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A Study on the Sound Field in a Vault with Two Open Ends

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Abstract

The sound field in a vault with two open ends is studied in this paper and its sound pressure distribution is compared with that in an enclosure and a long space. The accuracy of estimation on this kind of space by classic Sabine Formula, modified Sabine Formula and ray tracing method are compared through numerical and experimental results. Non-exponential decay is found in this open vault, and the reason and precondition of its occurrence are discussed. Ray tracing method has been used to conduct major numerical simulations in this article. Results of experiments have been compared with the numerical results to verify the conclusion. The steady sound pressure distribution in the vault with open ends is obviously different from that in enclosure and long space. The classic Sabine Formula cannot be used to calculate reverberation time in this open vault. As for the reason of the occurrence of non-exponential decay curve, it is because the coupling of sound energy between

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small zones of different 'live' degrees within the space and it also depends on if requirements of double-sloped decay curve in coupled volumes theory can be fulfilled or not. If the distance between the observation spot and sound source is not big and both of them are not in the middle of the space, then double-sloped decay curve could be observed very obviously.

Keywords: vault with openings, reverberation, decay curve

1. Introduction

Other than the common rooms seen in daily life which have the acoustical characteristics of enclosures and close dimensions, some rooms with special configurations have been extensively applied in architectural design. A typical example is the long space, whose length is more than 3 times larger than the width and height. In the past two decades, along with the massive development of tunnels and subways, many research works are conducted on the long spaces [1][2][3][4][5]. In public places which have long space's nature, sound field distribution and speech intelligibility are what people mostly concern about.

There are some practical spaces, which have similar relative dimensions with common closed rooms except for some open surfaces, have different acoustical properties from simple rooms and long spaces. Maa explained the phenomenon of flutter echoes between two paralleled walls theoretically by using the normal mode technique and the geometrical method[6]. The space referred in Maa's paper is the one with three open surfaces, and the assumption was that the two paralleled walls are close to each other and in infinite size. Wang conducted a primary research on courtyards with open roofs, and discussed the effects of opening to sound quality[7]. Sound field was frequently investigated in rooms in which absorption was nonuniformly distributed on the inner surfaces through different methods[8][9][10][11][12][13][14][15][16]. When the absorption coefficients of these open surfaces are defined as 1, rooms with open surfaces can be dealt as some special nonuniform rooms. By investigating rooms with openings, the particularity and essence of sound field in nondiffused rooms can be observed, for example, the multi-sloped sound decay curves.

The influence which decay rates of energy decay curves have on the sound quality is obvious [17]. In addition to the distribution of sound pressure, it is also important to investigate temporal characteristics of sound field, such as the energy decay process. Many researchers were dedicated to calculate, record and analyze decay curves[18][19][20][21][22][23][24]. In rooms with nonuniform absorption distribution, decay curves in some positions have similar non-exponential decay styles with those found in coupled rooms [15][25]. Although difference exists between these two, the acoustical phenomenon in rooms with openings can be explained by the viewpoint of coupling, and analysis methods used in coupled volumes is also helpful to quantify the decay curves in these spaces[21].

This paper investigates a vault with two open ends. Public buildings with this type of structure include the gate of ancient fortress, sunshade of the platform, etc. The type of building structure is increasingly applied in public, particularly in train and bus stations. Some relative work had been conducted in some railway stations. Lang investigated the effect of noise to acoustic measurements in subway stations[26]. Kootwijk investigated the speech intelligibility of the public address system in 14 Dutch railway stations[27]. A sheltered integrated station for bus and rail was investigated by Chew[28], which was an approximate space with some surface open. A perceptual study of soundscapes was conducted in train station by Tardieu last year[29]. It is necessary to investigate the sound field in this commonly used space with openings for improve the performance of noise control and information broadcast. Spaces of this configuration can neither be taken as a simple room nor as a long space by ignoring two open ends. The effect of openings on sound decay can be more severe than that introduced by the source position, absorption and its distribution. The double sloped decay curves can also be observed in this space with openings.

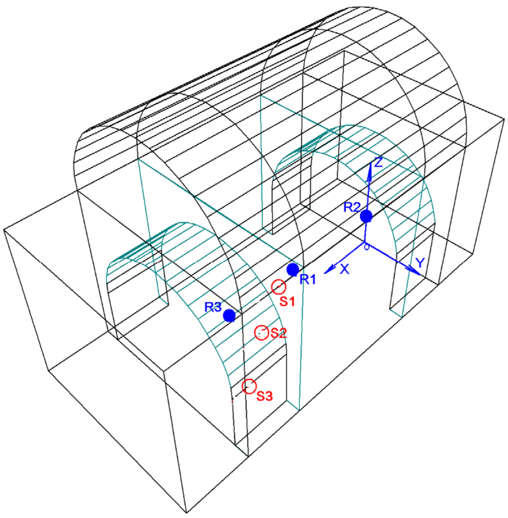
The purpose of this article is to characterize the sound field in the space with two open ends. In Section 2, the geometrical configuration and the materials covered on the inner surfaces are depicted. In Section 3, numerical simulations are conducted. The distribution of steady sound pressure level (SPL), distribution of reverberation time (RT) and decay curves in 3 typical observe positions are provided. By discussing the distributions and decay curves, the sound field in the vault was compared with that in simple and long spaces. In Section 4, experimental results are presented to compare with numerical results. Double sloped decay curves can be observed both in numerical simulations and experiments, and the "sag" double sloped decay can provide higher clarity level (in C_{80}) than exponential decay curves. Finally, conclusions will be drawn in Section 5.

2. Geometrical configuration

The geometrical mode used in this paper is presented in Fig 1(a). It is a vault with a length of 8.20 m, with a width of 5.83 m and with a height of 8.10 m. This geometrical model is used all through the numerical simulations. Fig 1(b) is a photo of a vault in an ancient fortress of Zhonghua Gate in Nanjing, and all experiments were conducted in this vault. It is of the same size with the model used in numerical simulation as in Fig 1(a). Three acoustical absorption materials are used on the inner surfaces of the vault, cement (the floor), granite (two side walls) and limed brick walls (the ceiling). The non-regular absorption coefficients of these three materials are shown in Table 1 below[30].

Table 1 Non-regular absorption coefficients of three materials

Frequency(Hz)	63	125	250	500	1000	2000	4000	8000
cement	0.01	0.01	0.01	0.01	0.02	0.02	0.04	0.04
granite	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02
Limed brick	0.03	0.03	0.03	0.04	0.05	0.06	0.06	0.06



(a) (b)

Fig 1 The geometrical configuration of a vault with two open ends. (a) The geometrical model used in numerical simulations, (b) The vault (gate of an ancient fortress) in which the experiments were conducted.

3. Numerical simulations

A commercial software ODEON V7.01 is applied in parts of numerical simulations, which is a professional tool for acoustic field estimation based mainly on ray tracing method. As in coupled volumes, the openings induce an egregious vanishing of sound energy when the decay begins, and in order to avoid the estimation errors, 100 million acoustical rays were used. The length of room impulse response (RIR) or the upper limit on the (Schroeder backward) integration (ULI), is set to 2 seconds, which is sufficient for calculating acoustical indicates such as T_{30}, EDT and C_{80}.

Other than the distribution of SPL and RT, sound energy decay curves in 3 typical positions were presented in this paper. The 3 typical positions are located in the coordinate of R1(0, 0, 1.2) m, R2(3.5, 0, 1.2) m and R3(6.0, 0, 1.2) m (blue points in Fig 1(a)). The origin of the rectangular coordinate is located in the center of right end on the floor. A simple source with omni-directivity is used, and three different positions are chosen to locate the sound source, S1(4.1, 0, 1.0) m, S2(5.7, 1.0, 1.0) m and S3(7.2, 2.0, 1.0) m (red points in Fig 1(b)). According to the simulation results for distribution and these 3 source and receiver positions, the properties of the sound field in this vault is discussed. All results in this paper are illustrated with the values in 1 kHz octave band. The values at the other frequency bands were also obtained but will not be discussed here.

3.1 Distribution of SPL

Fig 2 shows SPL distribution in the vault with two ends opened and closed. Fig 2(a-c) are distributions when the source is located in S1, S2 and S3 respectively. In contrast, Fig 2(d-f) are SPL distributions when the source is at the 3 positions but with the both ends closed using limed brick walls. It is obvious that with the excitation of a source of the same power, the overall SPL is 10 dB below in the vault with open ends than with close ends. The SPL distribution in close space is more uniform than that in a vault with open ends, especially at the openings where the sound pressure declines faster than that in other positions, but the decay speed is still slower than that in free spaces (-6 dB when distance doubled).

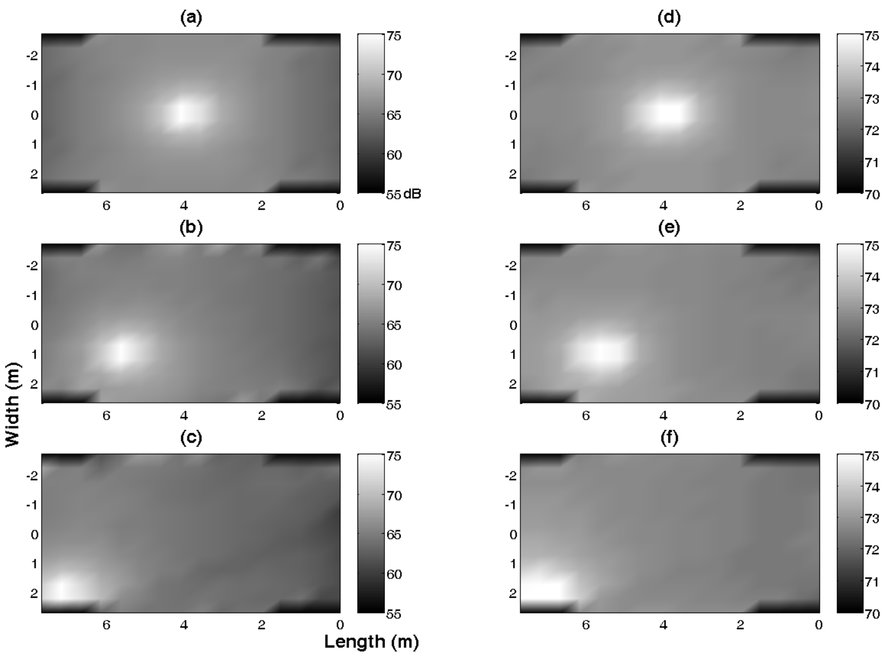


Fig 2 SPL distribution (1 kHz octave band) in a vault with two ends opened and closed. (a) S1, ends open, (b) S2, ends open, (c) S3, ends open, (d) S1, ends close, (e) S2, ends close, (f) S3, ends close.

SPL distributions in the vault with two open ends are different with that when the two ends were closed. The distributions are also different from that in long space. Fig 3 is truncations of long space, which has the same width and height with the open ends vault. Sound source is located at the corresponding positions of S1 and S3 in the truncated long spaces. No steep decline is observed in long space and its uniformity appears between open vault and close vault.

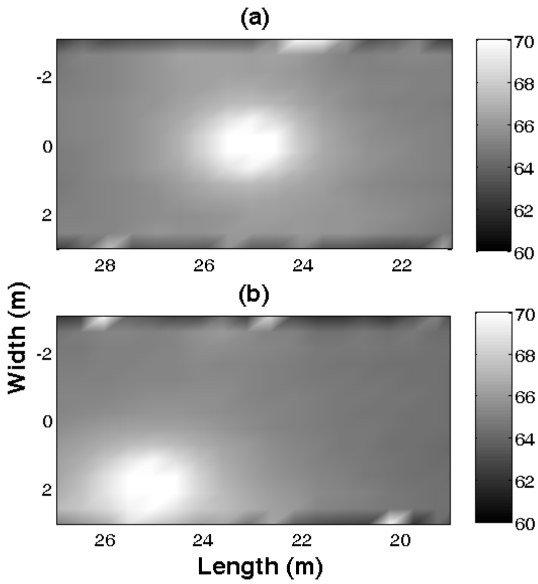


Fig 3 SPL distribution in long space, truncated to the size of the vault. (a) source position S1, (b) source position S3

3.2 Reverberation time

When the openings defined as a material with absorption coefficient equals to 1, the vault with open ends can be treated as a special enclosure with absorption non-uniformly distributed. So the average absorption coefficient equals to 0.17, which fulfils the requirement of $\overline{\alpha} < 0.2$, under which Sabine Formula can be applied[31]. A modified Sabine Formula is also used to estimate reverberation time in this paper, which modifies the average absorption coefficient according to the contribution of each surface. In Table 2, reverberation times estimated by different methods are presented and compared. Reverberation times at position R1, R2 and R3 are calculated with the ray tracing method. The RT values estimated by modified Sabine Fomula are much smaller than the ray tracing results and classic Sabine RTs. Because there is a lack of evidence that ray tracing method can precisely estimate the reverberation time in open spaces, the verdict for which method is most suitable for open spaces will be discussed in Section 4 with experimental results.

Table 2 Comparison between RTs calculated by different methods

	R1	R2	R3	Sabine RT	Modified Sabine RT
S1	1.37	1.34	1.34	1.25	0.87
S2	1.27	1.25	1.38	1.25	0.92
S3	1.31	1.43	1.39	1.25	0.86

Fig 4 presents the spatial distribution of reverberation time in the vault, which is another approach to check the uniformity of sound field beside the SPL distribution. Fig 4(a-c) are distribution maps when the source is at S1, S2 and S3 respectively. Fig 4(d) shows the applicability of classic Sabine Formula in contrast to the ray tracing method in this open vault, with an error rate of 10%. When the source is at S1, 70% of the area in the vault can be estimated by the classic Sabine Formula, however, when the source is at S2 and S3, the value declines to 35% and 45% respectively. In most cases, the uniformity in vault with open ends is at a low level.

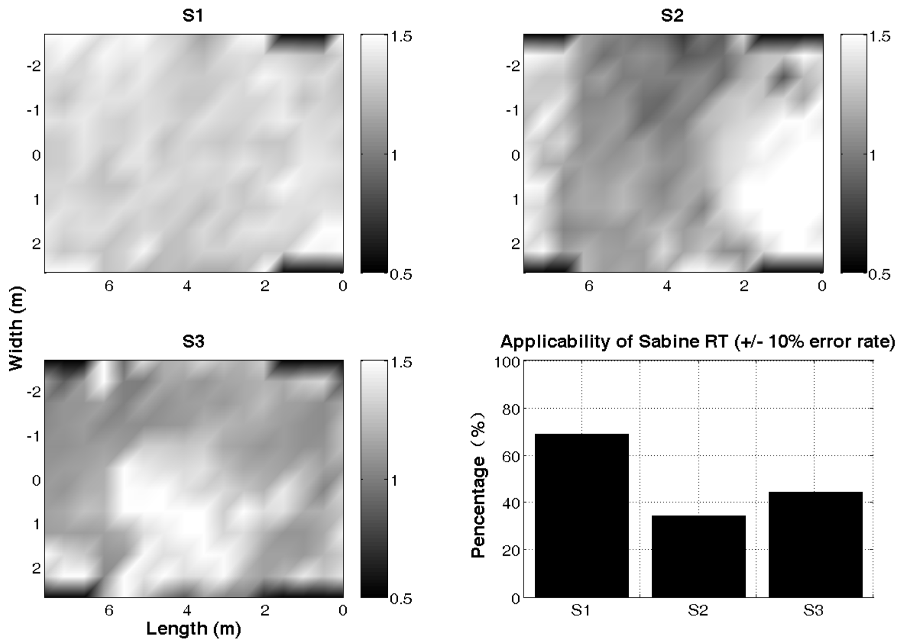


Fig 4 The distribution of RT in a vault with two open ends. (a) with source position S1, (b) with source position S2, (c) with source position S3, (d) applicability of the classic Sabine Formula in the open vault.

3.3 Double sloped decay curves

Besides the sound pressure, the process of sound energy decay also influences people’s subjective perception. Subsistent researches reveal that different decay processes provide different hearing impacts, despite of a same RT value they may have[32]. For example, the double sloped decay in coupled volumes, which has different decay rates in the beginning and the tail, provides eclectic scheme for both clarity and reverberation[33]. In the vault with two open ends, decay curves in 3 typical receiver positions were analyzed. A conclusion can be positively drawn from the results that double sloped decay curves exist in this open vault. The change of curvature does not seem to be very acute, however, it rather influences the estimation of EDT (early decay time) and RT.

Fig 5 shows nine decay curves in three positions when the sound source was located in three different positions. The openings make decay curves in different positions distinctive from each other except when the source is at S1. When the sound source is at S2, double sloped decay can be surely found at R3, which is considered to occur due to the coupling between the vault and the free space. According to the theory of coupled volumes, multi-sloped decay appears due to the discrepancy of sound energy density between sub-volumes. Sound decays slowly in "live" sub-volume and fast in less "live" sub-volume, so the energy in "live" chamber will feed to the less "live" one to slow down the decay rate in the middle and later part of decay duration, and then a "sag" double sloped decay curve can be observed[34]. However, double sloped decay in open vault cannot be explained simply by the model of two sub-rooms coupling, because, according to the coupling theory, if the vault ("live" sub-volume) couples with the free space ("dead" sub-volume), and both the source and receiver are located in the vault, no non-exponential decay can be found. Furthermore, sound field in the vault is absolutely non-diffused, which cannot be considered as a sub-system in statistical acoustics to solve the coupling problem.

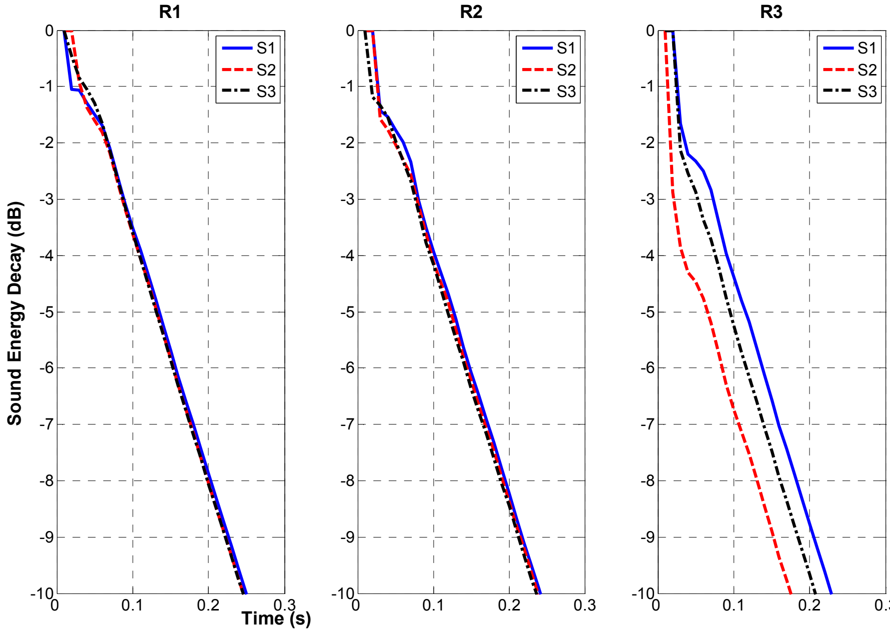


Fig 5 Decay curves in three different positions with three different sources positions.

A model of diffused zone coupling is proposed to explain why double sloped decay appears in this open vault. As shown in Fig 6, zone A and zone B are sufficiently small zones which fulfil the diffusion assumption. If a disparity of the "live" degree exists between zone A and its adjacent zone B, and both the source and receiver are located in the less "live" zone, a "sag" double sloped decay occurs. Here comes the two key points: (1) the source and receiver should be close enough to make sure they can be placed in a same zone; (2) the zone containing the source and receiver is a less "live" one comparing with its vicinity. For example, when the source is at S1 and the receiver is at R1, though they are very close and easy to be included in a zone, they located in the center of vault, the most “live” area, and no more “live” zones could be found, so non-exponential decay cannot be found.

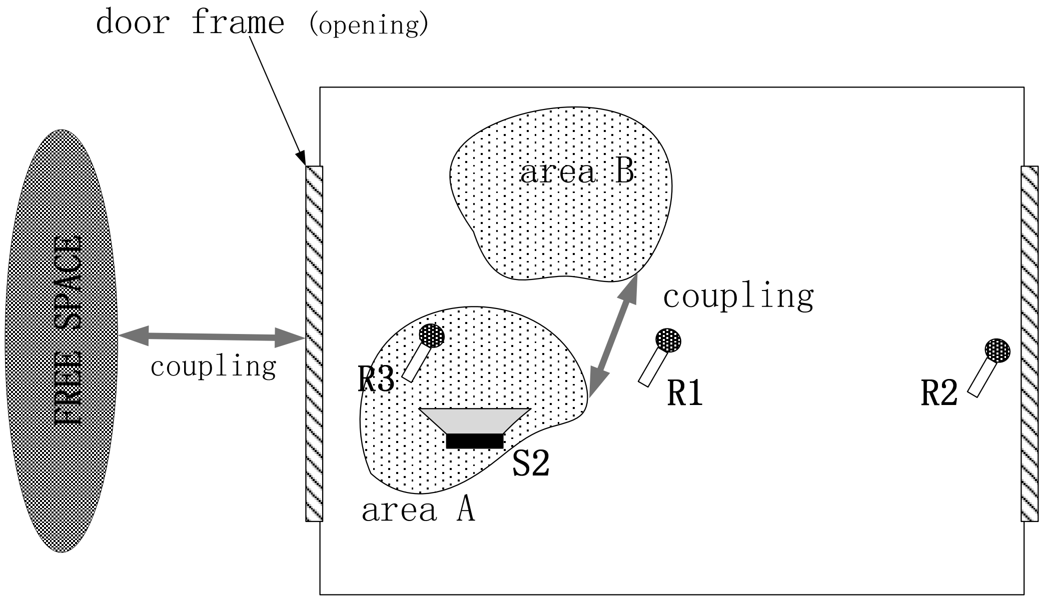


Fig 6 Coupling model for diffused “zone” in the open vault.

4. Experimental results

Experiments were conducted in #1 (long space) and #2 (open vault, see in Fig 1(b)) gates in an ancient fortress Zhonghua Gate in Nanjing. Receivers are set in an 18x11 grid with an interval of 0.5 m, and 1.2 m height away from the floor. A dodecahedral omni-directional louder speak was applied as the exciter, the power level of which was pre-measured in anechoic chamber, see in Table 3.

Table 3 Sound power level of the source.

Frequency（Hz）	63	125	250	500	1000	2000	4000	8000
SWL (dB)	51	58	73.5	78.5	76.3	76.3	80.6	79.0

Nor-sonic840 was used in recording measurements, which can generator a Maximum Length Sequence (MLS), record the response and process Fast Hadamard Transform (FHT) to obtain the impulse response. The decay curve can be drawn by conducting reversed integration to the impulse response. To abate the background noise, 10 measurements were repeated and finally drew the results by averaging.

Fig 7 shows the experimental results of distribution of SPL in the open vault. It has the similar spatial property with the simulated results, but has some 1 to 2 dB below in value.

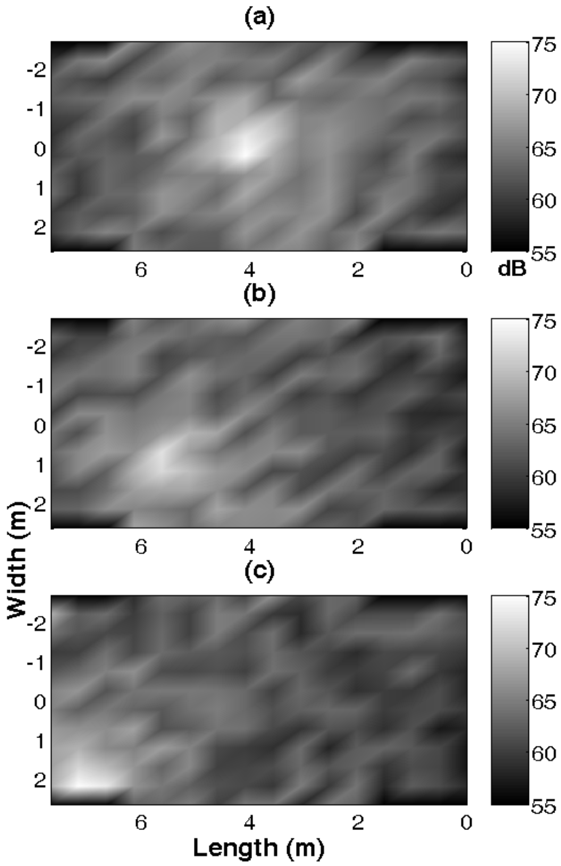


Fig 7 Distribution of SPL in experiments.

Fig 8 is the experimental distribution of RT in the open vault and the accumulation distribution curves of RT values. From the accumulation distribution curves, it can be easy to conclude that when the source is in the center, the sound field is the most uniform and the RT value mainly lies between 0.8 s and 1 s. When the source is in the other two positions, the spatial discrepancy becomes more severe, with the values mainly from 0.6 s to 1s. By compared with the numerical results, it seems that, the ray tracing method and classic Sabine Formula over estimate the RT value. Ray tracing method performs well in SPL estimation in spaces with openings; however, it is not very accurate in RT estimation. The modified Sabine Formula seems to be the most accurate estimation method for RT in this type of vault with openings.

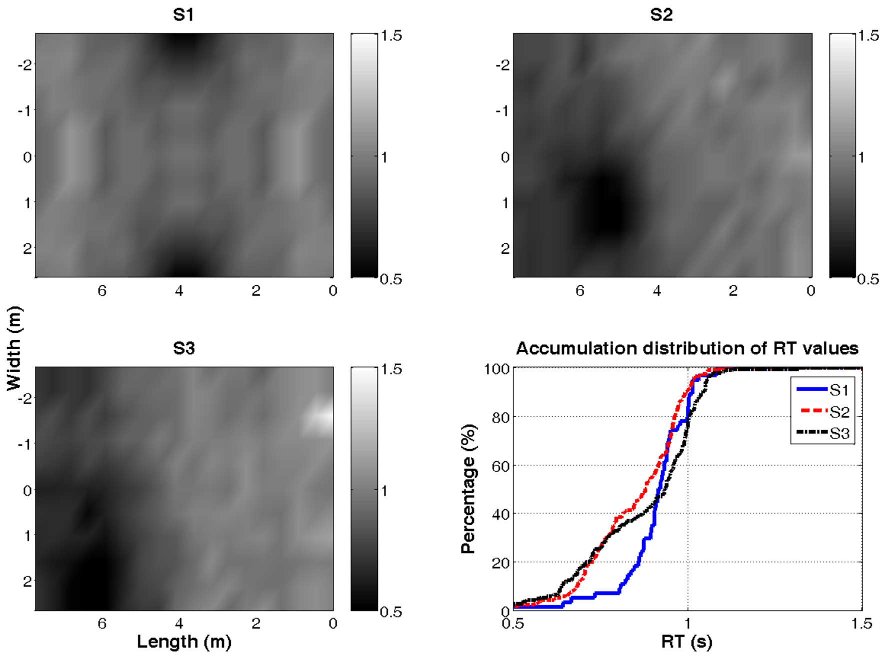


Fig 8 Experimental RT distribution and their accumulation distribution curves.

Fig 9 represents decay curves obtained in experimental measurements. The results well inosculates to simulations in Fig 5, particularly in the occurrence of double sloped decay. As discussed in Section 3.3, double sloped decay can be observed only when the two conditions are fulfilled. In area near the openings, sound energy density decays rapidly in initial, and slowly after that. The rapid initial decay can provide a small EDT value, and has little impact to the estimation of RT. Subsequently, a higher C_{80} value can be obtained without victimizing the length of RT.

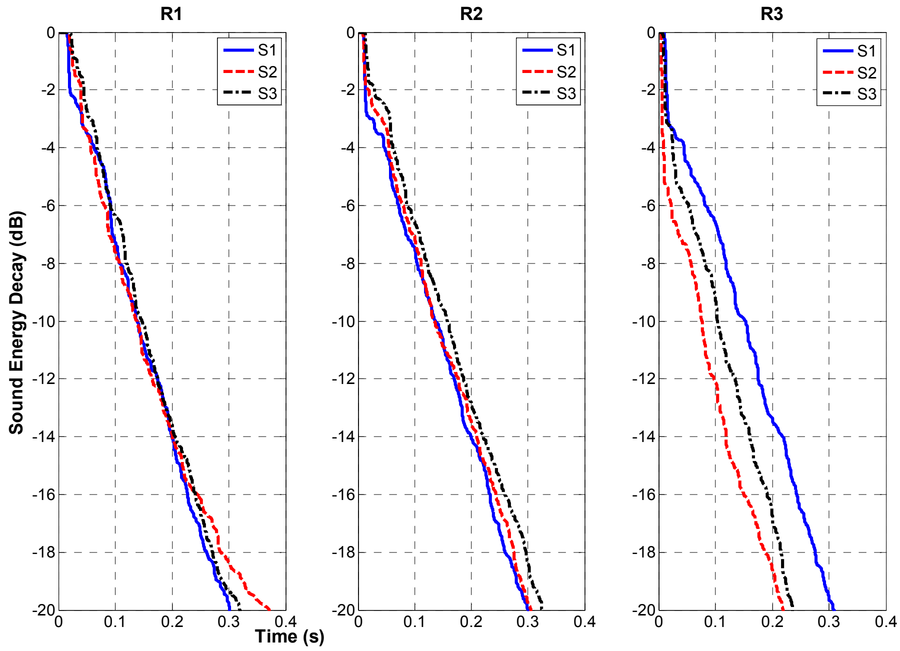


Fig 9 Experimental decay curves, 3 source positions and 3 reciever positions.

5. Conclusion remarks

In this paper numerical simulations and experiments were conducted to analyze the sound field in a vault with two open ends. The distributions of SPL and RT in the open vault were compared with that in enclosure and long space. In this type of non-close space, the sound field is nonuniform, and SPL declines fast around openings, RT values have a large span when the source is not in the center. Modified Sabine Formula seems to be the most suitable method for RT estimation in this type of open vault. In decay curve analysis, double sloped decay was found in this open vault, and a zone coupling model was proposed to explain both its occurrence and the precondition of its occurrence. When two key points: (1) small distance between source and receiver, (2) both in less “live” area, are fulfilled, double sloped decay can be observed in an open vault.

Acknowledgements

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