ORCHESTRA CANOPY ARRAYS
- SOME SIGNIFICANT FEATURES

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ABSTRACT

The objective of this paper is to discuss some of the significant features of an orchestra canopy in general, and the panel array in particular. Many factors that affect the acoustical conditions on a stage appear to be very sensitive to the design and positioning of the orchestra canopy. Among the common design issues are those concerning size, geometry and patterns of elements forming a canopy array. While much focus has been on the quantity of the foldback, the musicians may be equally as much sensitive to the quality of the reflected energy, such as diffusivity – balance and evenness in time and frequency as well as spatially. Measurement and prediction techniques are important in the design, optimization, assessment and justification of canopies.

1. INTRODUCTION

To install some kind of canopy above stage and sometimes above seating areas in concert halls has become usual in the last 50 years. They vary in design, height and extent, but in one way or another, they reduce the acoustic height of the hall. In most cases, the motivation is to provide more early sound energy fraction at the receivers' ears. Typical purposes are:

1. to provide foldback to the musician her/himself
2. to provide a communication channel for mutual hearing among musicians at stage
3. to provide more early sound (<50ms delayed) to the audience

Some canopies are designed as one large, single element, while others are made up by an array of (typically) smaller elements with openings in-between. The canopy array in the 6000 seat Tanglewood Shed, completed in 1959 is one of the earliest well-known examples. It extends from the stage into the audience area, with the main purpose to reduce the initial time delay gap IDTG, an acoustical parameter which enjoyed a lot of attention at the time. Another important design criterion in Tanglewood was to maintain sufficient sound transmission through to the upper volume of the hall in order to maintain an adequate reverberation time, which was provided by 50% opening area in the canopy.

2. PREVIOUS WORK

Some selected papers presenting results relevant to this paper are given in bullets below:

- The Tanglewood Shed paper [1]
- Leonard, Delsasso, Knudsen 1964 [2], established that size of panel elements relative to wavelength, defines three frequency regions with different reflection modes – no reflections (or attenuated, editorial remark) in the low frequency region, specular reflections in the high frequency region, and a complex scattering mode in the middle region
- Rindel 1986: Attenuation of panel reflections due to diffraction[3]
- Ando 1989 [4], on panel shape significance: Triangular panels appear to provide more even distribution in the reflected energy spectrum than does rectangular or circular elements
- Rindel 1991, on panel arrays: Attenuation $20\cdot\log(\mu)$ due to panel surface density μ in the middle frequency region, attenuation due to array (finite size) diffraction, and geometrically dependant reflections in the high frequency region (specular reflections from panel elements) [5]
- D'Antonio and Cox, over the past decade: Several papers on canopy design and optimization
- Skålevik 2006: Attenuation due to element size small compared to wavelengths revisited, showing that the low frequency limit covaries with the edge density of a panel array [6]

3. IS A CANOPY NECESSARY?

Today, one might get the impression that a canopy is “a must” in every new concert hall, and a magic recipe in any refurbishment. Some of the unique features of a well-designed canopy are to be treated in this paper, together with a discussion of significant design issues.

There are, however, cases where canopies would be unwanted, unnecessary, insufficient, inadequate, or even deteriorating to the acoustics on stage or in the rest of the hall. One should keep in mind the following:

- Some of the highest rated concert halls among musicians and audience – Musikvereinsaal in Vienna, Concertgebouw in Amsterdam and Boston Symphony Hall – all fail to have a canopy
- Early reflections are often effectively provided by lateral reflections, and these may also fill the requirement for early lateral energy to broaden the apparent source width ASW of the orchestra
- Since a canopy contributes with non-lateral early reflections from above, it may reduce the early lateral fraction in the auditorium to much, reducing the LF value and thus the sought-after broadening of the source, the ASW.
- It is often difficult to achieve the recommended ST_{early} support level with a canopy as a single remedy, e.g. the specular reflection component from a canopy 7m above the musician could only provide a support value of -23dB (10dB weaker than recommended) if there are not other reflections contributing
- Stage acoustics dominated by early reflections from above only may suffer from too low diffusivity due to weaker horizontal reflections
- A canopy that is very dense and/or very low may give too much early sound and too little late reverberance, resulting in too high clarity and the impression that the stage is decoupled from the rest of the hall, not to mention the obstruction of sightlines from galleries, lighting and stage machinery, and air-circulation
- A canopy that is open and/or high enough to avoid the unwanted obstructions mentioned above, may give too weak and late reflections to give the wanted effect
- A canopy that makes the platform and its volume turn into a separate acoustic space can not be expected to be preferred

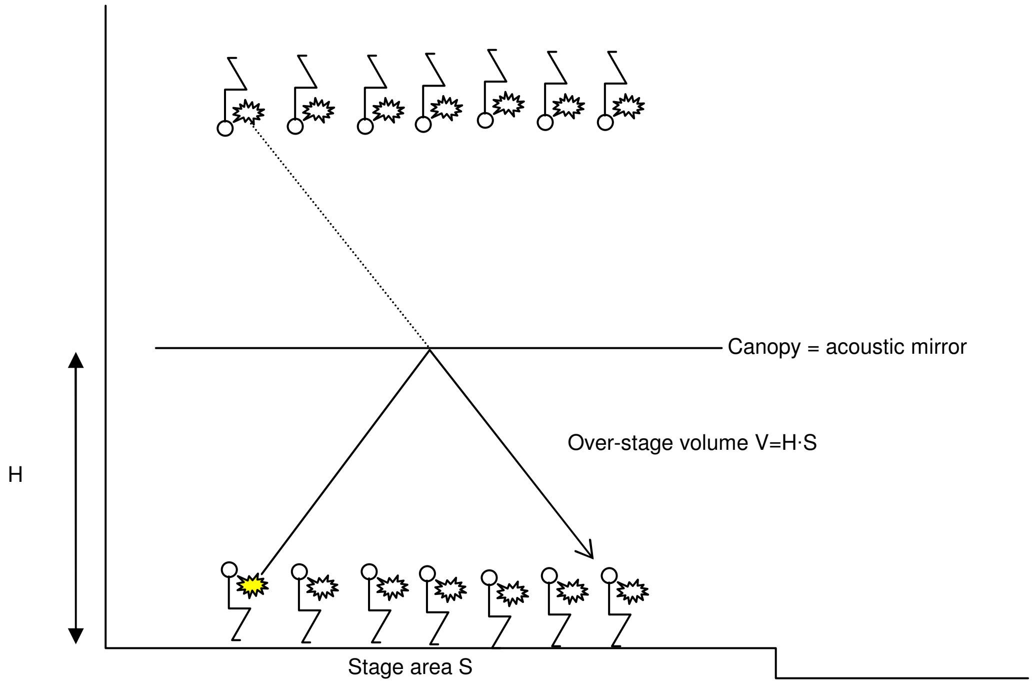
Whenever a canopy is applied as an acoustic measure in the making of a new concert hall, or in improving an existing one, it is essential to have defined exactly what to require from it. A canopy will easily make a difference, but not necessarily the effect one would like. The reason why some concert halls seem to benefit from a canopy while others do perfectly well without is not clear, and it is currently an interesting research field.

4. BENEFICIAL FEATURES

Though wonderful acoustics can be achieved without a canopy, there are some unique features that a canopy or a canopy array can provide. We shall focus on some of these below.

4.1. Support level adjustment

Together with the platform floor and the surrounding walls, a properly designed canopy array can define the acoustic volume that the musician or the orchestra needs to fill. This volume will have a higher early energy density than the rest of the hall, given the canopy height is sufficiently low. By adjusting the height of the canopy, the volume and thus the early energy density can be adjusted. Since the support parameter ST1 is the early (20-100ms) energy level related to direct omni-directional level at 1m, ST1 will be sensitive to this volume. If there is no canopy, the over-stage volume is defined by the ceiling. A brief study of some halls without canopy indicates that ST1 often depends on the over-stage volume V as ST1≈18-10·log(V). This means that to achieve a recommendation of, for example ST1=-12dB, the over-stage volume must not exceed $V=1000m^3$, e.g. a platform that is 14m wide and 10m deep, and a ceiling or a closed (100% dense) canopy at 7m above the platform floor. The recommended ST1 value is subject to discussion, but for now we just state that it depends on stage volume dimensions and can be adjusted by the height of a canopy. In this context, the volume should be determined by V=H·S, where H is the volume height above the platform, and S is the area over which the ST1 is the mean value, see *Figur 1*.



Figur 1: The image orchestra above a plane surface canopy

The perceived early energy density on the platform will also depend on the source density – the number of musicians per square meter, and on the panel surface density of the array – since a more dense canopy will keep more early energy inside the over-stage volume. Note that by definition, ST1 does not depend on source density. Surface density μ, or perforation degree $1-\mu$, of the canopy also affects the amount of late reverberance entering the platform from above, and thus the sense of envelopment on the platform, the sense of acoustic connection with the hall, and the ST_{late} (late support).

Conclusion: Canopy height and density is crucial to both ST1 and ST_{late}, but also to the delicate balance between them.

4.2. Synchronicity and level equality

A feature that has received little attention is the significance of synchronicity in the collected reflections from all orchestra members back to the performers. This is currently a research field. Earlier investigations, e.g. by Naylor (1988) and Gade (1989), has shown that delays, i.e. deviation from synchronicity, as small as 10ms can be disturbing for musicians trying to play synchronized in music of strict rhythm. Only within the distance of 3.4m can such conditions be achieved by unobstructed direct sound transmission. On the other hand, the transmission of musical details is unreliable due to source directivity and obstructed transmission paths through the orchestra over distances larger than a few meters anyway, so synchronicity must be supported by other means (direction, rehearsal, foldback via).

While the quantitative early energy on the platform can be described by parameters like ST1, the quality of receiving the reflections synchronized is not described by such parameters. The same ST1 value can be achieved in many different halls while the impulse responses measured may differ noticeably in detail. In this context the ceiling height, or the canopy height, may make a significant difference.

Considering the image source of an orchestra, as “seen” in the “mirror” formed by the ceiling or the canopy, an orchestra member will have a free sightline to the image of every colleague in the orchestra, as shown in *Figur 1*. These image colleagues appears to be at approximately the same distance from the observer, which means that the observer will receive sound with approximately the same delay and attenuation due to distance from each image colleague. As a result of this, an orchestra member receives a level-balanced, synchronized image orchestra (given an orchestra actually playing in-sync) in the ceiling or the canopy above.

Now, whether the perception of an image orchestra of this quality is preferred by musicians or not, is subject to research, but physically this unique acoustic foldback condition can be provided by a horizontal reflecting surface above the orchestra. A similar condition can not be provided by surrounding walls and cue-ball reflection from underneath balconies, even if such reflections can contribute to high ST1 levels, for at least two reasons: Members of an image-orchestra as seen in a vertical surface are located at very different distances, resulting in each source being received with different delays and attenuation. Secondly, such image orchestras depend on horizontal sound paths that are most often obstructed by colleagues, music stands, and so on.

Again, the height of the canopy or ceiling is important, since it determines the delay and the attenuation of the image orchestra.

> Example: If the horizontal surface is located 10m above the head of the musicians, the delay of the image orchestra is 59-72ms (deviation due to different instrument positions). If the distance between two co-players vary from 1m to 14m, then the received time and level difference between the nearest and the farthest co-player through the orchestra would be 38ms and 23dB (in practice far more due to obstructed direct sound path), while the received time and level differences from within the image orchestra in a canopy 10m above their heads would be 13ms and 2dB. If the canopy height is reduced to 7m above their heads, the overall delay would be only 41ms, while time and level differences would be 17ms and 3dB. Both 7m and 10m height provide far more synchronicity and level equality, but obviously the musicians’ sensitivity to synchronicity as well as the overall delay should be investigated.

Conclusion: A canopy or ceiling can provide a unique image orchestra, but we do not yet know if this quality is appreciated or even perceived by musicians.

4.3. Unobstructed transmission channel

As mentioned above, reflections via vertical surfaces are very unreliable due to many natural obstructions. The canopy surface will most often be seen by every instrument in the orchestra as well as at least one ear of every orchestra member, and thus provides a unique transmission channel between orchestra colleagues.

4.4. Directivity and obstructed sound paths

As mentioned above and in a separate BNAM 2006 paper [7] by this author, the direct sound component is an unreliable carrier of the sound produced by a musical instrument or a singer. In an orchestra this is not only due to instrument directivity, but also the inherent obstructions of sound paths through the orchestra. There must be expected to be a significant difference between ideal sound transmission predicted with omni-directional sources in unobstructed conditions, and practical conditions. As long as synchronicity down to

10ms precision is kept out of consideration, adequate early energy transmission can compensate for the lack of direct sound transmission. If early diffusivity is good, i.e. the early (0-50ms) energy level E50 from directive sources is received with relatively little deviation from the omni-directional equivalent, this is presumed to compensate from the lack of direct sound transmission. Early diffusivity can in general be achieved by limiting the volume, in this case by a properly designed canopy that defines the over-stage volume.

It is under investigation to what extent the sound scattering properties of a canopy improves early diffusivity at high frequencies, when source directivity is high. Curved elements and surface scattering is believed to provide for an abundance of transmission paths that is appreciable in cases of high directivity.

5. DESIGN ISSUES

Some design issues that are important in orchestra canopy design is listed with bullets below

- Early-to-Late balance
- Early diffusivity
- Reflection frequency range
- Coordination with stage equipment, such as lighting bars etc.
- Overall size of the canopy
- Element size
- Surface density
- Density and height optimization
- Element shape
- Element curvature and surface treatment, scattering properties

Early-to-Late energy balance is a basic stage acoustic property that governs the choice of overall size, surface density and height of the canopy. Early diffusivity is affected by canopy height, element size, curvature and surface treatment. Element size, and ultimately canopy size, should be chosen sufficiently large to satisfy the required reflection frequency range. A surface density of μ=50% seems to stand firm as a rule of thumb since first suggested over 50 years ago.

This author suggests that this balance should not exceed ST1- ST_{late} =3dB, and it should probably be in the range of 0 to 3dB. If the 3dB limit is exceeded, there will be a risk of stage acoustics being decoupled from the acoustics in rest of the hall, since early energy will dominate too much over late energy.

> Example: In a 16.000m^3 volume hall with ideal reverberation decay of RT=2.0s, the theoretical late support equals ST_{late} =-17dB. This means that the early support should not exceed ST1=-14dB if the musicians shall avoid to feel separated from the hall. Another consequence of this 3dB balance criterion is that a recommendation of ST=-12dB only can apply to concert halls of volume 10.000m^3 or less, given the common concert hall value of RT=2.0s.

6. PREDICTION AND MEASUREMENTS

Predictions and measurements of the difference to the stage acoustics provided by a canopy should be performed carefully. Whatever method chosen for this purpose should in particular include two concerns that up to now has been paid little attention in discussions of stage acoustics and their parameters:

- the time-varying radiation patterns of musical sources should be taken into account
- the inherent obstructions of sound paths through the orchestra should be taken into account

For example, the usual method of predicting the early support parameter ST1 with an omni-directional source, or measured with a dodecahedron does not meet the concerns above.

Predictions and measurements of support and ease of ensemble is an issue that is not yet settled among acousticians. More knowledge must be collected about radiation from musical instruments, the acoustic transmission, and the performers' perception of the sound that is being received from one self and from others.

7. ST1 AND PLATFORM CONDITIONS

Gade and Rindel [8] concluded that ST1, the support parameter, correlates well with subjective ease of ensemble.

In the computer software ODEON, the ST1 is defined as the level of the ratio between early energy in the period of 20-100ms (nominator) and the initial energy in the period of 0-10ms (denominator) as received at approximately 1.0m (in practice 0.9-1.1m) from the source, time related to first arrival. The denominator represents the energy that would be received if source and receiver was to be placed on a small piece of platform in otherwise an-echoic environment.

So the reference level 0dB is the energy received in a stage environment contained by an ellipsoid with source and receiver 1.0m apart in each of the eccentric focal points. The length of the ellipsoid would be 4.4m (1m+c·10ms) and the diameter around the source-receiver axis would be 4.3m. The platform floor piece would be typically 6-8m^2, depending on height of source-receiver. If this is measured physically with chairs and music stands, the reflected energy, and thus the reference level, could be considerably different from the empty platform condition.

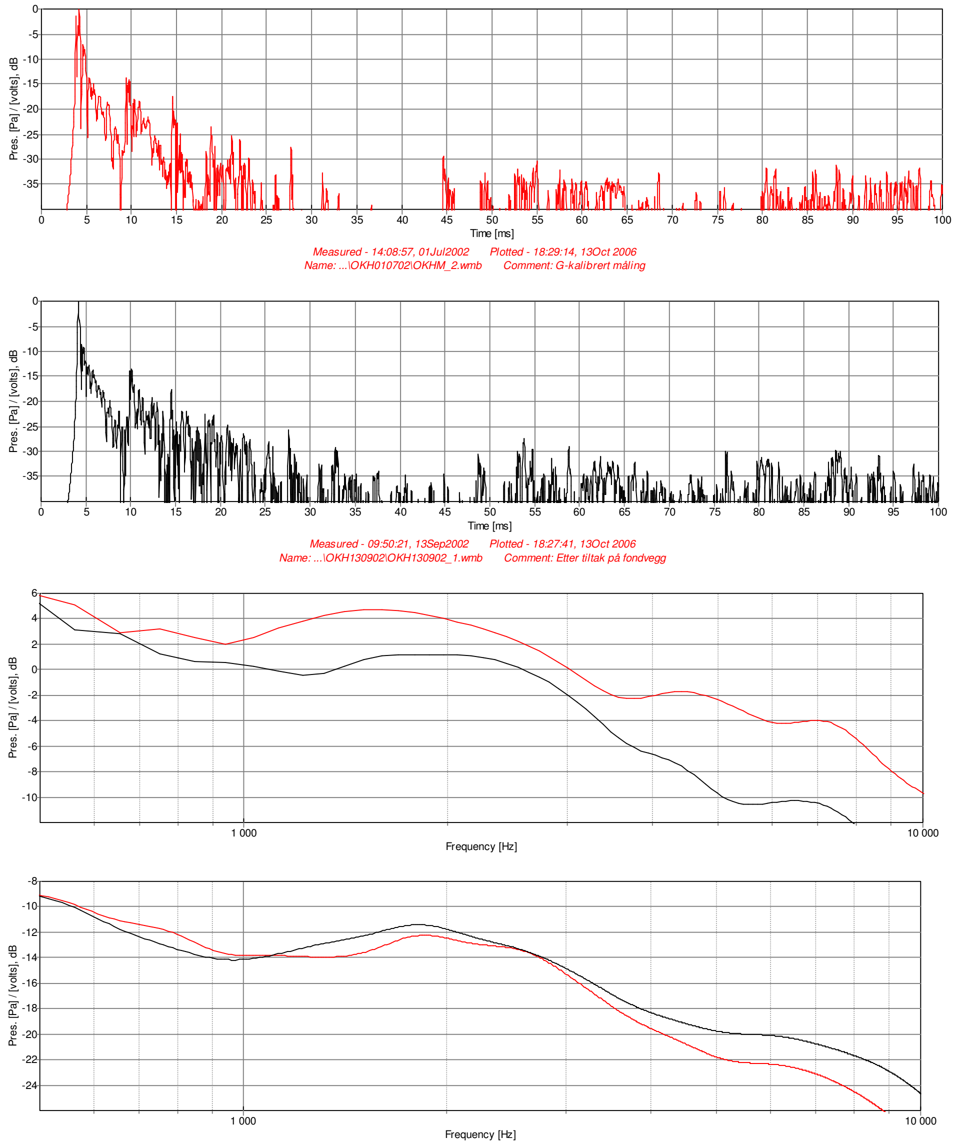
The nominator in the ST1 level contains the energy that has traveled between 7.8m (1m+c·20ms) and 34m. In the case of an empty platform, no surfaces closer than 3.9m from source or receiver are expected to contribute to the nominator. This corresponds to a surrounding 45m^2 of platform floor. In the case of a complex acoustic environment with music stands, instruments, chairs, etc., an early reverberant field is created and the environment also within these 45m^2 will have an effect. So, the actual platform condition makes a difference. The 100ms limit ensures that no surfaces farther than 17m from the receiver contribute to the ST1.

In it self, ST1 describes the early energy conditions on a concert hall platform, related to the energy that would have been received on a small extraction of the same platform located in otherwise an-echoic environment (e.g. 6-8m^2 platform area placed outdoors on a large grass field, or even more exact – covered with soft snow). If ST1 in one hall is compared to ST1 from another hall, and the platform conditions are identical, the difference between the two ST1's would describe significant differences in the support and ensemble conditions of the halls. On the other hand, if the two ST1's are measured under different platform conditions, the measured difference in ST1's is affected by the differences in platform conditions.

An example of two measurements at the same position in the same hall, but under different stage conditions – one with the platform empty and the other with instruments, chairs and music stands – is presented in Figur 2. The frequency responses show that the difference in the ST1 values is mainly due to difference in initial energy 0-10ms – not differences in the energy of interest, namely the energy in the 20-100ms period.

Radiation pattern is very significant. If averages from omni-directional sources are used, then the ST1 results only describe the early energy at the average receiver from a long-term average, ensemble average source. Since neither the average source nor average receiver exists (or only with probability zero), important information may get lost. Musical instruments are omni-directional only at frequencies lower than 500Hz and from 500Hz and upwards most horizontal sound paths will expectedly be partly obstructed and absorbed. At least, the omni-directional source should be substituted with a directive source with some upward emphasis increasing towards higher frequencies, whenever measurements or predictions are carried out without relevant obstructions. This is important when trying to measure the influence of a canopy.

Conclusion: When differences in ST1 are used to describe differences in stage acoustics, the platform conditions must be kept the same. The ST1 measured or predicted is only valid for the actual platform condition in the measurement or prediction. Measurements and predictions should be carried out with relevant elements (musicians, chairs, stands, instruments) or using a source with statistical directivity taking natural stage obstacles into account.



F(Hz)	125	250	500	1000	2000	4000	8000
ST1, empty platform	-17	-16	-15	-17	-17	-17	-19
ST1, w instruments etc	-17	-14	-13	-14	-14	-13	-10

Figur 2*: Two measurements in the same hall, on the same platform, with equal source and receiver positions. 1: Impulse response on empty platform; 2: Impulse response with instruments, chairs and music stands; 3: Frequency responses from 0-10ms, the empty platform case is evidently containing more initial energy (red curve); 4: Frequency responses from 20-100ms, the empty platform case containing slightly less energy (red curve); 5: Table showing ST1 values in octave bands. The major differences are mainly due to differences indirect+ initial energy 0-10ms.*

8. FURTHER WORK

It is often difficult to explain subjective support and ease-of-ensemble, or justify the need for a canopy by common quantitative objective measures. Even if the recommended ST1 values are often hard to achieve, the musicians often respond positively to the presence of a canopy. As long as omni-directional sources and free sound paths are presumed, the level of the early reflected energy is low compared to the sound from the performers own instrument. Possible explanations may be found in sound quality, and the significance of source radiation patterns, diffusivity of stage acoustic environment, performers perception of own instrument and other instruments, and the development of stage parameters is being pursued by this in current research. Though there has been evidence of correlation between the support parameter ST1 and the subjective ease of ensemble, it is unsettling to predict and measure conditions regarding mutual hearing with only 1m between source and receiver. A method that takes the longer distances into account should be developed. The denominator in the ST1 level is still problematic, since changes in the initial energy may cause variations in the ST1 that correlates poorly with the early energy of 20-100ms that is supposed to provide support and good ensemble conditions.

9. CONCLUSION

Though orchestra canopies are reported to provide for subjective support and ease of ensemble appreciated by musicians, it is not yet settled how such favorable conditions can be predicted and measured. Canopies are not a “must have”, but they do offer unique features like early energy control, foldback with synchronicity, and unobstructed sound paths. In order to improve, optimize and even justify the use of canopies, objective measures and measurement techniques must be further developed, though the stage parameter ST1 still seems to be a good start despite its weaknesses, particularly regarding its reference value – the initial energy in the denominator. Measurements and predictions based on omni-directional sources are probably insufficient in describing the stage acoustics. Source radiation changes randomly with time, direction and frequency, and sound paths are obstructed, which makes the direct sound component inherently unreliable. Support and mutual hearing must depend on a redundancy of sound transmission paths for the musicians. It is currently being investigated whether more reliability of early energy transmission can be achieved by providing for sufficient diffusivity in the musicians acoustic environment, like in rehearsal rooms and for the audience in a performance space [7].

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