ACOUSTICS OF LARGE SPACES

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Most of the consulting work dealing with room acoustics is based on reverberation time predictions which use simplified formulas. If the volume of the room is between 30 and 30000 cubic meters, a great deal of useful though inaccurate data is available on theaters, music rooms and concert halls, conference rooms, etc.

The role of the acoustical consultant consists in adjusting the acoustical characteristics of a room to its uses and to provide acoustical comfort and good listening conditions. In the case of multi-purpose halls, this is a challenge. In the case of very large spaces which can accomodate large crowds, data is scarce and the consultant soon discovers that classical prediction methods fail, that existing models are useless and that common criteria do not apply.

Introduction

Physically, very large volumes can be considered to be non-diffusing; the sound pressure level varies with the distance from the source. Reverberation time, which is commonly used to describe the acoustical characteristics of a bounded diffused sound field, is no longer unique: its value varies according to the position of the listening point and, in particular, near the volume boundaries. Often, walls which are far from one another are parallel and generate annoying echoes. Also, for architectural effects or structural reasons, large spaces are enclosed in concave surfaces which are focalizing.

To obtain good speech listening conditions and a satisfactory comfort, one has to deal in particular with frequencies between 125 and 1000 Hz; for higher frequencies, air absorption over long travelling distances plays an important role.

1. Elementary theory

In practice, the acoustical consultant may have to face two types problems:

a. a very large volume exists and its architecture has to be preserved,
b. the building is a new one and proper architectural design, excluding parallel walls, focalizing surfaces, etc., can be implemented.

In the first case, 'in situ' measurements of the impulse response and an average evaluation of reverberation time for various points will be used to determine the acoustical properties of the room, identify focal points and to seek solutions. If the building is in use, a measurement of noise levels for octave bands between 125 and 4000 Hz can be performed; speech intelligibility requires an emergence of about 20 dB of the useful signal above background noise. (Since the sound power level of a normal voice in the low and medium frequencies is approximately 60 dB, the background noise level should not exceed 40 dB.)

In both cases, to estimate the equivalent absorption area of the room, one may use classical formulas for reverberant rooms and diffuse fields using in Sabine's formula a value of mean free path which takes into account the room dimensions.

The formulas which can be used to estimate the useful parameters are:

$$L_p^{ambient} = 10 \log \left(n \frac{\bar{W}^{voice}}{R} \frac{1\, S}{V} \rho c \right)$$

$$R = \frac{S(\bar{\alpha} + m\,l)}{(1 - (\bar{\alpha} + m\,l))} = \frac{\bar{A}_{room}}{(1 - (\bar{\alpha} + ml))}$$

$$T = 0.04 \frac{S\, l}{\bar{A}_{room}}$$

where

$L_p^{ambient}$ (dB) is the ambient sound pressure level,

n is the average number of people in the space under study,

$\bar{W}^{voice}$ is the average sound power level of a normal voice,

$\bar{A}_{room}$ is the equivalent absorption area of the room, m is the absorption coefficient in neper per meter,

l is the mean free path (taking into account the room dimensions)

V is the room volume,

0.04 is a constant of dimensions [sec/m],

$\bar{\alpha}$ is the average absorption coefficient of the room,

S is the total area of the walls,

T is the reverbation time.

Listening conditions in large spaces can be improved with an ancient technique, used in antique theaters and in churches, Helmholtz resonators. They have been used in Greek theaters to increase the duration of the sound; vases release energy after the direct sound from the source has vanished. In churches, on the contrary, they have been used to absorb unneeded energy, thus increasing speech intelligibility.

In contemporary buildings, series of resonators tuned at different frequencies such as 125, 250 and 500 Hz, have been designed; the distance between resonators can be optimized to reinforce their effects.

Simple formulas can determine the resonance frequency, the optimum absorption area and the average absorption area per resonator, the number of resonators and the average distance between them:

$$f_0 = \frac{c}{2\pi} \frac{S}{\sqrt{\nu . V}}$$

$$(\delta A_{max})_{opt} = \frac{\lambda_0}{2\pi}$$

$$\delta A_{ave} = (\delta A_{max})_{opt} * \cos 45$$

$$\delta A_{ave} = \frac{A}{n}$$

$$e_{ave} = 0.4 \lambda_0$$

where

f_0 is the resonance frequency,

S is the cross-section area of the neck,

l is the neck length,

V is the cavity's volume,

ν is the neck's volume: $\pi a^2 * (1 + \frac{16\ a}{3\pi})$

a is the neck's radius,

$(\delta A_{max})_{opt}$ is the optimal absorption area of the resonator at its resonant frequency,

A is the total absorption area needed at the design frequency,

n is the number of resonators,

e is the average distance between resonators.

2. Real examples of treated large spaces

Recently, some very large volumes have been studied and have received an acoustic treatment designed to improve acoustical comfort and communication:

- the Great Hall of the Orsay Museum in Paris (180000 m3),
- the architecturally famous 'Halle Tony Garnier' in Lyon with 275000 m3,
- the Grande Halle at La Villette in Paris with 300000 m3.

Problems other than internal acoustics have been dealt with in those buildings:
- effect of external environment, insulation against airborne noise and vibrations,
- effect of internal environment, insulation against airborne noise and vibrations created by technical equipment.

Of course, reverberation time measurements have been performed in the buildings before transformation; simple octave band procedures, between 63 and 4000 Hz were followed.

In the Orsay museum, values varied between 8 and 4 seconds in the empty volume with reflecting walls (figure 1). In the Halle Tony Garnier, results are shown in figure 2; the volume was empty but large openings existed in the walls altering results at medium frequencies.We will look in detail at the case of the Orsay Museum, the most complex and elaborate.

From the measured results, it was deemed necessary to decrease reverberation time to 3 seconds if possible or, at least, to 4 seconds. One thousand visitors would generate levels of 50 dB(A) and speech intelligibility would be sufficient only within one meter of the speaker.

Some critical areas were identified such as the end of the large hall where visitors can take escalators to higher levels. Special treatment was needed there because of higher noise levels and of easy propagation along the walls to the rest of the Great Hall. Moreover, the main central street or 'Cours' is limited by parallel stone walls.A number of measures were needed to obtain the required acoustical comfort. The small exhibition rooms lining the main street were left open playing the role of open windows. But more importantly it was necessary to reduce reverberation time around 500 Hz, with the worst values of 8.5 seconds, and eliminate focalizations without altering the existing building, a classified historical monument, or interfering too much with the project of the interior architect, Gae Aulenti. Helmholtz resonators provided the answer.

2.1. Large resonators

Large cubic resonators were designed around four complementary frequencies for each of the 996 plaster decorative 'flowers' of the Great Hall of the Orsay Museum (figure 3). This option became possible only when the architects decided to replace all the existing 'flowers' with identical but brand new plaster 'flowers'. It was then relatively easy to hide behind the 'petals' the necks of the four resonators.They were tuned respectively around 80, 125, 180 and 250 Hz with Q's chosen to create overlap; mineral wool was placed inside each of the 3984 resonators.

2.2. Small resonators in rows

Spherical and cylindrical resonators centered around frequencies between 125 and 400 Hz were spread throughout the building and notably around the escalators'area and, whenever possible, on vertical walls of the ground floor and along the 'Cours'.

Typically two neck lengths were used, 5cm and 17 cm, with six center frequencies between 127 and 412 Hz (figure 4). Glass wool was used in the cylindrical and spherical volumes, which varied between 2.2 and 0.32 liters.

2.3. 'Classical absorption'

Even though the interior of the building is almost entirely mineral, it was possible to hide in remote invisible corners and edges some absorbing material. It was not much but it helped solve the problem at medium and high frequencies.

2.4. Results

A rough computation of reverberation time in the 'Great Hall' had predicted a reduction from 8.5 to 6 seconds in the mediums.

Once construction was completed, it was possible to repeat the initial reverberation measurements and to compare results before and after as shown in figure 5.

The results show a significant reduction of reverberation time and a smooth curve is obtained for medium frequencies; in fact, reverberation time is quasi-constant between 125 and 1000 Hz and drops dramatically at low and high frequencies.

When one walks into the completed building, several striking phenomena can be observed:

- in spite of the large crowds, reaching sometimes 10000 people in the 'Great Hall', the background noise is comfortable,
- focalization effects and echoes from distant flat glass walls are no longer disturbing,
- speech intelligibility is remarkably good and the critical distance is often larger than two meters; conversations can easily be held and tour guides can be heard by a relatively large number of visitors.

Several experiments have been made since in the building to assess whether acoustical comfort and speech intelligibility is satisfactory to most users.It actually seems to be the case! It means that reverberation time is not a good measure in very large volumes and that new methods could be developped to predict and evaluate acoustical comfort and speech intelligibility in volumes of the order of 200000 m3. The Orsay Museum, the Grande Halle and the 'Halle Tony Garnier' where similar results have been obtained or can be expected constitute a rare experimental set up.

In any case, one can conclude the a pragmatic approach making use of ancient techniques such as resonators combined with classical absorption can bring results which are beyond what the designer had expected using the rough prediction methods available today.

o. References

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Figure 1: Orsay Museum, Reverberation Time before Treatment

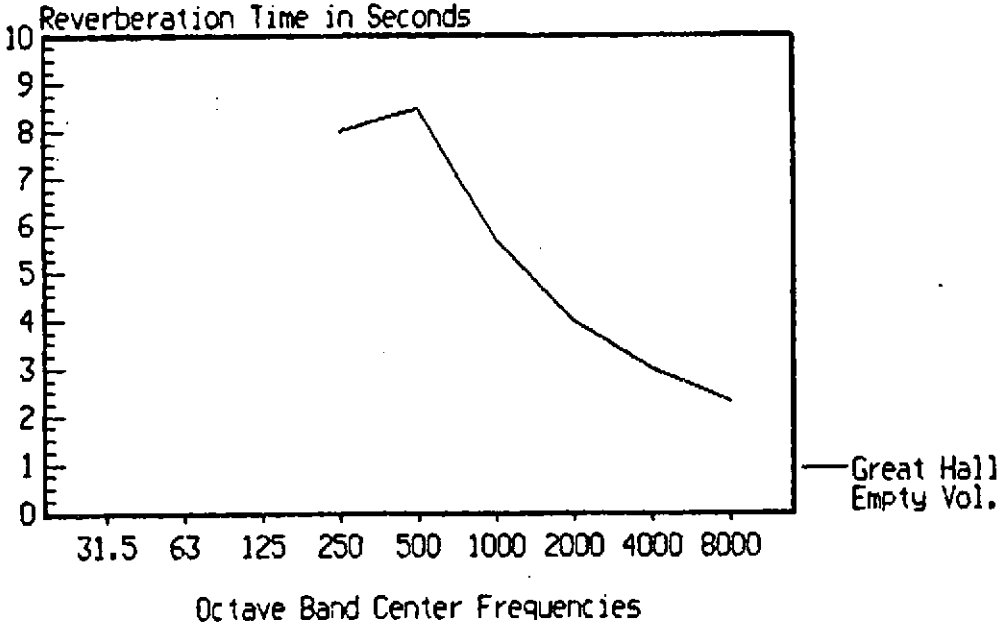
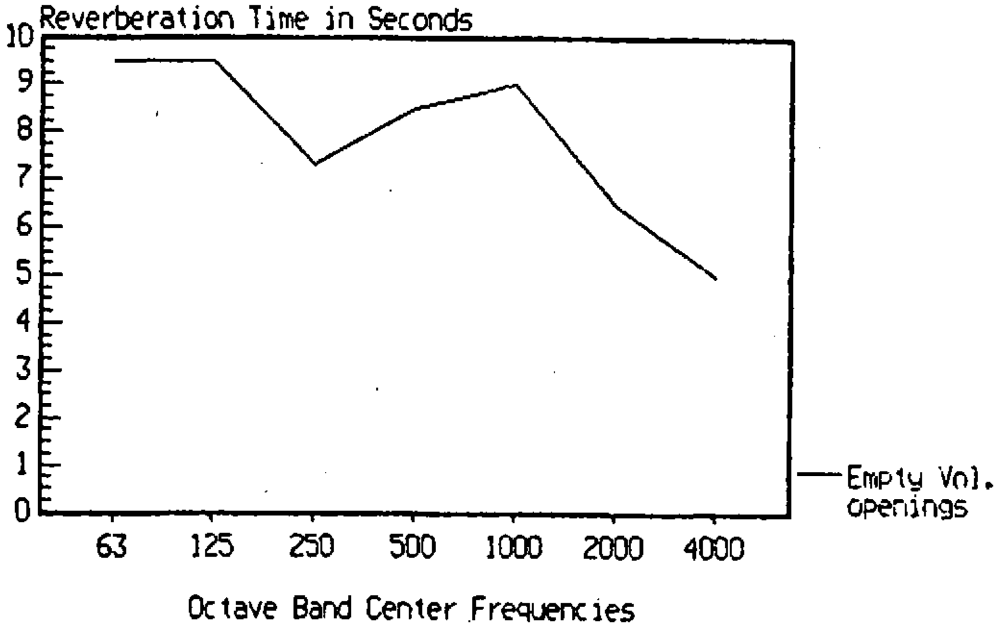


Figure 2:"Halle Tony Garnier"
Initial Reverberation Time



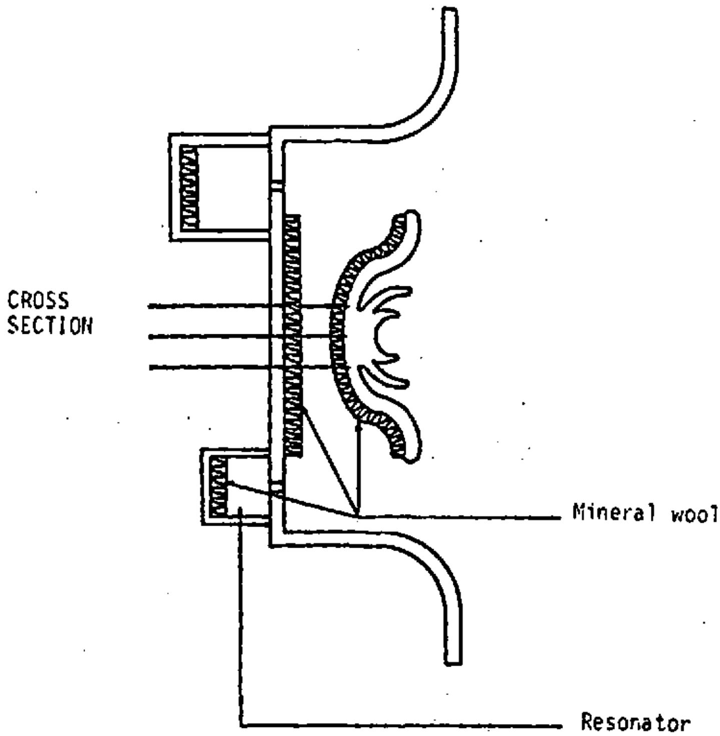
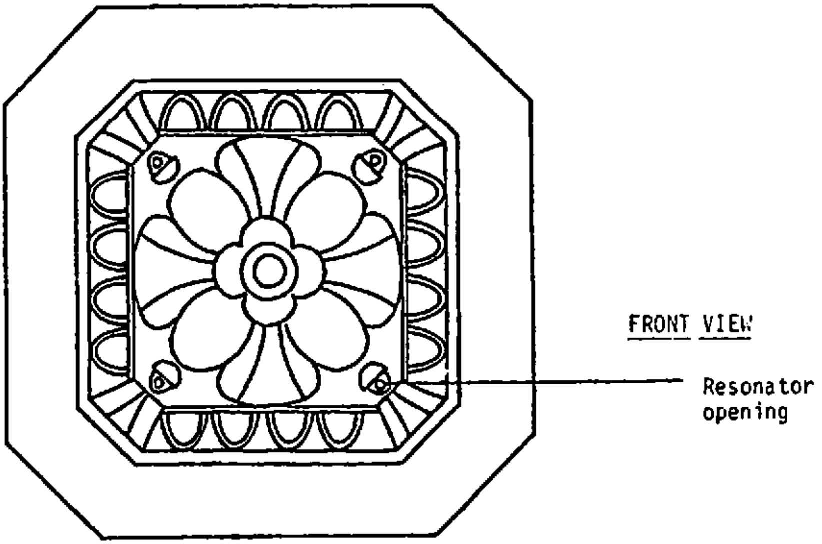
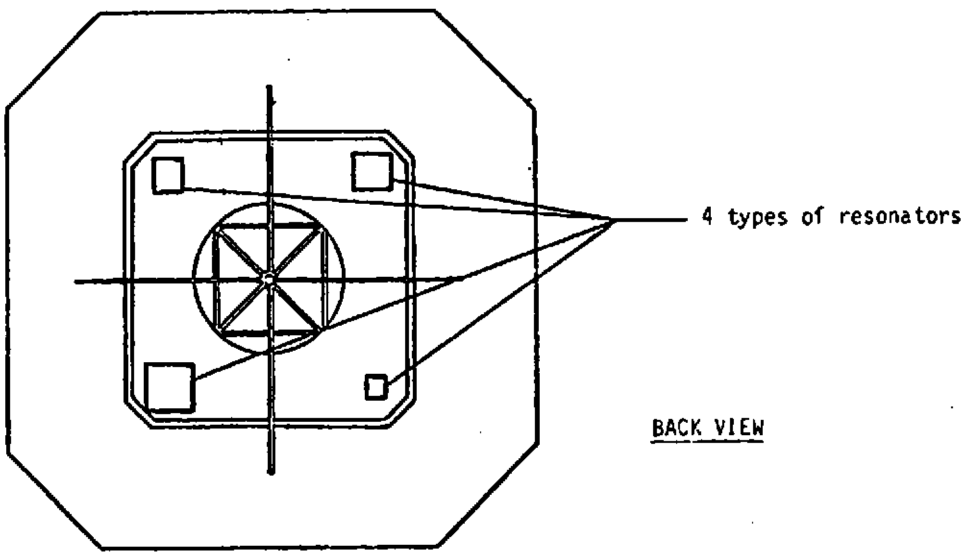


fig 3


FRONT VIEW
Resonator opening


4 types of resonators
BACK VIEW

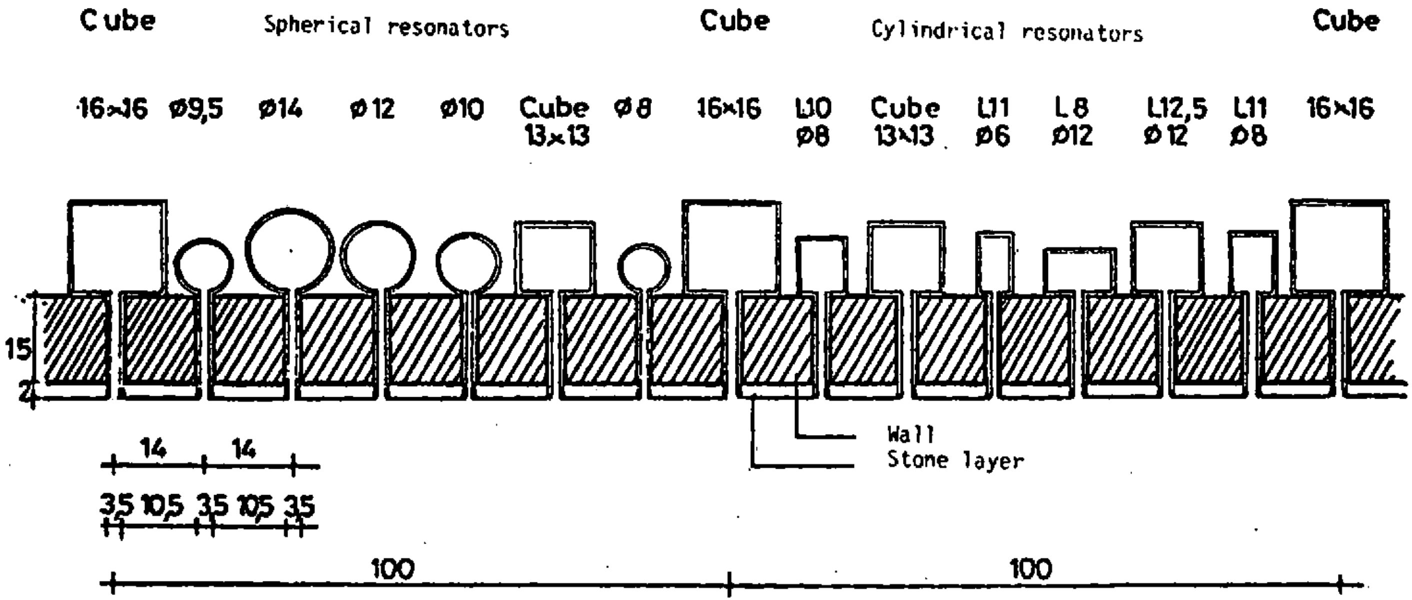

Cube
Spherical resonators
Cube
Cylindrical resonators
Cube
16×16
Ø9,5
Ø14
Ø 12
Ø10
Cube 13×13
Ø 8
16×16
L10 Ø8
Cube 13×13
L11 Ø6
L 8 Ø12
L12,5 Ø 12
L11 Ø8
16×16
15
2
Wall
Stone layer
14
14
3,5 10,5 3,5 10,5 3,5
100
100

Figure 5: Orsay Museum, Reverberation Time with Acoustical Treatment