Agorá Acoustics - Effects of arcades on the acoustics of public squares

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This paper is part of a PhD work, dealing with the acoustics of the public squares (‘Agorá Acoustics’), especially when music (amplified or not) is played. Consequently, our approach will be to evaluate public squares using the same set of acoustics concepts for subjective evaluation and objective measurements as applied for concert halls and theatres. In this paper the acoustical effects of arcades will be studied, in terms of reverberation (EDT and T30), clarity (C80), intelligibility (STI) and other acoustical parameters. For this purpose, also the theory of coupled rooms is applied and compared with results. An acoustic modelling program, ODEON 7.0, was used for this investigation. Three different sizes of public squares were considered. In order to evaluate the ‘real’ effects of the arcades on the open square, models of all three squares were designed both with and without arcades. The sound source and the receivers were positioned in the open square as well as in the arcades (making four different combinations).The results show that, when adding arcades to an open square, an increase in reverberation time is observed: a criterion is studied to predict in which cases arcades have this effect. Arcades can also cause a decrease in Clarity (C80), Strength (G) and STI in the main open area. Arcades cannot be considered responsible for double decay in the open area; however the open square can cause a double decay under the arcades, if both sound source and receiver are positioned in the same arcade. Finally, the distribution of energy through the coupling surface is discussed using Statistical Energy Analysis (SEA).

1 Introduction

The acoustical effects of coupled rooms -a large room (R_1) coupled through a surface (S_{12}) to a small[1] room (R_2)- are well-known [1, 2].

Four different cases can be discussed:

A. Sound source and receiver in R_1
B. Sound source in R_1 and receiver in R_2
C. Sound source in R_2, receiver in R_1
D. Sound source and receiver in R_2

If the sound source is positioned in R_1 (cases ‘A’ and ‘B’), its sound power cannot be equally distributed into the two rooms; A_{10} is the equivalent absorption area of R_1 (all the surfaces except S_{12}), and A_{20} represents the same for R_2; calculating the power balance for the two rooms [2], the energy density for R_1 is obtained:

$$E_1 = \frac{4 \cdot W_1 / c}{A_{10} + A_{20} \cdot \dfrac{S_{12}}{A_{20} + S_{12}}} \qquad (1)$$

where: W_1 is the sound power.

[1] The adjectives “small” and “big” in this case are referring to the equivalent absorbing area related to the volume. In principle, the large room is the most reverberant of the two.

If the two rooms were treated as a single one, the term $S_{12}/(A_{20}+S_{12})$ (*‘coupling factor’*, k_2) would have been set to 1.

Two extreme cases can be studied:

1. $A_{20} >> S_{12}$ ($k_2 << 1$); in this case the coupling area is to be regarded as an open window.
2. $A_{20} << S_{12}$ ($k_2 \sim 1$); this is the case where the two rooms can be treated as one volume.

A case in between can be considered, too, when $k_2 = 0{,}5 \pm 0{,}3$. In this case the following rule-of-thumb can be adopted: if $A_{20} > S_{12}$, then the coupling area can be treated as an open window, otherwise R_2 can be treated as part of R_1 [2]. It is also important to observe that $k_2 = E_1/E_2$: if $k_2 \sim 1$ there will not be significant decrease in loudness passing from R_1 to R_2 [2]. Vice versa, if $k_2 \sim 0$, the drop-off of energy will be quite evident.

Also the coupling factor $k_1 = S_{12}/(A_{10}+S_{12})$, can be calculated. This is used when the sound source is positioned in R_2 (cases ‘C’ and ‘D’).

If the *‘mean coupling coefficient’* $\sqrt{k_1 \cdot k_2} << 1$, a non-linear sound decay is possible ([2, 5]).

2 Applying the theory to the case of public square and arcades

Our investigation concerns three public squares: a small (surface: 20 x 15m - height: 16m), a medium (surface: 39,2 x 24,8 - height: 20m) and a large open square[2] (surface: 68 x 44 - height: 20 m). Referring to the previous paragraph, the large room (R_1) is represented by the open *public square* area, while the small room (R_2) is represented by the covered *arcades*, which surround the 4 sides of the square. All arcades are 6m deep, 6m high and the coupling area is represented by the openings between the columns (section: 0,8m x 0,6m and height: 4m) placed with a mutual distance of 4 m. The floor is considered to be paved with smoothed tiles, the columns are of marble, while the façades consists of a mixture of concrete (~80%), glass (windows) and wood (doors and shutters). A scattering of 0,3 was chosen for both the façades and the walls inside the arcades to take irregularities into account. Values of A_{10}, A_{20}, S_{12}, as well as k_1 and k_2 and $\sqrt{k_1 \cdot k_2}$ and for all the squares, were calculated considering all the four sides/arcades: the 'coupling factor' k_2~0.85, which means that the two volumes (square + four arcades) can be treated as one. A non-linear sound decay is in principles not possible because the 'mean coupling coefficient' lies in the interval 0.4-0.6.

3 Running Odeon

Making measurements in real public squares is usually really complicated: background noises (cars, alarms, air-conditioning systems, church bells, tourists, etc.) make the work very difficult.

Nevertheless, one measurement campaign was done in a quite silent square in Copenhagen [7], and the results demonstrated that predictions by Odeon agreed well with measurements *in situ*. This indicated simulations to be a valid tool for study of the influence of the arcades.

3.1 The Odeon software

ODEON is a PC software used for simulation of interior acoustics of buildings. It uses prediction algorithms based on the image-source method combined with ray tracing and it's usually used for the prediction of acoustics in large rooms such as concert halls, opera halls, auditoria, etc.

3.2 Simulations and results

Figure 1 and Figure 2 show the models of the public square without and *with* arcades respectively.

[2] The proportions (3 x 2) of the large and medium squares respect the suggestion given by Vitruvius [3]

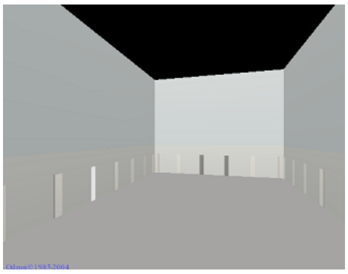

Figure 1 - Public square *without* arcades.

Figure 2 - Public square *with* arcades

All the acoustical parameters where calculated per octave by Odeon, and displayed in coloured grids showing the distribution of the acoustical parameters (EDT, T30, C80, STI, G, etc.) over the area of interest. In this way it was easy to compare results coming from the two different settings[3]. The grid represents the response for an empty square (i.e. without people). A large number of rays: 0,7 million (small square) to 1,5 million (large square), was used as the large totally absorbing sky surface causes a huge amount of energy (rays in the Odeon simulation) to be lost after a few reflections. An omni-directional point source was used.

All the results shown represent the mid frequency range (500 – 1k Hz octave band).

3.2.1 Cases[4] A & B

The sound source was positioned in the centre of the longer dimension. The condition $A_{20} < S_{12}$ is respected in all the three cases: the two 'coupled rooms' (open square area + arcades) can be treated as one volume, and adding the arcades can in principle cause a higher reverberation time.

T30

Regarding the small square, an increase of 0,4 s (from 2,9 to 3,3 s) in T30 is observed when adding arcades. Still a slight increase in T30 can be observed in the

[3] Adding arcades would be, of course, impossible in real life, where one has to deal with the characteristics of a place, without the possibility of changing any parameter and/or dimensions.

[4] For practical reasons cases A and B are discussed together, as well as cases C with D

medium sized square, while an imperceptible chance is observed on the large square.

Once it has been demonstrated that k_2 has the same value for all the considered cases and that $A_{20} < S_{12}$, one can predict the possible differences by comparing A_{20} and A_{10}.

Defining:

$$AA = \frac{A_{20}}{A_{10}} \quad (2)$$

The higher this ratio, the greater the effect of the arcades on the reverberation time. If AA is very close to 0 (like in the case of the large square), then it can be assumed that the second room will not have any effect on the reverberation. All the results regarding T30 are summarized in the following table.

Table 1: Values of the index AA and corresponding variations of T30.

	AA	$T30_{without}$	$T30_{with}$	ΔT30 (%)
Small sq.	0,11	2,90	3,30	14%
Medium sq.	0,06	3,60	3,70	2,8%
Large sq.	0,03	4,00	4,04	1%

STI[5]

Just considering the open area, when adding arcades a noticeable decrease in STI is observed (compare the open area in Figure 3 with the same area in Figure 4). Especially in the small square STI is affected by late reflections coming from the arcades. Also, one could notice that there is a part, around the source, which is not affected by the presence of arcades: this area is within the reverberation distance, and this behaviour is strongly correlated with the distribution of EDT. Even worse values of STI can be noticed under he arcades.

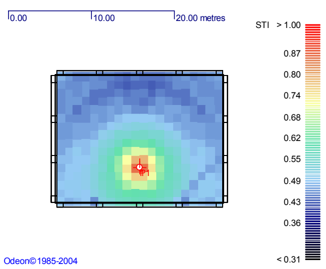

Figure 3 – Grid plot of STI – without arcades

[5] The considerations regarding STI are valid for the three sizes of squares considered.

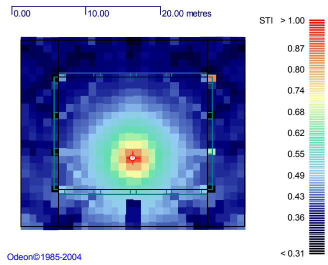

Figure 4 - Grid plot of STI – with arcades

SPL (G) and C80

For the three squares studied, the coupling factor is k_2 = 0,85-0,87: passing from the square area into the arcades, there will be a minor decrease in loudness. But in real situations an opposite behaviour can be perceived: the *impression* of *higher* loudness under the arcades than in the open square area, may be the result of geometric room acoustics conditions, causing shorter delay times, rather than a simple energy issue. This can be accompanied by a great clarity of sound, as well. Also, in real situations most of the late reflections (potential echoes or even flutter echoes) can actually be absorbed by the audience because, with all the façades being vertical, all these late reflections are coming mainly at a height from 0 to 2,5m (maximum source height), which is partially covered by the audience itself. Usually this causes C80 to increase (compare Figure 5 with Figure 6), especially under the arcades.

The first author once had the opportunity to listen to a concert in a small public square (actually the internal 'patio' of an old monastery) with arcades surrounding the main central area. The sound source was represented by a "viola da gamba", positioned in the main open area, played without amplification (quite low sound power). It was interesting to notice that a lot of listeners just left their positions in the centre of the main area (few meters from the musician) and went to listen to the music under the arcades, at *further* distance. In those new positions the music simply sounded better, having higher values of C80, shorter delay times, and some frequencies were "amplified" and "coloured" by the reflections from the floor and the ceiling.

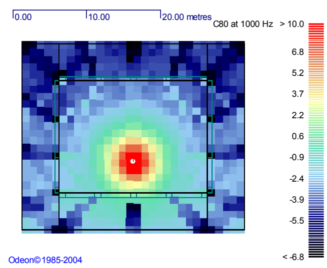

Figure 5 - C80. Grid response *without audience* in both the open square and the arcades' area.

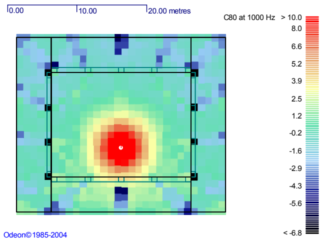

Figure 6 - C80. Grid response *with audience* in both the open square and the arcades' area.

3.2.2 Cases C & D

EDT and T30

Under the arcades EDT has low values if the receiver and the source are in the same arcade (see Figure 7). A very strong direct sound and early reflections are present, while the late reflections do not contribute to this part of the decay (0 to –10 dB). In the other three sides, the early components are weaker causing a less steep initial decay and EDT becoming higher and about equal to T30 (Figure 8). T30 shows much less variation between open area and arcades and between arcades (Figure 8). The fact that EDT is lower than T30 (when source and receiver are positioned in the same arcade) is actually a cue to detect a coupling decay.

STI

STI has very low values in almost all receiver positions, especially in the arcades' area far from the sound source. If a qualitative comparison is made between grid response from EDT (Figure 7) and STI (Figure 9) it's demonstrated once more that STI is more related to EDT than to T30.

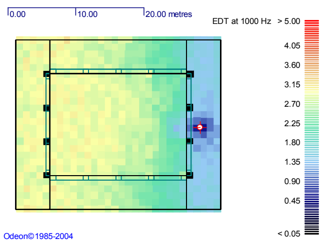

Figure 7 – EDT. Source in the arcade

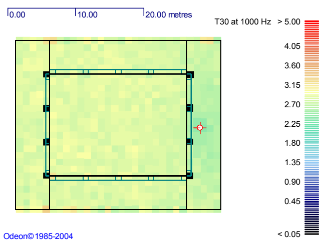

Figure 8 – T30. Source in the arcade

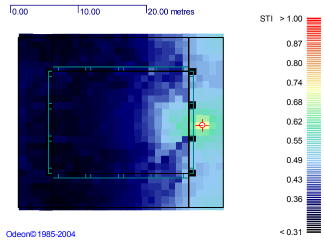

Figure 9 - STI. Source in the arcade

SPL (G)

An interesting observation can be made regarding SPL(=Strength[6], or G). If a comparison is made between Figure 10 (source in the arcade) and Figure 11 (source in the centre of the open area), G has higher values in one arcade if the receiver is positioned in the same arcade: one can conclude that, during a concert, positioning the source in the arcade, higher values (>3dB) of G are reached. This is because the energy density is greater by a factor A_{11}/A_{22} ($A_{ii} = A_{i0} + S_{12}$) than the energy density that would be produced by the same noise/music in the large square [2]. The ratio A_{11}/A_{22} is not calculated considering all the four arcades, but just the arcade in which the source and the receiver are positioned, because the other three arcades do not have any effect and can be treated as part of the open square. A_{11}/A_{22}, in these cases, can vary from 5,5 (small square) to 18 (large square), i.e. from 7,4 to 12 dB.

The influence of this factor is demonstrated by the fact that "street musicians" are usually playing under the arcades and not in the street/square (open space); of course this can be due also to other reasons: it is like playing in a room, which gives a higher sense of "intimacy". Also the presence of early reflections or modes give coloration to the sound.

Figure 10 also shows that high G values are found all along the arcade in which the source is placed, while the sound encounters some "difficulty" in getting out of the arcade. In fact in this case (source under the arcade) the ratio $E_{open\ square}/E_{arcade} = k_1$ which is always quite low.

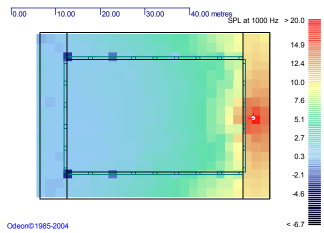

Figure 10 - SPL (=G) for the medium square. Source in the arcades

[6] In Odeon, when the gain is at 31 dB, SPL = G

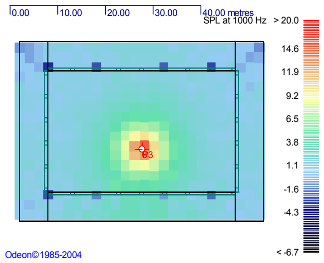

Figure 11 - SPL (=G) for the medium square. Source in the square area

Another way to explain this fact is by means of *Statistical Energy Analysis (SEA)*; If E_i is the energy density of the "room" I, V_i is the volume and M_1 is the modal density, then:

$$E_{mi} = \frac{E_i \cdot V_i}{M_i} \tag{3}$$

E_i is the energy per mode, where i=1 (for the open square) and i=2 (for the arcades). As $V_1 > V_2$, this yields $E_{m1} > E_{m2}$: i.e. the energy is transferred from the open square to the arcades and not vice versa.

C80

Plot of C80 (Figure 12) shows that under the arcades where the source is positioned, clarity has high values, and within the interval usually found in concert halls (from -5 to +3 dB) [9] In the other three sides of the arcades C80 is very low meaning that there are either low early reflections or strong late reflections, or both of them. The same can be argued for a large part of the open area.

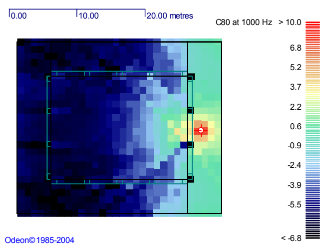

Figure 12 - C80. Source in the arcade

4 Considerations about the decay curves

Until now all the results considered relate to the acoustical parameters, which are calculated from the impulse responses. In the following we will look at whether the decay curve is linear or not.

A typical decay from a public square is shown in Figure 13 (along with the related impulse response, Figure 14). A linear decay was observed in the open square area when the source was positioned both in the same area and in the arcades. A strong direct sound and a certain delay between the direct sound and the first significant reflection cause a deep step (indicated by the dotted circle) in the very first part of the decay curve accompanied by a horizontal plateau (the "Initial Time Delay Gap").

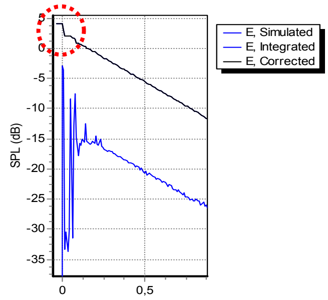

Figure 13 - Typical decay curve at one ear when both sound source and receiver are positioned in the open area.

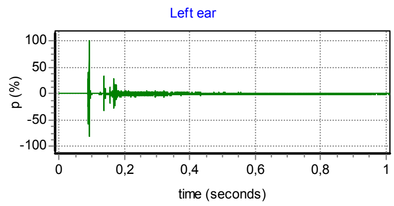

Figure 14 - Impulse response at one hear, when both sound source and receiver are positioned in the open area

4.1 Source in the arcade, receiver under the arcades

When the source is positioned in one of the arcades, two possible cases can be considered:

1. *Receiver in the same arcade as the source*

When positioning the source and receiver in the same arcade, it is relevant to relate A_{10} and S_{12} to *one* arcade only, as this behaves differently from the rest of the square as described in the previous sections. In this case $\sqrt{k_1 \cdot k_2}$ =0,2, so that a double sloped decay is still possible.

This is illustrated in Figure 15 and Figure 16. Obviously, there are many strong early reflections within 30 ms (Figure 16), then, after a certain delay some new strong reflections are heard, mainly from the square area. By means of auralisation it's possible to detect if such late reflections are perceived as echoes: during a song it is not really possible to hear the double decay because this is "hidden" by further notes, but at the end of the song/speech one can hear the tail of the decay, coming from the open square. Of course this is possible only if the level in the second slope is higher than the background noise or at least higher than the threshold of human hearing; in other words one has to play/talk loud to be able to hear the sound coming also from the coupled room.

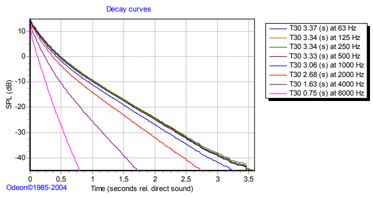

Figure 15 - Double slope decay curve for the large square, when both sound source and receiver are positioned under the same arcade.

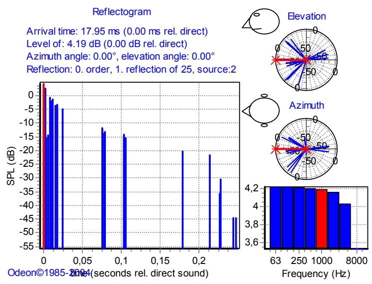

Figure 16 - Reflectogram for the large square, when both sound source and receiver are positioned under the same arcade.

2. Receiver in one of the other arcades

Positioning the receiver in the other arcades (without changing the position of the source), a linear decay is heard. The slope of the decay in Figure 17 is the same as the slope in the second part of the decay in Figure 15, meaning that one hears mainly the reverberation of the open square; no early reflections are present.

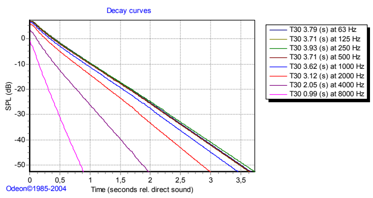

Figure 17: Decay curve for the case 'source in one arcade and receiver in another arcade'.

5 Summary

Adding arcades to a public square causes EDT and T30 to increase with a percentage which is function of the defined AA ratio once one knows that the two coupled spaces can be treated as one.

Other parameters (C80, STI, G) decrease in the open area when adding the arcades, especially in the zone/area closest to the arcades.

When the sound source is positioned in the open square, perceived high loudness in the arcades is mainly caused by increases in early reflections, rather than energy balance between the two 'rooms'.

Clarity of sound has higher values, especially in the arcades, when the audience is added into the square and the arcades, because many of the late reflections are attenuated by the audience itself, demonstrating that the height of the façades is not responsible for late strong reflections, if a low scattering is assumed.

The main consequence of positioning the source under an arcade is higher values of SPL in this arcade, compared with the case when the source is positioned in the open square area.

A double slope decay can be observed (and "heard" by means of auralisation), when both sound source and receiver are positioned under the same arcade.

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