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An experimental study of the sound field in a large atrium

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In large atria acoustic comfort is an important consideration, but it is less studied compared to other physical environmental factors. In this study, sound distribution and reverberation in a typical large atrium have been experimentally examined, revealing the basic sound field characteristics. The results show that in terms of sound distribution, at all frequencies there is a continuous decrease in sound pressure level (SPL) with increasing distance to the source, both vertically with increasing floor level, and horizontally at each floor. The patterns of SPL decrease with increasing source–receiver distance are rather complicated, and also vary considerably at different frequencies. There is a considerable difference between the maximum and minimum SPL at each floor, ranging from 31 dBA to 18 dBA from ground to top floor, but in terms of the average SPL across each floor, the decrease is only 4.4 dBA from ground to top floor. With different source positions, the average SPL in the whole atrium could be rather different, up to about 10 dBA. In terms of reverberation, at all frequencies there is generally a continuous increase with increasing source–receiver distance. With a source at the ground floor, the reverberation time variation on the ground floor could be about 100%, and in the side corridors, the reverberation time is rather long, up to about 5 s across frequencies. The decay curves are generally not linear, and the non-linearity is more significant in side corridors and also, at lower frequencies. The above features suggest the non-diffuse characteristics of such a typical atrium.

1. Introduction

Atria have been used since ancient time and exist widely in historic buildings [1,2]. With the development of modern construction technology, large atria have been commonly designed in various building types, in particular, following the promotion of central atrium space in large hotels in the 1960s, for example, the Atlanta Hyatt Regency, opened in 1967, with glass elevators and a rotating rooftop restaurant [3].

Along with common use of large atria, the environmental performances of such spaces have been studied, including their thermal parameters [4], daylighting performance [5,6] and related energy use [7], ventilation [8], heat transfer and fluid flow [9], and smoke and fire safety [10]. The overall performance of different aspects has also been examined, such as integrated assessment of thermal performance and room acoustics [11]. Linked with environmental performance, economic analyses have been made too [12].

Atria are a common type of non-acoustic spaces, where the acoustic comfort is an important consideration [13,14]. Through field surveys in a number of atria in a shopping centre, it was found that subjective evaluations of acoustic comfort might be influenced by objective acoustic indices and sound types, as well as users' duration of stay, activities, and their acoustic conditions at home [15], with many similarities with the results in urban environments [16–19]. Correspondingly, some measurements have been made in different types of atria, in residential buildings, shopping centres, university buildings, office buildings, hospital buildings, and other public and commercial buildings [14,15,20–24]. Those measurements considered the sound environment in occupied conditions, namely spatial and temporal sound level distribution caused by various activities, as well as basic sound field characteristics of the spaces, including reverberation time (RT) and sound pressure level (SPL) distribution. Computer simulations have also been made for such spaces, to be compared with measurements [23–26].

The sound fields in large atria spaces have many special characteristics, due to the large volume, special shape, interactions between the main space and the linked smaller spaces, and boundary conditions. The study of the basic characteristics of the sound fields would therefore be important for the design of such spaces, which is relevant to a wide range of commercial and public

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building types. It is also useful for a better understanding of the sound field in similar spaces, such as shoe-box type of auditoria and long spaces including long enclosures and urban streets [27–37]. Two basic aspects need to be considered in studying the sound field, namely spatial SPL distribution and reverberation distribution. The former is relevant in terms of communication or noise disturbance between different parts of an atrium and its surrounding spaces [38–40]; and the latter is relevant to the overall acoustic impression and comfort [38] as well as speech intelligibility for conversation and public address (PA) system [41], for example.

Although some measurements have been made for the sound field in atria, as mentioned above, they were mostly based on rather limited source and receiver positions, or only considered actual sound sources such as sounds from crowd. There is still a lack of detailed and systematic measurement, with a large number of evenly distributed receivers, so that the sound field can be illustrated. Such bench-marking work would be useful for a better understanding of such sound fields, as well as for comparisons with theoretical and computer simulation results. Therefore, in this study, a detailed and systematic experimental study has been carried out in a carefully selected typical large atrium, thus the fundamental spatial and temporal characteristics of the sound field can be better understood, presented through SPL distribution and RT across the space (RT). This in turn will lead to a better design of large atria, in terms of arrangements of different spaces and sound source, for example.

This paper first introduces the site and measurement method, and it then presents the measurement results and analyses the basic characteristics of the sound field in terms of sound distribution and reverberation.

2. Methodology

2.1. The building and the atrium

The building containing the case study atrium is an office complex for a large architectural design practice. Officially opened in 2009, there are five floors above the ground and one lower ground floor. The total floor area is 27,090 m^2, the base area is 4601 m^2, the total building height is 23.9 m, and the floor height is 4.35 m. The building uses a frame structure, with a column grid spacing of 8 m by 8 m. In the middle of the building there is a large rectangular atrium of 16 m wide, 66 m long and 23 m high, which is surrounded on three sides by large open plan design studios and offices, but open with external windows to the south side. There is a glass roof with side windows, which introduce sunlight in cold winter whereas in summer blinds are used for solar shading. The main interior materials are timber and concrete, as well as large glass walls, to reflect the design idea of transparency and communication. Fig. 1 gives three photos, showing different parts of the atrium, and in Fig. 2 the plan and cross-sections of the buildings are shown.

There are corridors surrounding the atrium at each floor except the ground floor, and also side corridors leading to offices and design studios. Those provide effective spaces for communication. They are main sound channels and also, the footsteps and speech in the corridors are among main sound sources in the building. At the ground floor there is a large artificial waterfall, to adjust the microclimate as well as to generate an interesting soundscape. Open staircases, glass lifts and escalators are also located around the atrium, which can be regarded as another type of sound source. Air-conditioning systems are used in the building, which could generate background sounds.

2.2. Measurement method

The measurement was designed to examine the sound field in detail. As illustrated in Fig. 2, five sound source positions, marked as S1–S5, were considered, four at the ground floor and one at the third floor. At the ground floor, two source positions were considered along the short side of the atrium, one in the middle of the short side (S1) and the other near a corner (S2); one source position (S3) was between the atrium centre and the short side of the atrium; and one source position was near the entrance of the building (S4), examining the sound propagation from a side space to the atrium space. At the third floor, the source (S5) was positioned at a similar plan location with S1. The sound source was an omni-directional source, using a cluster of 12 loudspeakers in a dodecahedral configuration that radiates sound evenly with a spherical distribution. The source height was 1.5 m.

For a given source position, 50–70 receiver positions were considered at each floor level, generally evenly distributed across the space with a spacing of 3–8 m, but some special locations were also taken into account, for example, the turning points to the corridors, as well as some points near the edge of the corridors surrounding the main atrium space, so that the direct sound from the source can be received. The distribution of the receiver positions is shown in Fig. 2. Several sets of equipment were used to measure and record sound at receivers, including Norsonic 121 measurement system (Type I), BSWA 801 sound level metres (Type I), and high quality sound recorders. A device calibration was carried out before and after the measurement. The receiver height was 1.5 m, considering the standing ear height.

The measured indices included SPL and reverberation time at different frequencies. The SPL distribution was measured using steady-state pink noise generated from the omni-directional loudspeaker. During the measurement the sound power level of the loudspeaker was 77.7, 83.0 and 86.3 dB at 125, 500 and 2 kHz, respectively, although it is noted that this study examines relative sound attenuation rather than absolute SPL. The reverberation time was measured using interrupted pink noise. Sound signals were also recorded, for more detailed analysis including decay process. To minimise the effects of background noise, the measurements were made during night time, and all the sound sources inside the atrium

Fig. 1. Photos of the atrium. (a) The main atrium; (b) Corridors around the main atrium; (c) View from the main atrium to the entrance, where the source position 4 S4 was located.