ACOUSTICAL ASPECTS OF THE SAGRADA FAMILIA CHURCH

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ABSTRACT
It is said that Antoni Gaudi (1852-1926) envisaged the Sagrada Familia as a gigantic musical instrument. Each pinnacle seems to be designed as a belfry, in which many tubular bells will be installed. Its upper section of the Nativity Façade has numerous windows with characteristic louvers. The lower section is almost closed and connected to the nave through muffler-like structures. Therefore, Gaudi’s bell music is to be radiated exterior as well as to be propagated interior to the nave. Acoustic radiation from the windows and propagation through lower structures are simulated by two-dimensional FDTD (Finite Difference in Time Domain) method. The window yields a broad directivity pattern in lower frequencies (63 Hz – 500 Hz) and a beam pattern formed by a kind of line array consisting of secondary sources in higher frequencies (500 Hz – 2 kHz). Six receiving points along the lower structure indicate interactions between the direct sound from the top of the lower section and the reflection from the floor. Also, an impulse-response measurement on a 1/25-scaled model of the lower structure suggests that an attenuation of 40 dB is estimated above 100 Hz and that the frequencies below 110 Hz are strongly cut off.

INTRODUCTION
The construction of the Sagrada Familia Church began in 1882. Gaudi was commissioned with the direction of the work in 1883 shortly after the resignation of the architect Francesc de P. Villar. However, Gaudi died by traffic accident in 1926 at the first stage of the huge Sagrada Familia Project. In 1936 the Civil War destroyed the Gaudi’s studio and workshop, from which Gaudi’s original materials were lost. Nevertheless, the construction is still going on. The support to this construction should be considered from various directions. It is important for the future continuators to create new ideas and incorporate them into the construction. In addition, it is needed to look for Gaudi’s original intention based on the surviving things and matters.

According to the ground plan of the Sagrada Familia [1, 2], three facades (the Nativity, the Passion, and the Glory Façade) are constructed facing to the east, west, and south, respectively. Each Façade consists of the four bell towers. The height of the longest tower exceeds 100 meters. The Nativity Façade was almost completed by Gaudi himself, and the Passion Façade was completed by the next-generation architects. The Glory façade has not been completed yet. The altar faces the north. Furthermore, six main towers will rise over the central nave, which is surrounded by the side aisles. The 12 towers rising from the three facades are the belfries. It is said that Gaudi planed to install many bells and transmit bell music to the city of Barcelona. In fact, Gaudi carried out the propagation experiment using a model bell in 1914. Also, it is designed to lead this bell music to the central nave in the Sagrada familia.

BASIC STRUCTURE OF THE NATIVITY FAÇADE
The Façade of Nativity, which was constructed by Gaudi, is divided into two both horizontally and vertically. Figure 1 depicts the cross-sectional view. The Façade is vertically divided at the central surface passing through the choir loft. That is, the Façade has twin-tower structure. We thus consider the left half. Also, the Façade may be horizontally divided into the upper structure (the bell tower with many windows) and the lower structure (the lower section of the bell tower.
with very few windows). The bell sound is radiated from the windows in the upper structure. The passage of the lower structure conveys the bell sound to the nave. The lower structure consists of several cylinder-like rooms, which are connected vertically and horizontally. Particularly, the vertical connection is done with a short circular neck. Such a connection is similar to the muffler used for the automobiles. Thus, the lower structure possibly works as an acoustic attenuator (silencer).

Also, the choir loft is constructed at the height of about 30 meters. Therefore, we may assume that Gaudi envisaged the music of bells and chant in the central nave. In other word, the Sagrada Familia was considered as a kind of huge musical instruments, whose music was to be heard both outside and inside. The objective of this paper is to examine its characteristics of acoustic radiation and propagation based on numerical simulation and model experiment.

Specifically speaking, acoustic radiation from the windows in the upper section enclosed by a blue rectangle (see Fig. 1) and acoustic propagation through the uppermost cylinders in the lower section enclosed by a red rectangle will be considered in the following. The geometries of the interested sections are determined from Dr. Tanaka’s reference book [3], where the detail structures and configurations of the windows and cylindrical passages are given.

**ACOUSTIC RADIATION FROM THE BELFRY WINDOWS**

**Basic window structure**

The window section of a blue rectangle in Fig. 1 is illustrated in Fig. 2 based on Ref. [3]. Basically, this window section consists of two types. Type A is made of four to six smaller windows with louvers and is arranged along the inner spiral stairs. Type B is made of three or four larger windows with louvers. Such an arrangement of Types A and B is rotating up along the parabolic tower in the interval of about 30 degrees. Also, the louver has a slant angle of about 45 degrees, and we may expect the downward radiation of the bell sound. Moreover, the louver surface is not flat but corrugated, showing Gaudi’s characteristic design. This corrugation might have any acoustical effect.

**Numerical simulations using FDTD method**

The two-dimensional FDTD (Finite-Difference Time-Domain) method [4,5] is applied to our numerical calculation. This FDTD method is more suitable for the visualization than the FE (Finite-Element) and BE (Boundary-Element) methods.

The acoustic pressure and the particle velocities (in x and y directions) are discretized by placing a Staggered-Grid mesh. The equations of motion and the equation of continuity are expressed by the finite-difference scheme. Specifically, the Matlab source code in 2-D FD equations is created but it is omitted here for saving the space (cf. Ref. [4]).
Computational assumptions and conditions

Since it is difficult to analyse a series of windows shown in Fig. 2, only Type A or Type B is treated separately as depicted in Fig. 3. For example, Type A is put in the region for computation as indicated in Fig. 4, which has the area of 14 m x 14 m, and the radiated sound pressure level is computed in the meshed area (10 m x 5 m) in steps of 0.5 m x 0.5 m. The edges of the right-half area are guarded by a quasi-reflection-free layer [6]. The grid widths in the x and y directions are respectively given as $\Delta x = 0.01$ m and $\Delta y = 0.01$ m. The sampling time is given by $\Delta t = \Delta x / 1.5 c = 19.6$ s, where $c$ denotes the sound speed. This $\Delta t$ satisfies the stability condition.

The sound source $p_{IN}$ is simplified as the following Gaussian pulse: $p_{IN} = \exp\left\{-\frac{(t - 30 \Delta t)^2}{8 \Delta t}\right\}$. The frequency characteristic of this pulse is almost flat up to 3 kHz. The symbols $O_1$, $O_2$, and $O_3$ in Fig. 4 denote the assumed source positions. Also, the wall is assumed upside and downside the window as shown in Figs. 3 and 4. Acoustic impedance of the normal incidence to the wall surface is assumed to be 50 times the air impedance. This wall impedance corresponds to the reflection coefficient of about 0.96 defined by the acoustic pressure. The magnitude of the corrugation (‰š"Ê) made on the actual louver surface is about 0.3 to 0.5 meters.

Simulations of the outward sound propagation

The acoustic propagation is visualized in Fig. 5 after the above Gaussian pulse is generated at point $O_2$ shown in Fig. 4. The window is Type A with the corrugation. At $t = 10$ ms after the pulse generation, we can clearly see the wave front passing through the space between the louvers. Also, the circular wave fronts of the reflecting waves are very clear, and the sources of these waves are the left-side edges of the louvers. At $t = 15$ ms the situation of sound propagation is already considerably complicated. Observing the wave fronts in detail, we may understand that the passages between the louvers and the right-side edges of the louvers are working as the secondary sources. Since the phase difference between these secondary sources is ambiguous, it may be assumed that several point sources with the opposite phases are formed at the window in an average sense. As a result, the sound propagates toward almost all directions as shown in the frame of $t = 20$ ms, although the directivity pattern has a strong frequency dependence as indicated in Fig. 6. Also, from this frame we can recognize that both edges of the louvers form the secondary sources for the outward radiation and for the inward reflection, respectively. The upward and downward propagations are a little retarded than the frontal propagation, and thus the reflections between the louvers are suggested.

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Fig. 3. Geometry of the separated windows used for simulations.

Fig. 4. Point source and calculation area.

Fig. 5. Sound propagation through the window louvers (Type A with surface corrugations).
Radiated sound pressure level
The frequency dependence of the acoustic radiation is illustrated in Fig. 6 when the Gaussian pulse is generated at the point $O_2$ shown in Fig. 4. Broad directivity patterns are indicated in 63, 125, and 250 Hz. The wavelength of the 125-Hz component is 2.7 m, and the window length is 3.7 m. Thus, the radiation directivity is not sharp in these lower frequencies. However, at 500 Hz a beam-like directivity pattern is indicated. There seem to be five beams. Also, at 2 kHz many speckles due to the interference are recognized. These radiation characteristics in higher frequencies (0.5 – 2.0 kHz) may be interpreted as the results of so-called “line array” formed along the window. The number of (secondary) sources arranged along this line array can be varied according to the frequency and the louver interval.

Moreover, the acoustic radiation when the source is located at $O_1$ or $O_3$ is simulated (cf. Fig. 4). When the source is located at $O_1$, the downward radiation is yielded for all frequency bands between 63 Hz and 2 kHz. However, when the source is located at $O_3$, the upward radiation is yielded in lower frequencies and a decrease in sound pressure level is distinct in higher frequencies. Generally, when the source lies below the window, the incidence angle to the louver is smaller than 45 degrees. Thus, the sound is radiated upward after being reflected between the louvers as shown in Fig. 7. Therefore, it may be concluded that the bell should not be installed below the window.

Comparing the results on the louvers with and without the surface corrugation, we know that there is no appreciable difference in the directivity pattern below 2 kHz, although the sound pressure level in the case of the louvers with the corrugation is reduced by a few dBs only in higher frequencies. See Ref [7] for more detailed information and discussion.

SOUND PROPAGATION THROUGH THE LOWER STRUCTURE OF THE BELL TOWERS
Measurement on a 1/25-scaled model of the lower structure
According to Gaudi’s plans that were actually measured later by Dr. Hiroya Tanaka, a simplified 1/25-scaled model of the lower structure was made of acrylic resin (Plexiglas). This model corresponds to the section enclosed by a red rectangle shown in Fig. 1. The details in structure are simplified, but major geometries are correct. Figure 8 shows (a) a drawing by computer graphics and (b) a photo of the acrylic resin model. It is well demonstrated that the lower structure consists of five or six rooms, which are vertically connected by short cylindrical necks. Moreover, each room has a few small openings. The openings in lower rooms may collect the bell sound and radiate it toward the nave space. In this section attenuation effects of the lower structure are examined experimentally. However, we have no intention to carry out the scaled-model experiment in its rigorous meaning.

Fig. 6. Frequency dependence of acoustic radiation field. Sound source position: $O_2$.

Fig. 7. Schematic on the multiple reflections between the louvers.
Fig. 8. A 1/25-scaled model of the lower structure. (a): computer graphics; (b): experimental model. The size is about 0.5 x 0.8 x 1.7 m. Actual height is about 45 m.

Since our experimental model was scaled in 1/25, acoustical measurement was carried out in low- and high-frequency ranges using different speaker systems. According to the frequency characteristics of the measuring systems, the measurement was feasible in a lower frequency range of 500 Hz to 17.5 kHz (20 Hz to 700 Hz in actual scale) and in a higher frequency range of 15 kHz to 50 kHz (600 Hz to 2 kHz in actual scale). The result measured in the lower frequency range is illustrated in Fig. 9. The speaker is set up on the top of the lower tower (the outward tower when the belfries are seen from the outside, cf. Fig. 1). A TSP (Time-Stretched Pulse) signal is used as the input signal. The sampling frequency is 48 kHz and the DFT points are $2^{16}$. Alphabets “a” to “k” shown in Fig. 9 denote the measurement points in the model.

The measurement result of Fig. 9 shows relatively flat frequency characteristic when the frequency higher than about 100 Hz is considered. An octave band of the centre frequency 1 kHz is examined, the acoustic pressure received at point “f” is weaker than that at point “a” by 37 dB. The response in the higher frequency range (600 Hz to 2 kHz in actual scale) indicates similar flat attenuation, which can be attributed to the diffuse-like field formed in large rooms. Since the speaker is not omnidirectional, this level difference of 37 dB should be corrected and we may possibly expect the attenuation of over 40 dB between 100 Hz and 2 kHz. The attenuation level at each point in Fig. 9 is also calculated by considering the lower structure as the coupling rooms on the basis of the diffractive field. The result (not shown here) confirms an increase in the attenuation level.

On the other hand, the frequency response is strongly cut off below about 100 Hz as clearly shown in the data of points “a”, “b”, and “c”. A series of the enlargement and constriction in cross section can be considered as the acoustic low-pass filter, but it is correct only if the change in cross section is small. In Fig. 9 the left, top room consists of an opening of diameter 1.5 m and a cylinder of diameter 4 m. We may thus assume the situation that the sound is radiated from a vibrating piston surrounded by an infinite baffle. Low-frequency radiation is very weak in this configuration, and the cutoff frequency is estimated by (wavelength = 2 x diameter) and is approximately given as $f_{\text{cutoff}} = 110$ Hz.
Numerical simulations using 2-D FDTD method
Since the height of the upper structure is about 40 m, the bell sound can be propagated to the opening of room “a” as the plane wave in the first approximation. Although the data are not shown here, the following results are obtained:

1. The impulse responses suggest the significant influence of the reflection at the floor.
2. The low-frequency cutoff is seen near 200 Hz. The discrepancy with the experimental value (100 Hz) may be due to the 2-D assumption.
3. The attenuation between 200 Hz and 2 kHz is about 20 dB in average. This very low attenuation may be also due to the 2-D assumption.

Furthermore, the effects of the curved ceiling seen in actual structure are simulated by comparing with the flat ceiling. The reverberation time of a room with a curved ceiling is 0.35 s and that of a room with flat ceiling is 0.42 s. This is possibly because the curved ceiling can diverge the wave direction. Such a reduction of the reverberation time might be desirable to hear bell music in the nave. However, simulations on the curved ceiling in the configuration of Fig. 9 do not indicate any appreciable difference in the attenuation characteristics. See Ref. [8] for more detailed discussion.

CONCLUSIONS
1. The upper-structure window of the Nativity Façade yields a broad directivity pattern in lower frequencies (63 – 250 Hz) and a beam pattern in higher frequencies up to 2 kHz. The louver edges forms secondary sources.
2. When the sound source lies below the window, the sound is radiated upward and attenuated.
3. The lower structure can yield an attenuation of about 40 dB between 100 Hz and 2 kHz.
4. The lower structure does not work as an acoustic low-pass filter, but has a cutoff (near 100 Hz) below which sound cannot propagate.
5. The curved ceiling can serve to reduce the reverberation time but cannot yield stronger attenuation for vertical propagation to the floor.

References: