# Study on sound propagation of long enclosures with a vertical/inclined branch

**Abstract:** It is of interest to investigate the sound propagation of long enclosures with a vertical/inclined branch, since there may exist some branches inside the long enclosures in practical applications, such as in high-speed railway tunnels. However, much research on sound propagation of long enclosures available is concerning the straight long enclosures. In this paper, the sound pressure level (SPL) attenuation, early decay time (EDT), and reverberation time (RT30) of the long enclosures with vertical/inclined branches have been studied by the experimental results from the constructed physical scale models, and which also are compared with the straight long enclosure. This experimental investigation gives interesting results on the behavior of sound propagation of the long enclosures with vertical/inclined branches. Compared with the straight long enclosure, the inclined branch makes more difference to the SPL, EDT and RT30 of the long enclosure than the vertical branch though both kinds of branches have the equivalent volume.

*Keywords:* Sound propagation; long enclosures with a vertical/inclined branch

## 1. Introduction

It has been known that the classical room acoustics are not applicable to long enclosures, such as railway tunnels, underground stations, due to the inhomogeneous sound field therein [1]. To better understand and predict the non-diffuse sound field of long enclosures, much research work has been reported in the literature during recent years [2-8, 14]. Basically, these can be divided into two categories, i.e. one using physical scale model or/and full scale models [14, 16-17] and the other computer simulation based methods [2-5]. Comparatively speaking, the advantages of using scale modeling lie in that it takes into account some complex acoustic phenomena as sound diffraction, etc [14].

It should be noted that, however, most of the researches dealt with long enclosures without branches. In practice, there may exist some branch tunnels inside real long enclosures, such as in high-speed railway tunnels, which usually used as a passage to maintain tunnel and track system, or to store some tools [9]. With the increasing requirements for both safe and speed-up transportation, many countries have developed the high-speed railway trains. However, the destructive compression wave will be generated when a train entering a tunnel with a high speed [10-11]. The main influences brought by compression wave are two folds, i.e., it can result in structural damage of the tunnel, and create unfavorable aural effects causing discomfort to passengers. In this regard, the branch tunnels can also play an important role to considerably reduce effectively the compression wave inside a high-speed railway tunnel [9]. H. Imaizumi has investigated the sound propagation in a branching underground tunnel [8]. But it should be noted that this kind of tunnel with a two-open-end branch is different from the above mentioned as depicted in Fig. 62 of [9].

Although there have been much research results on sound propagation in straight long enclosures, to the best of the author′s knowledge, no such investigations dealing with long enclosures with a vertical/inclined branch have been reported in the literature. To best understand the acoustics of tunnels with vertical/inclined branches, and hence be helpful for the acoustic design of these kinds of long enclosures, in this study we have investigated the sound attenuation, early decay time and reverberation time by a physical scale model method. This experimental research reveals some interesting results on the behavior of sound field in the long enclosures with vertical/inclined branches.

This paper is organized as follows. Section 2 presents the four scale models to be investigated, and the measurement configuration of the experiments. The experimental results and discussion on relative sound pressure level, early decay time and reverberation time are given in section 3, respectively. Finally, several interesting conclusions are drawn in section 4.

## 2. Experiments

*2.1 Scale models*

In order to investigate sound propagation in long enclosures such as traffic tunnels with a vertical/inclined branch, four physical scale models were built as depicted in Fig.1, all in the 1:10 scale. Fig. 1(a) is the schematic scratch of the straight long enclosure, and Figs. 1(b), 1(c) and 1(d) are the plan views of the long enclosures with a vertical, left inclined and right inclined branches, respectively. The main long enclosures for the scale models are all with a rectangular cross-section, and the inner cross-sections of which are all 9.4 m long (94 m full scale), 0.7 m wide (7 m full scale) and 0.5 m high (5 m full scale). All the branches in the above models locate at the midpoint of their main long enclosures along the length dimension with 0.7 m wide and the same height 0.5 m as the main enclosures, i.e. the upper and lower surfaces of the branches are coplanar with those of the main enclosures, respectively. The vertical branch is 0.7 m wide (7 m full scale), 0.5 m wide (5 m full scale), i.e. AB = 0.5 m (5 m full scale), AD = 0.7 m (7 m full scale), as shown in Fig. 1(b). For ease of construction, we set the orientation of the left and right inclined branches $45^\circ$ inclined relative to main enclosures as illustrated in Fig. 1(c) and 1(d) respectively. For the left inclined branch case, BC = $0.7\cos 45^\circ$ = 0.49 m (4.9 m full scale), and we choose AB = 0.46 m (4.6 m full scale), CD = 0.95 m (9.5 m full scale). For the right inclined branch case, BC = 0.49 m (4.9 m full scale), and we set CD = 0.46 m (4.6 m full scale), AB = 0.95 m (9.5 m full scale). The model with right inclined branch can be viewed as a rotated version of the one with left inclined branch relative to the main enclosure. It should be noted that, for ease of comparison, we have deliberately set the volumes of the left and right inclined branches are both equal to that of the vertical one.

The two ends of the main enclosures for the all models are designed to be anechoic, and each end attached with a 20 cm (2m full scale) thick glass wool with the absorption coefficient over 0.9 within the measurement frequency bands 5~10 kHz. The other surfaces of the scale models are constructed by the same well-varnished timber to simulate the hard surfaces of practical tunnels, with the measured absorption coefficient about 0.05 within the measurement frequency bands.

*2.2 Acoustic measurement system*

As shown in Fig. 1, the sound source and receiver positions are all arranged along the central lines of all main enclosures of the scale models. The Tannoy type T300 was chosen as the sound source driven by the power preamplifier Bruel & Kjær type 2619. The sound source in each measurement was fixed on the central line with a distance of 1 m (10 m full scale) from one end of the main enclosure, and 8.4 m (84 m full scale) from the other end. The receivers used were Bruel & Kjær microphones type 2669, and the receiver points were distributed evenly with a 0.5 m spacing (5 m full scale), while the starting receiver position is at a distance of 1 m (10 m full scale) from the sound source. The extensively used maximum length sequence system analyzer MLSSA [3,5,12] is adopted in the experimental measurements, both as the source signal generator and as the post-processor of the measured data. In the following sections, all dimensions mentioned are corresponding to their full scales except where stated.

## 3. Results and discussion

In this section, the sound attenuation or relative sound pressure level (SPL), Early decay time (EDT) and Reverberation time (T30) are measured based on the above scale models, i.e. the straight long enclosure, and the long enclosures with vertical, left inclined and right inclined branches. Each measurement presented below is the arithmetic average of 500 and 1000 Hz (1/3 octave bands).

### *3.1 Sound pressure level (SPL)*

The relative sound pressure level measured at various source-receiver distances is shown in Fig. 2. It can be seen that, with the distance of sound source to the entry of the vertical or inclined branch as the threshold distance, namely about 37 m, the sound attenuation for the straight long enclosure is nearly the same as those for other three long enclosures with vertical or inclined branches when source-receiver distance is within the threshold distance. While the source-receiver distance exceeds the threshold distance, the sound attenuation of the long enclosures with vertical or inclined branches are all larger than that of straight long enclosure. Specifically, the relative SPL of the long enclosures with the inclined branches is around 2 dB lower the counterpart of straight one. This is mainly because that reason that sound pressure level is principally determined by the early acoustic reflections. When the source-receiver distance is less than the threshold distance, or in other word, in the near sound field, the reflections from the surfaces of the vertical or inclined branches do not contribute much to the early reflections, due to its relatively long sound transmission path. While at rather far sound field, the sound transmission path by branches is near those through main enclosures, thus the branches will have an obvious effect on early sound reflections.

It also should be noted that, as far as sound attenuation is concerned, they are nearly the same for the long enclosures with left or right inclined branches. That is to say, the orientation of the inclined branch makes no differences to sound attenuation. Comparatively speaking, when the source-receiver distance is above the threshold distance and with the equal branch volumes, the relative SPL of the long enclosures with left/right inclined branches is lower than that of the long enclosure with the vertical branch.

### *3.2 Early decay time (EDT)*

Fig. 3 shows the EDT of the four kinds of long enclosures with the increasing source-receiver distance. As can be seen, when the source-receiver distance is less than the threshold distance, i.e. the distance of sound source to the entry of the vertical/inclined branch, the EDT of all long enclosures increase with the increase of source-receiver distance, and the EDT’s of long enclosures with vertical/inclined branches are larger than that of straight long enclosure. While the source-receiver distance exceeds the threshold distance, the EDT of the straight long enclosure is slightly longer than that of with a straight branch until the source-receiver distance exceeding about 65 m. However, with the source-receiver distance increasing, the EDT′s of the long enclosures with left/right inclined branches are both lower than that of the straight long enclosure and one with a vertical branch. It is shown that the orientation of the inclined branch can make a difference on EDT of long enclosures, and the long enclosure with the left inclined branch has the rather stable and minimum EDT.

### *3.3 Reverberation time (RT30)*

The reverberation time RT30 for the four long enclosures at various source-receiver distances is shown in Fig. 4. The RT30 calculated with Eyring formula is 1.41 s for straight long enclosure and 1.56 s for long enclosures with vertical/inclined branches, respectively, which are much lower than those of measured. Compared with the measurement results in Fig. 4, we can conclude that the sound fields of long enclosures with vertical/inclined branches are also non-diffuse like the straight long enclosure.

When the source-receiver distance is less than the threshold distance, the RT30 of the straight long enclosure is much close to that of long enclosures with vertical/inclined branches. With the source-receiver distance exceeding the threshold distance, the RT30 of the straight long enclosure becomes longer than that of long enclosure with a vertical branch, and especially much longer than that of long enclosures with an inclined branch. Moreover, it is also shown that the inclined branch has greater impact on RT30 than the vertical branch though their volumes are equal. Generally speaking, unlike the long enclosures with left/right inclined branches, the RT30 of the long enclosure with a vertical branch varies in a much similar way as the straight one. In other word, the orientation of the branch plays an important role in reverberation time RT30 of long enclosures, especially when source-receiver distance exceeding the above-mentioned threshold distance. It should also be noted that, firstly, the RT30 of the long enclosure with an inclined branch regardless of left or right oriented exhibits a more stable value except a small fluctuation at the entries of the branch; secondly, compared with the EDT, the RT30′s of long enclosures with left/right inclined branches are very near under various source-receiver distance.

## 4. Conclusions

In this paper, experimental evaluation has been conducted to investigate the sound propagation of long enclosures with a vertical/inclined branch. Based on the experimental results on sound attenuation SPL, early decay time EDT and reverberation time RT30 of four typical models, i.e. the straight long enclosure, and long enclosures with a vertical, left inclined and right inclined branch respectively, several conclusions can be drawn as follows.

As for the sound attenuation, in the near sound field, the vertical/inclined branches almost make no difference to sound attenuation of long enclosures. But in the far field, explicitly when the source-receiver distance exceeds the so-called threshold distance, i. e. the distance of sound source to the entry of the vertical or inclined branch as the threshold distance, the sound attenuation of the long enclosure with vertical/inclined branch is lower than that of straight one. Under the condition of equal volumes, the sound attenuation of long enclosure with an inclined branch is lower than its counterpart with a vertical branch.

When the source-receiver distance is less than the threshold distance, and the EDT′s of long enclosures with vertical/inclined branch are larger than that of straight one. While the source-receiver distance exceeding the threshold distance, the EDT′s of the long enclosures with left/right inclined branches are both lower than that of the straight long enclosure and one with a vertical branch. It is also shown that the orientation of the inclined branch can make a difference on EDT of long enclosures.

Similar as the straight long enclosure, the sound field of long enclosures with branches is also non-diffuse. When the source-receiver distance is within the threshold distance, the branches have little impact on the RT30 of the long enclosures. With the source-receiver distance larger than the threshold distance, the RT30 of the straight long enclosure becomes longer than that of long enclosures with vertical/inclined branches. With the increasing of source-receiver distance, the RT30′s of long enclosures with left/right inclined branches are very close, and becomes much lower than that of one with vertical branch. Comparatively, the RT30 of long enclosure with the inclined branch is more stable than that of straight one or one with the vertical branch.

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# Figure captions

**Fig. 1. The schematic diagrams of the scale models for four long enclosures:**

(a) the straight long enclosure;

(b) the long enclosure with a vertical branch;

(c) the long enclosure with a left inclined branch;

(d) the long enclosure with a right inclined branch.

**Fig. 2. The relative sound pressure level (SPL) attenuation at various source-receiver distances, average of 500 and 1000 Hz (1/3 octave bands) : the straight long enclosure (○); the long enclosure with a vertical branch (+) ; the long enclosure with a left inclined branch (*); and the long enclosure with a right inclined branch (□)**.

**Fig. 3. The early decay time (EDT) at various source-receiver distances, average of 500 and 1000 Hz (1/3 octave bands): the straight long enclosure (○); the long enclosure with a vertical branch (+) ; the long enclosure with a left inclined branch (*); and the long enclosure with a right inclined branch (□)**.

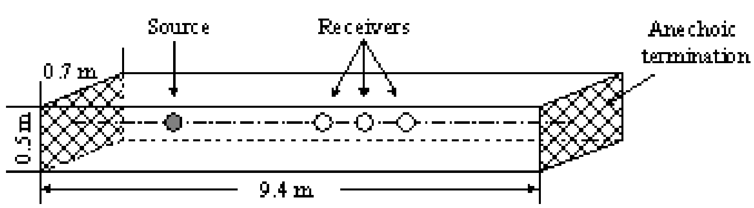
**Fig. 4. The reverberation time (RT30) at various source-receiver distances, average of 500 and 1000 Hz (1/3 octave bands): the**

**straight long enclosure (○); the long enclosure with a vertical branch (+) ; the long enclosure with a left inclined branch (∗); and the long enclosure with a right inclined branch (□)**.

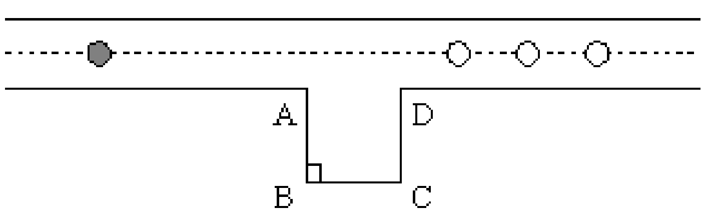
## Figures

**Fig. 1**

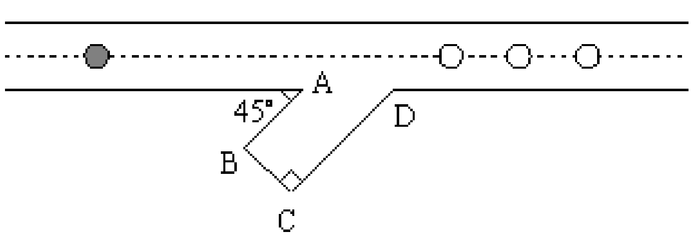
(a)



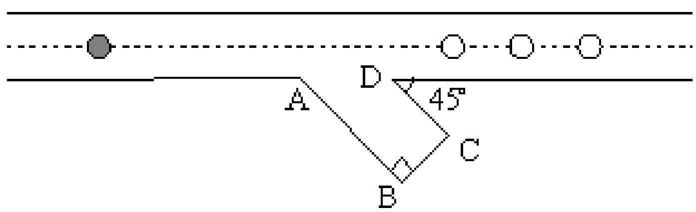

(b)




(c)



(d)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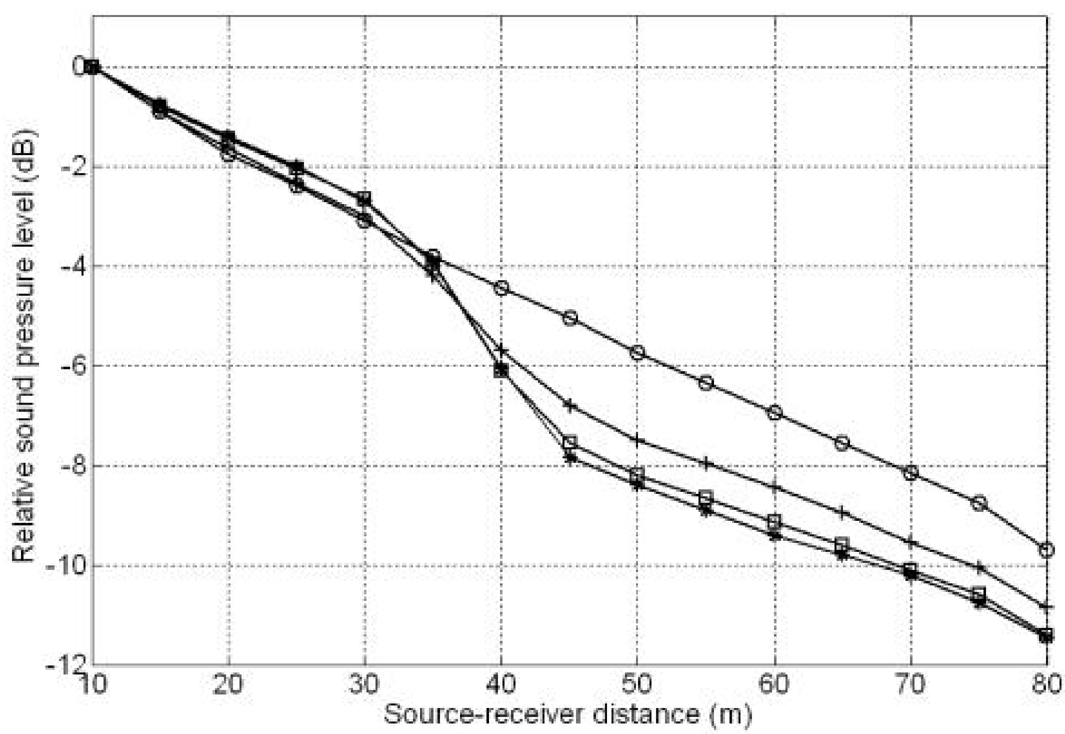
45°
A
C
B

**Fig. 2**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-4
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-8
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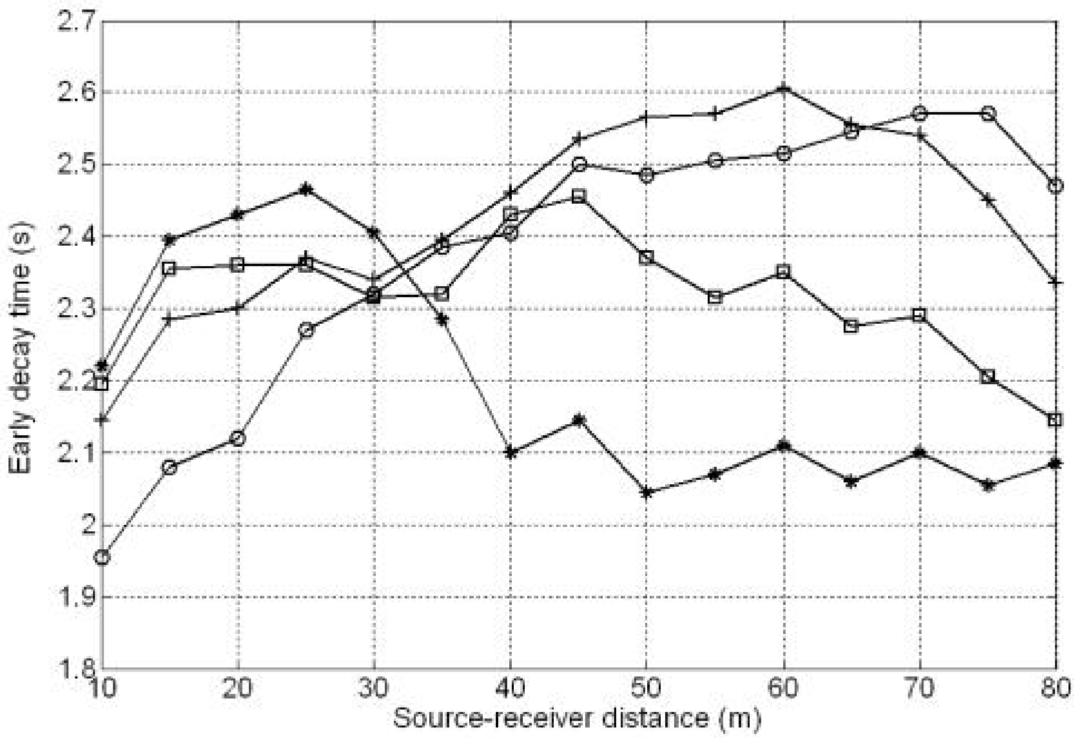
Relative sound pressure level (dB)
Source-receiver distance (m)

**Fig. 3**


2.7
2.6
2.5
2.4
2.3
2.2
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2
1.9
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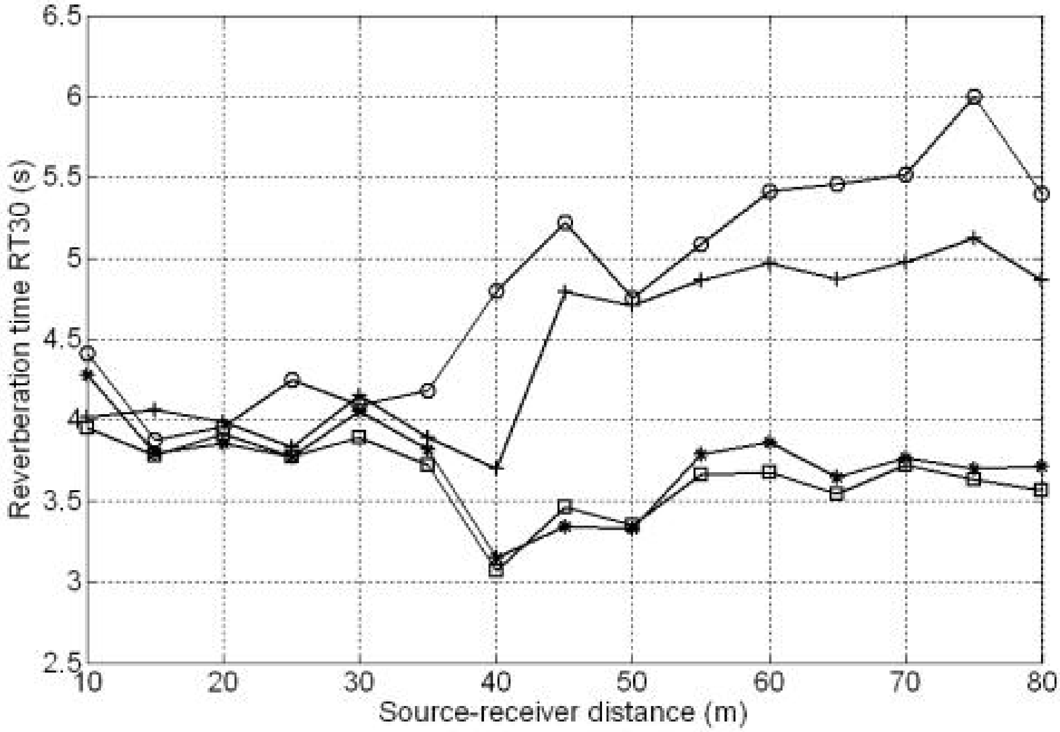
70
80
Early decay time (s)
Source-receiver distance (m)

**Fig. 4**



6.5
6
5.5
5
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4
3.5
3
2.5
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20
30
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80
Reverberation time RT30 (s)
Source-receiver distance (m)