scale models over the past years has made it clear that there are two independent low frequency limits associated with reflector panels and panel arrays. The limit due to the total size of the reflecting surface relative to the Fresnel-Zone has been explored in detail by Rindel for the single panel case and the for the case of a panel array. This paper reports from the investigation on the low frequency limit that depends on the size and geometry of each panel element. When used as an orchestra canopy, panel elements of an array should be designed with a frequency range taking the orchestras need for internal sound transmission into account.

This paper focuses on thin, flat panel arrays.



a.
$f > f_c$: Reflected pressure
$f < f_c$: Transmission

b.
Passing pressure information from Fresnel-zone

c.
$f>f_c$ Passing reflected pressure from panels in Fresnel-zone

Figure 1. Frequency response as a serial combination of two filters

2 LOW FREQUENCY LIMITS

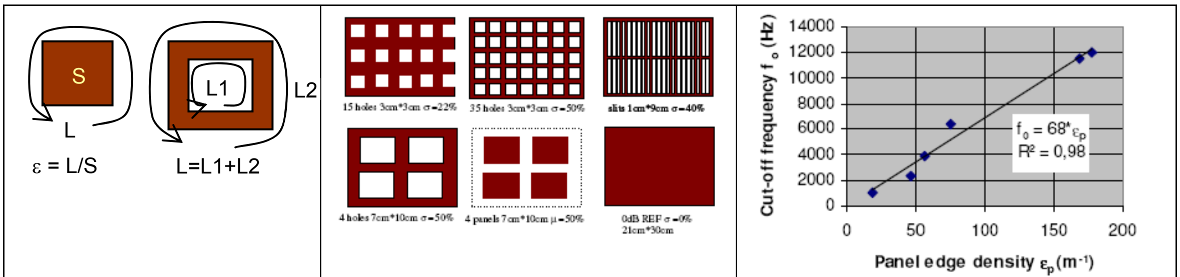
There are two frequency limits, F_c and F_g, for the reflecting frequency range of reflector panel arrays [3], Figure 1. This can be predicted with the Boundary Element Method (BEM), taking frequency dependant panel surface pressure into account. A double slope in the frequency response as f→0 will be observed. A way to explain the low frequency behavior is a model with two first order high pass filters [1][8], one describing the panel's ability to reflect incident sound pressure, the Reflection Filter, and another describing the array's ability to transmit sound by diffraction, the Fresnel-Kirchhoff (hereafter FK) filter, Figure 1. The FK filter is what results from BEM when assuming

perfect reflection, associated with pressure doubling at all panel surfaces. Since both low frequency slopes are 6dB per octave, there will be a 12dB per octave slope below the lower of the two limits.
In practice, the reflection filter acts like switch between the reflection mode and the transmission mode of the panel. In the reflection mode above F_c, the panel reflects sound because the surface pressure is twice the incident pressure. In the transmission mode, the panel is too small affect the pressure, and sound is transmitted as if the panel was not there, Figure 1 a.

Measurements and theory has shown that the frequency response of single reflectors as well as reflector arrays may differ from the ideal constant level pass band in filter models. Reflections at grazing incidence may exhibit a raise with frequency, and peaks and dips may deviate more than ±3dB relative to the ideal level. Still, the filter model is useful because one can describe the useful range by a level and by its limiting frequencies.

2.1 Reflection filter and the F_c limit

The low frequency attenuation due to insufficient panel size compared to the wavelength was reported in 1964 [4]. From the results by Pierce [7] (1981), it can be shown that the FK approximation alone would overestimate reflections from a circular disc of radius a whenever ka< 3π /4, at normal incidence. This can be corrected by combining the FK-filter with a high pass reflection filter with cut off frequency F_c= 3c/(8a) ~128/a. For other geometries than discs, the panel edge density ε = L/S, where S is the total panel area and L the total perimeter of the panels, has been suggested as a predictor for F_c [3]. The theoretical result from the disc implies F_c ~64·ε. Scale model measurements on 6 different rectangular-like geometrical patterns in 2006 were best predicted by Fc~68· ε , see Figure 2. Since then, three different student projects [10] concluded from scale model measurements with F_c/ ε in the vicinity of 64-68.



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 phenomenon of frequency dependent pressure doubling on a surface at normal incidence is well documented on frequency response plots coming with microphones. Depending on the size of the microphone membrane and its capsule the typical rise occurs commonly on axis in the 10-20kHz range, while the response is flat in the lower range, i.e. the useful range, of the microphone. At random incidence, the effect is far less prominent, indicating that reflections may be weaker with incidence off axis.

Currently it seems evident from theory and measurements that the reflection filter and the F_c exists. What remains is to settle a reliable predictor for Fc based on simple geometrical properties of arrays, even though arrays geometry may be anything but simple.

Investigations this far does not indicate that the F_c limit for an array of similar elements are any different from that of the single element. This can be explained by the fact that a single, flat, thin panel acts like a dipole, radiating zero pressure in the plane of other panel elements. There is however an uncertainty associated to the fact that the gradient from the dipole is different from zero in the array plane, though it can be shown that it decreases rapidly with distance.
F_c at incidence angles other than normal are still under investigation. There are indications that F_c varies little when angles are 0-15 degrees from normal, but increases more and more towards

higher angles, Figure 3. However, there are uncertainties in detection of F_c due to peaks and dips in the transition around F_c. What seams to be more certain, is that the transition region around Fc is affected by angle.

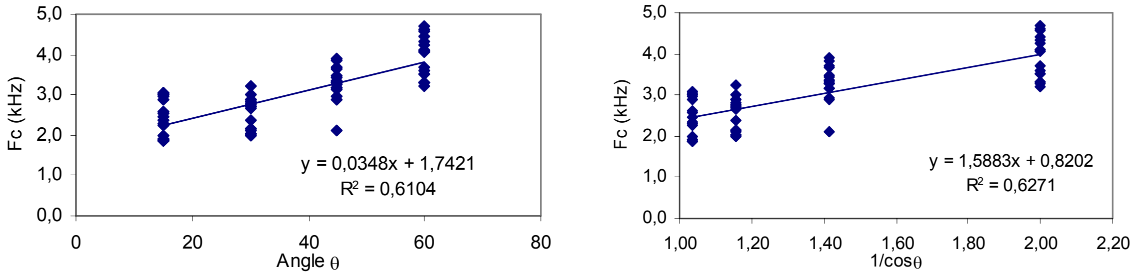


Figure 3. High pass filter cut off frequencies F_c plotted against incidence angles (left), and against projected element density 1/cosθ , re 1 at normal incidence.

The frequency responses from scale models of flat panel arrays of varying geometry are often very uneven at frequencies close to F_c or higher, and the deviations may exceed ±3dB relative to an ideal high pass filter. This has two practical implications: 1) It is difficult to determine F_c, and 2) when used as an orchestra canopy the flat panel reflector array may not provide proper sound quality to the orchestra intercom.

2.2 FK-filter and the F_g limit

The pass band level and the cut off frequency of the FK-filter are both expressed by Rindel's formulas for a single panel [5], and for an array of panels [6]. The low frequency limit F_g is in most cases lower lower than F_c. The pass band value is 20·log(μ) 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.

Equivalent to the flat panel array of panel density μ, is the large perforated single panel with perforation degree $\sigma = 1- \mu$. The latter model is a simpler one when only the lower frequency range is considered.

3 HIGH FREQUENCY LIMIT

The useful frequency range (the pass band) of single panel reflectors as well as panel reflector arrays, are in practice determined by the FK-filter, and its limits are expressed by the same formulas as in 2.2. The reason for the limited usefulness at higher frequencies is that the Fresnel-Zone projected on the array plane gets smaller with higher frequencies. When the Fresnel-Zone is small compared to panel elements, the reflection level will depend very much on whether the geometrical reflection point is on a panel or in between. The highs may at some frequencies be even higher than the level of a perfect specular reflection, and the lows are only restricted by a -6dB/octave slope with starting point depending on the distance between the elements.

Ando [14] found that the peaks and dips in the frequency response depended on panel geometries, suggesting that triangular elements were beneficial.

4 USEFUL FREQUENCY RANGE

The pass band of the combined filters and their frequency limits defines the useful frequency range of the reflector array, as shown in the summarizing diagram in Figure 4. For an orchestra canopy array of size X·X and N square panels of size x·x, at height H above the head of the musicians, the limits for normal reflection are: $F_g = c \cdot H/(2 \cdot X^2)$, $Fc \sim 64 \cdot 4/x$, and $F1 = c \cdot H/(2 \cdot x^2)$, with $\mu = N \cdot x^2/X^2$.

Scale model measurements have indicated that with the relative distances and μ typical for the orchestra canopy case, the pass band level may be 0-2dB higher than $20 \cdot \lg \mu$, but this is not yet explained by theory.

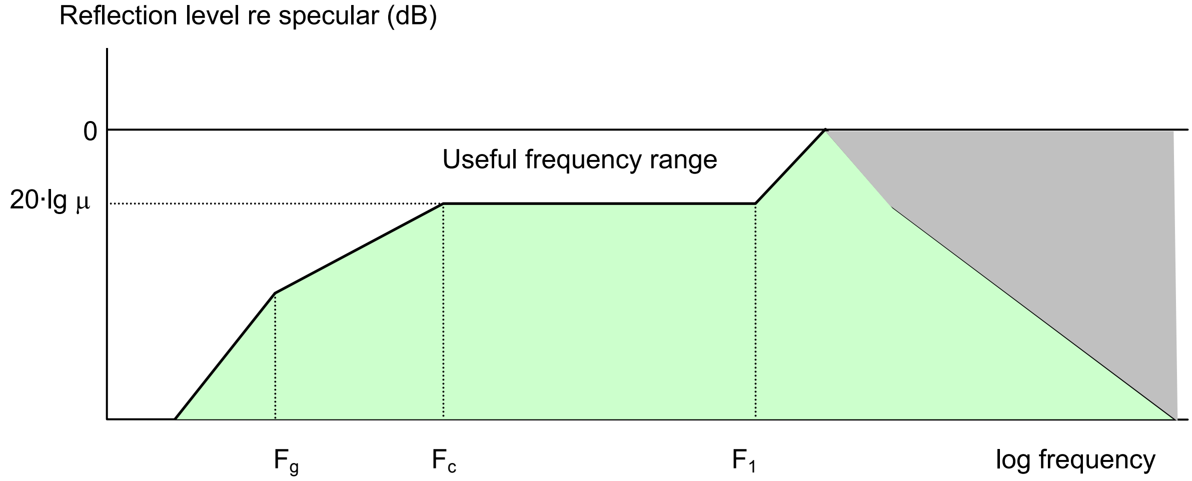


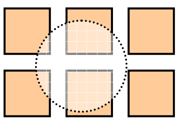
Figure 4: A summary of the flat panel array frequency limits.

5 IMPLICATIONS

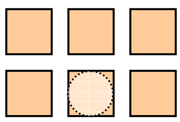
5.1 Orchestra canopy

A well designed orchestra canopy should provide proper stage support and intercom for the players. The frequency response in the range of 500Hz to 4 kHz is important [17] 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. There may be need for canopy reflections below 500Hz, but this may vary from case to case. However, current recommendations for stage support (ST_{early}) include the 250Hz octave. To provide response in the 250Hz octave, reflector panels should be at least 1m*1m in size. In this case, the high frequency limit calculated from Rindel's formulas is 1360Hz, which is lower than recommended. This illustrates the inherent narrow frequency range of flat panel reflector arrays. It is quite common improve the high frequency response by using use curved panels in stead of flat panels. Curved panels will in the higher frequency range provide several minor reflection paths in stead of one geometrical path that may or may not hit a panel. This will reduce peaks as well as dips.

Example: Applying $F_c = 64 \cdot \varepsilon$ as low limit and the Critical Zone[1] 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

[1] The Critical Zone CZ is designed proportional to the Fresnel-Zone, such that the FK filter frequency response is S/CZ, where S is the total reflecting surface inside the CZ.

5.2 Computer models

It is recommended to implement the low frequency limit F_c in computer models, e.g. ODEON and CATT. Below the transition range around F_c, a panel array will appear to switch into transmission mode with transmission factor close to unity.

6 FURTHER WORK

Though the response from reflectors and reflector arrays can be predicted accurately by BEM, there is need for a simpler method that could provide adequate accuracy with less computational effort. Further work should aim to settle a predictor for F_c based on geometrical properties of the panel array.

It can be shown that F_c is closely related to the frequency limits of radiators and their radiation impedances. The reflected sound from a rigid panel can be simulated by an equivalent source that makes the resultant pressure gradient on the reflecting surface equal to zero. The fact that radiation impedance is a geometrical property, improves the chances to find geometrical predictor for F_c. One should not forget the significance of the acoustic impedance in the air-gaps between the panels. Below a certain frequency depending on aperture geometry, these apertures will transmit more sound than predicted by FK [21][22] [7], and inherently the panels must reflect less than predicted by FK. Thus, the aperture geometry affects F_c.

Flat panel arrays very often have strong peaks and dips. One should try to find ways of achieving more even frequency response in reflector arrays. Curved panel elements or panels with curved edges [11] is one alternative, the double layer array applied in Oslo Concert Hall is another alternative.

7 CONCLUSION

The useful range of reflector arrays is restricted by two independent low frequency limits and one high frequency limit. Flat panel arrays have inherently narrow frequency range, and it is therefore important to predict and to control its frequency limits. A suggested predictor for F_c, based on array geometry, has been verified by measurements at normal incidence and for certain geometrical patterns. Further work should aim for general confirmation of this predictor, or an improvement if needed. It is recommended to develop array design with a more even frequency response within ±3dB deviation from the ideal level, and with a frequency range of at least the 250-4kHz octave bands. This requirement may imply that the flat panel in its simplest form is not adequate.

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