

On the Importance of the Loudspeaker Lay-out of a Room Acoustic Enhancement System

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Abstract

Since the introduction of room acoustical enhancement systems some half a century ago, the quality of these systems has increased dramatically. As a result the contemporary room acoustic enhancement systems are widely accepted as a tool to improve a poor acoustical quality of a hall or to make a certain environment well suited for multipurpose use.

More than fifteen years of experience with one such a system, i.e. Systems for Improved Acoustic Performance (SIAP), revealed that not only the desired reverberation time is an important measure in order to optimise such an installation. The final quality of such a system is also dependent on the loudspeaker coverage, sound level distribution and natural acoustics of the acoustic environment in which such a system will be installed.

In order to outline the importance of an extensive loudspeaker lay out, especially for poorly coupled areas such as under balcony areas and wide halls, measurements have been performed. This paper discusses the theory of coupled spaces and the results of measurements performed in a venue. Furthermore the results will be considered with respect to the natural acoustical qualities of the hall itself.

1. Introduction

In the past 50 years a lot of theatres have been built. In contrary to earlier theatres and opera houses a lot of modern theatres have large balcony overhangs and accordingly a large under balcony volume. In a lot of situations these under balcony areas are poorly designed whereby the volume of the under balcony area is acoustically detached from the main volume. As a result there is a lack of reverberation and listeners envelopment whereby these areas are not suited for e.g. concert performances.

In order to be able to make also these spaces suited for concert performances an electro-acoustic enhancement system can be applied. Attention should not only be paid to the reverberation time, but also

to the distribution of the loudspeakers and level of the loudspeakers and reverberation. In order to be able to determine what performance is required from the enhancement system, it has to be determined primarily to what extent both volumes are coupled to each other. Therefore the theory of coupled spaces will be outlined in higher detail. Subsequently the design criteria in order to achieve a uniformity of coverage will be presented. Hereafter the presented theory will be applied on the design of one such a system, i.e. Systems for Improved Acoustic Performance (SIAP).

2. Theory of coupled spaces

Under balcony areas typically have a lack of late reflections, i.e. a lack of reverberance. This reduction in reverberant sound is already perceived after a few rows and is mainly a problem for concert performances. The fact that the under balcony area is acoustically detached from the main volume is called the coupled spaces effect.

In order to design a good coupled under balcony area, Beranek [1] has suggested that the depth of the under balcony area should not exceed the height of the opening of the under balcony area. Besides geometry of the under balcony area Barron [2] indicates that also the degree to which the sound is reflected from the main auditorium into the overhung space is of importance. Therefore an opening angle (θ) of at least 45° is suggested for every position in the under balcony area. Figure 1 presents a recommendation for a good under balcony design for concert halls.

Unfortunately there are a lot of under balcony areas which are not designed according to the design principles as suggested by Beranek and Barron. As a result the under balcony volumes are acoustically detached from the main volume.

When the coupling area is small relative to the under balcony volume the sound will not be uniformly distributed across the main volume and the under balcony volume. Based on statistical room acoustics it is possible to determine to what extent both areas are coupled with each other [3].

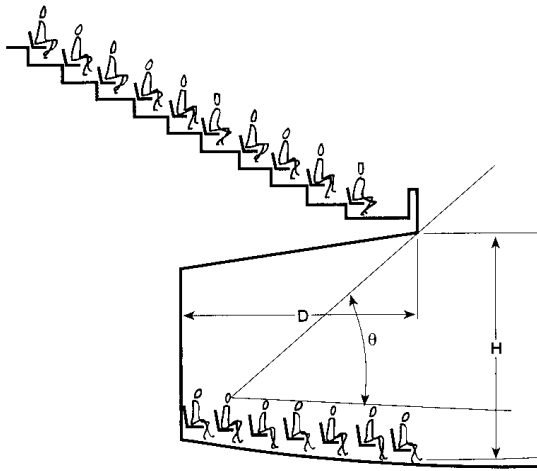


Figure 1 : Recommendation for a proper design of a balcony overhang [From: Beranek, 1996]

In order to explain the theory of the coupled spaces assume a multipurpose theatre with an orchestra shell on stage as presented below.

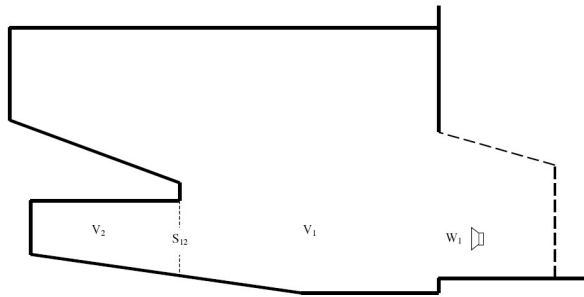


Figure 2: Multipurpose hall with under balcony area and orchestra shell

In the main volume V_1 a sound source with a sound power level W_1 is located on stage. Partly the sound in the main volume is absorbed, A_{10} , and partly the sound gets through the coupling area S_{12} into the under balcony area. Here again the sound is partly absorbed, A_{20} , and partly the sound gets back into the main volume.

When it is assumed that the sound source emits a constant sound power W_1 , there will be an equilibrium after a while.

As this is a so-called stationary situation it is possible to set-up energy equations. For the main volume this is:

$$(1) \quad W_1 - \frac{c}{4} A_{10} E_1 - \frac{c}{4} S_{12} E_1 + \frac{c}{4} S_{12} E_2 = 0$$

For the under balcony area the energy equation can be expressed as:

$$(2) \quad \frac{c}{4} S_{12} E_1 - \frac{c}{4} A_{20} E_2 - \frac{c}{4} S_{12} E_2 = 0$$

where

- W_1 : sound power level [W]
- c : speed of sound [$\text{m}\cdot\text{s}^{-1}$]
- A_{10} : absorption in the main volume [$\text{m}^2\cdot\text{Sab}$]
- A_{20} : absorption in the under balcony area [$\text{m}^2\cdot\text{Sab}$]
- E_1 : energy density in the main volume [$\text{J}\cdot\text{m}^{-3}$]
- E_2 : energy density in the under balcony area [$\text{J}\cdot\text{m}^{-3}$]
- S_{12} : coupling area [m^2]

As can be revealed the terms $\frac{c}{4} A_{10} E_1$ and $\frac{c}{4} A_{20} E_2$ in the equations (1) and (2) represent the amount of sound energy which is absorbed in the main volume in Watts, respectively the amount of absorbed sound energy in the under balcony area. Furthermore the terms $\frac{c}{4} S_{12} E_1$ and $\frac{c}{4} S_{12} E_2$ present the amount of energy, expressed in Watts, which travels from the main volume to the under balcony area and vice versa.

In order to calculate the total absorbing area of the main volume V_1 it is assumed that the coupling area S_{12} is completely absorptive. Thus the total absorbing area of the main volume can be expressed as

$$(3) \quad A_{11} = A_{10} + S_{12}$$

Similarly the total absorbing area of the under balcony area V_2 can be expressed as

$$(4) \quad A_{22} = A_{20} + S_{12}$$

2.1. Coupling factor

The coupling factor k_{21} determines to what extend the under balcony volume is coupled to the main volume. The coupling factor k_{21} can be expressed as:

$$(5) \quad k_{21} = \frac{E_2}{E_1} = \frac{S_{12}}{A_{22}} = \frac{S_{12}}{A_{20} + S_{12}}$$

When the coupling area S_{12} is much larger or equal to the absorbing area in the under balcony volume A_{20} , the factor k_{21} will become 1. Acoustically this implies that there is no significant reduction of energy at the transition from the main volume to the under balcony volume. Thus the under balcony area is coupled to the main volume.

On the other hand, when the coupling factor k_{21} is smaller than the absorbing area in the under balcony volume, the reduction of energy at the transition is

large. Generally the coupling is judged to be acceptable when the coupling factor k_{21} is 0.5 [3].

By combining the coupling factors k_{21} and k_{12} the mean coupling coefficient \bar{k} can be obtained. This is defined as [3]:

$$(6) \quad \bar{k} = \frac{S_{12}}{\sqrt{A_{11} \cdot A_{22}}}$$

This is the geometrical mean of each room's total absorption that is coupling absorption [4].

2.2. Prediction of the reverberation curve

In order to be able to determine the reverberation curve the dynamic situation instead of the stationary situation has to be evaluated. This is because of the fact that the energy density decreases when the sound source is turned off. Thus for the main volume equation (1) becomes:

$$(7) \quad \frac{c}{4}(A_{11}E_1 - S_{12}E_2) = -V_1 \frac{dE_1}{dt}$$

And similarly for the under balcony volume equation (2) becomes

$$(8) \quad \frac{c}{4}(-S_{12}E_1 + A_{22}E_2) = -V_2 \frac{dE_2}{dt}$$

Where V_1 and V_2 are respectively the main volume and the under balcony volume.

From the equations (7) and (8) a relation between the decay coefficient δ and the reverberation time T can be obtained:

$$(9) \quad \delta = \frac{6.9}{T}$$

As a result the reverberation time in the main volume can be approximated by

$$(10) \quad E_1 \approx \frac{4W_1}{cA_1} \left(e^{-2\delta_1 t} + x^2 \frac{\delta_1^2}{(\delta_2 - \delta_1)^2} \cdot e^{-2\delta_2 t} \right)$$

Where

- δ_1 : decay coefficient of the main volume [s^{-1}]
- δ_2 : decay coefficient of the under balcony volume [s^{-1}]
- t : time [s]

The factor x presents the geometrical average of both coupling factors k_{21} and k_{12} :

$$(11) \quad x = \sqrt{k_{12} \cdot k_{21}}$$

For the under balcony volume the reverberation time can be approximated by

$$(12) \quad E_2 \approx \frac{4W_1}{cA_1} \left(\frac{\delta_2}{\delta_2 - \delta_1} e^{-2\delta_1 t} - \frac{\delta_1}{\delta_2 - \delta_1} \cdot e^{-2\delta_2 t} \right)$$

3. Design criteria

After determining if a certain area is acoustically uncoupled from the main volume, an acoustic enhancement system can be used to fill in the missing reflections [5], [6]. Therefore not only attention has to be paid to the quality and the length of the reverberation but also to the loudspeaker characteristics and lay out. Concerning the loudspeakers a few criteria can be formulated. First of all it is important that the power out put of the loudspeakers is sufficient. Because of the dynamic range of an orchestra, the loudspeaker also needs to be capable to produce such a dynamic range.

Besides the quality of the loudspeaker output, the output itself, i.e. the level of the loudspeakers, has to be considered. As it is aimed to imitate a real concert hall, there is a certain amount of listeners envelopment required, which has to be perceived as it is a real concert hall one is listening in. This results in the second criterion, i.e. a correct balance of the loudspeakers. When the level of the loudspeakers is too low, the perception of envelopment is limited. On the other hand if the level of the loudspeakers is too high, the perception of envelopment becomes unnatural.

Another devastating problem could be that people are able to point out the loudspeaker where the reverberation is coming from. This indicates a lack of diffusion, or in terms of loudspeakers, poor loudspeaker coverage.

In order create a proper balance of the loudspeakers in an acoustically uncoupled area, the loudspeaker layout becomes very important. It is required to have a uniformity of coverage in the major part of the under balcony area.

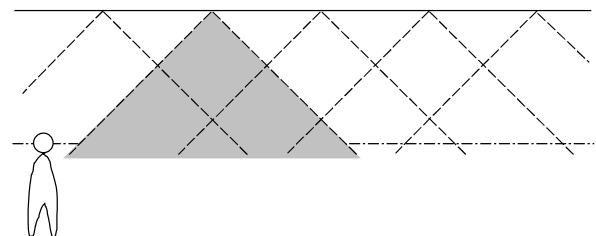


Figure 3: Concept of a good loudspeaker layout in order to meet the design criteria.

Therefore it is required that at least three different loudspeakers have to contribute to the perceived

reverberation at a certain position in the uncoupled area. Figure 3 shows the concept graphically.

As can be observed from the drawing, poorly coupled spaces, i.e. under balcony areas with little height relative to the depth of the under balcony area, requires more loudspeakers and loudspeaker groups in order to meet the rule of thumb.

4. Conclusion

Multipurpose theatres, especially the modern ones, have very often poorly coupled spaces. Mainly these are the under balcony areas. In order to make these environments also suited for concert performances, an acoustic enhancement system can be applied.

Therefore primarily the known theorem of coupled spaces has to be applied. Additionally a few design criteria are presented to which the design of such a system should meet in order to create a high quality sound field, comparable to the sound field in an actual concert hall.

5. References

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