Acoustic analysis by computer simulation for building restoration

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This paper presents the result of a didactic experience about the acoustic analysis of same ancient churches, in the study on the propagation of musical sound and, finally, in the proposal of acoustic modification with light interventions.

Introduction

The restoration of ancient buildings consists of two main applications: the restoration of architectural elements for to restore they own original performances and the maintenance or the change or the extension of use of architectural spaces.

In this meaning it’s very usually by now to search for particular ancient building different uses besides those original (i.e. ancient church for concert). In this way it’s possible to increase the interest for the restoration and to find the necessary financial resources.

We have treated this argument inside the teaching of “Design of building components” during the 4th year of degree in Building Engineering. In particular we have done a very interesting didactics experience about the plan of use of ancient church for concert.

Software programs used for computer simulation

Software programs which allow to make acoustic analysis by computer simulation represent an important innovation for design engineers in architectonic acoustic.

By these software programs it is possible to study acoustic characteristics of buildings, to plan hypothetical acoustic modifications and to simulate the consequences on the sound propagation.

At the moment they are on sale a lot of computer systems which perform acoustic simulation by Ray Tracing based methods.

In particular, the paper presents a study on the propagation of musical sound into ancient churches, where occasionally concert performances are held. The acoustic analysis is executed by computer simulation made by RAMSETE software.

The selected churches were built in Genoa city between the Eleventh and the Seventieth century. This work was developed in the framework of a project aimed at creating new music halls using the existing old buildings, generally dedicated to other purposes
RAMSETE software

- For computer simulation RAMSETE software uses the Pyramid Tracing method, which provides more precise results than Ray Tracing method. This software program presents the following improvements:
  - RAMSETE can take into account also second order diffraction's, which are important for studying thick sound barriers, or finite-size obstacles such as buildings. This make RAMSETE the only ray Tracing software which can be used in indoor-to-outdoor studies and vice versa. In fact on the road, in urban areas or in industrial areas there is the problem of noise needs to be monitored and to be obstructed with sound barriers.
  - RAMSETE software is very useful to estimate the acoustic parameters which regulate the sound propagation and the transmission of speech into closed spaces.

The following acoustic parameters are estimated by RAMSETE software:

- $T_{60}$ (reverberation time): the decay time of the sound level to one millionth of its initial energy;
- ITDG (initial time delay gap): the delay between arrival of direct sound and arrival of early reflection to listener;
- $C_80$ (early to late sound index or objective clarity): the ratio of direct sound to reverberation sound;
- $D$ (early energy fraction): it is defined conceptually as a subdivision between useful and detrimental energy;
- STI (speech transmission index): used for predicting speech intelligibility.

- The RAMSETE applications are in WINDOWS which is the most famous operating system for PCs; this allows an easy use to all users. The results files (impulse responses, acoustical parameters) can be imported in spreadsheets (e.g. Excel sheets) or edited in Microsoft editing programs.

RAMSETE characteristics

This software is composed by six programs:

- RAMSETE CAD which permits to draw geometric and structural modelling of analysed buildings.
- MATERIAL MANAGER which is a database where there are the absorption coefficients of the main materials used for building and furnishing.
- SOURCE MANAGER which is a database containing a lot of shapes of sound sources.
- RAMSETE TRACE which permits to evaluate the acoustic parameters by computer simulation.
- RAMSETE GRAPH and RAMSETE VIEW which allow to render the results of acoustic analysis by tables and by colour graphics.

RAMSETE CAD

This program is a CAD for the creation of tridimensional geometry which permits to work with the realised AUTOCAD designs. On video more windows are simultaneously shown reporting plant, section and assonometry of the studied building. In Fig. 1 there is an example of a RAMSETE screen.

There is a window of “tools”, like that showed in Fig. 2, which provides to introduce the main structural parts: floor, walls, roofs, doors, windows. The tracing is made by mouse, but in the tool windows always appear the revised co-ordinates. One can introduce directional springs and receivers.
MATERIAL MANAGER
Excel type sheets contain data about absorption and sound proofing of materials. The user shall be able to easily create new materials by introducing the name and the corresponding acoustic characteristics in the data sheet. One can visualise the absorption coefficients or the phonoisolation dB powers in the frequency band from 31.5 up to 16000 Hz.

SOURCE MANAGER
This program generates and visualise the files containing data on the sound sources (SPK). It contains a module, called ISO 3744 (3746), which allows the direct use of sound levels corresponding to a sound source.

It is possible to build 8 microphones surfaces, 5 or 9 parallelepiped surfaces and 10 microphones hemispherical surfaces.

Source data can be visualised or edited in tables.
The program allows to read results of RAMSETE TRACE computations and to see in graphic form the following informations:

- impulse response of each receiver or room average response;
- decay curve;
- octave spectrum for each receiver; Fig. 3,
- table containing numerical values of all parameters, Fig. 4.
RAMSETE VIEW

It is a post-processor useful for performing 3D views of structures plotted by RAMSETE CAD or AUTOCAD, or for mapping the results of RAMSETE analysis (reverberation times, sound levels) and the 2D or 3D acoustical parameters, like showed in Fig.5 and Fig 6.

Example of acoustic analysis by RAMSETE software: S. Donato church

San Donato church is the most important example of Romanic style in Genoa. The church has a rectangular plan (31.4x12.6 m), developed on three naves; over the transept, in the centre, there is a magnificent octagonal dome. The approximate volume is 5400 m$^3$. The walls rise by 10 m and consist of hewn stone. The roof has double wooden pitch. These building materials have good absorption coefficients, which cause fair sound propagation for a church.

Acoustic analysis included computer simulations and experimental tests:

Computer simulations consisted of the following steps:

- development of geometric and structural modelling of the analysed churches including the position and the type of sound source and the position of listeners;
- description of materials used in building and furnishing the churches;
evaluation of the acoustic absorption coefficient for each material;
comparison of results obtained by simulations with those obtained by experiments;
tuning of the computer model based on results coming from experimental tests;
project of not standing acoustic modifications to be placed in the churches;
recalculation of acoustic parameters by computer simulation after the designed acoustic modification.
In situ tests, conducted by using a sound level meter and a pistol-shot, allowed the computation of the experimental reverberation time.
Main acoustic parameters of San Donato church are exposed in the following tables:
a) Sabin’s reverberation time $T_{60}$ computed for octave centre frequency (see Table 1)
b) parameters calculated by computer simulations (see Table 2).
c) reverberation time $T_{60}$ obtained by experimental tests (see Table 3).

#### TABLE 1: Sabin’s reverberation time $T_{60}$ in S. Donato church

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>31.5 Hz</th>
<th>63 Hz</th>
<th>125 Hz</th>
<th>250 Hz</th>
<th>500 Hz</th>
<th>1 kHz</th>
<th>2 kHz</th>
<th>4 kHz</th>
<th>8 kHz</th>
<th>16 kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{60}$</td>
<td>11 s</td>
<td>7 s</td>
<td>7.7 s</td>
<td>6.8 s</td>
<td>5.5 s</td>
<td>4.7 s</td>
<td>4.4 s</td>
<td>4.3 s</td>
<td>3.3 s</td>
<td>3.0 s</td>
</tr>
</tbody>
</table>

#### TABLE 2: Acoustic parameters in S. Donato church by computer simulation

<table>
<thead>
<tr>
<th>Acoustic parameter</th>
<th>Frequency 1 kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDT</td>
<td>2.700 s</td>
</tr>
<tr>
<td>$T_{60}$</td>
<td>2.354 s</td>
</tr>
<tr>
<td>ITDG</td>
<td>45 ms</td>
</tr>
<tr>
<td>D</td>
<td>0.27</td>
</tr>
<tr>
<td>$C_s$</td>
<td>-0.8 dB</td>
</tr>
<tr>
<td>STI</td>
<td>0.41</td>
</tr>
</tbody>
</table>

#### TABLE 3: Reverberation time $T_{60}$ obtained by experimental tests

<table>
<thead>
<tr>
<th>Microphone position</th>
<th>63 Hz</th>
<th>125 Hz</th>
<th>250 Hz</th>
<th>500 Hz</th>
<th>1 kHz</th>
<th>2 kHz</th>
<th>4 kHz</th>
<th>8 kHz</th>
<th>16 kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.6 s</td>
<td>2.4 s</td>
<td>2.4 s</td>
<td>2.8 s</td>
<td>2.8 s</td>
<td>2.4 s</td>
<td>2 s</td>
<td>1.4 s</td>
<td>0.8 s</td>
</tr>
<tr>
<td>2</td>
<td>2.8 s</td>
<td>2.2 s</td>
<td>2.6 s</td>
<td>2.8 s</td>
<td>2.6 s</td>
<td>2.4 s</td>
<td>2 s</td>
<td>1.6 s</td>
<td>0.8 s</td>
</tr>
</tbody>
</table>

When the church is empty, a source placed in the centre of the transept causes a reverberation time $T_{60}$ varying in the range [1,3] seconds, which is acceptable for the audition of music and speech.

The other computed parameters show a good equilibrium between reverberated sound and direct sound.

For San Donato building, which presented itself good acoustic parameters, not standing acoustic modifications were designed in order to improve the quality of sound propagation when concert performances occur.
Since Italian authorities do not allow to make permanent and “strong” modifications into the ancient buildings, the acoustic project was aimed at performing light but effective modifications.

Absorbent curtains were placed in the central nave and moving panels were placed throughout the arcade of the lateral naves. After these light modifications, recalculation showed significative improvement in acoustical parameters (see Table 4).

**TABLE 4: Computed acoustic parameters in S. Donato church after acoustic modification**

<table>
<thead>
<tr>
<th>Acoustic parameter</th>
<th>Frequency</th>
<th>1 kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDT</td>
<td></td>
<td>1.4 s</td>
</tr>
<tr>
<td><strong>T</strong>&lt;sub&gt;30&lt;/sub&gt;</td>
<td></td>
<td>2.04 s</td>
</tr>
<tr>
<td>ITDG</td>
<td></td>
<td>40 ms</td>
</tr>
<tr>
<td>D</td>
<td></td>
<td>0.36</td>
</tr>
<tr>
<td><strong>C</strong>&lt;sub&gt;so&lt;/sub&gt;</td>
<td></td>
<td>2.7 dB</td>
</tr>
<tr>
<td>STI</td>
<td></td>
<td>0.51</td>
</tr>
</tbody>
</table>

Romanic churches generally present the best acoustic characteristics due to use of building materials with high absorption coefficient. Thus, they can be easily adapted to musical performances of good quality by introducing simple acoustical modifications.

In order to validate the proposed approach and the acoustic project, classical music was synthesised by a sound simulator, using the acoustical parameters computed before and after the proposed modifications. In the second case, an improved audition of the music was obtained.

**Conclusions**

Software programs such RAMSETE can efficiently improve the acoustic analysis and the design of acoustic modification in indoor and outdoor studies.

Computer simulation relates information on reverberated sound to direct sound and provides new parameters which are very useful for engineer projects.

**References**

