A METHOD FOR CALCULATING THE UTMOST HEARING DISTANCE IN A LECTURE HALL UNDER NATURAL PHONATION CONDITION

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ABSTRACT

The utmost hearing distance in surrounded structures under natural phonation condition is 30 m as reported in the literature. Under the condition of taking optimization values, this paper brings forward a method which calculates the utmost hearing distance in a lecture hall under natural phonation condition and finds that the utmost hearing distance in surrounded structures is 20.32 m. Also, it is found that the utmost hearing distance between the speaker and the audience under free sound field is 7.96 m. This value agrees well with the recommended value of 8 m by the State. Such information will be useful for the architects when designing lecture halls.

1. INTRODUCTION

Sound power of a sound source refers to the power radiated within the audible frequency range, or the power radiated within a certain finite frequency range (generally known as frequency band sound power). In architectural acoustics, the radiated sound power can be regarded as independent of the environmental conditions, it is a property [1] of the sound source itself. How to utilize effectively the limited sound power is one of the core questions in indoor acoustic design [1]. For the receiver of the sound (listener), sound sensation and discrimination are the two fundamental aspects of the hearing function. It is the sensation of sound that comes first, but sound discrimination is more important in retrieving useful information [2].

It has been reported in the literature that the utmost hearing distance in surrounded structures under natural phonation condition is 30 m [3,4], provided that the room has been well-designed in the aspect of acoustics. The result was based on the isogram of the understandability of spoken language of human (speaker), and the hearing distance in the other directions can be determined from the isogram in proportion. The authors of this paper believe that the hearing distance in surrounded structures is determined not only by the isogram of the understandability of spoken language of the speaker, but also other important factors such as the hearing discrimination threshold of the receiver, the acoustic design of the surrounded structures, the room geometry and background noise, etc. By taking these factors into account, this paper aims to determine more precisely the utmost hearing distance in surrounded structures under natural phonation condition by using the existing empirical formula and data from the literature.

2. DISTRIBUTION OF STEADY-STATE SOUND PRESSURE LEVEL AND DETERMINATION OF VARIOUS PARAMETERS IN A LECTURE HALL

In a lecture hall (classroom, theatre, etc.), the utmost hearing distance between the speaker and the audience is controlled by the visual and hearing conditions [5]. From the acoustics point of view, it is required to have clearness of speech, no disturbance of other noises, and guaranteed audibility for halls of a large volume [1]. The indoor steady-state sound pressure level at a distance r(m) from the sound source can be calculated by the following equation [3]:

\[ L_p = L_w + 10 \log \left( \frac{Q}{4\pi r^2} + \frac{4}{R} \right) \]  \hspace{1cm} (1)

where \( L_p \) is the indoor sound pressure level at a distance r from the sound source, \( L_w \) is the sound power of the sound source, Q is the directional factor of the sound source and R is the room constant.

The above four parameters affecting the distribution of indoor sound pressure level will be analyzed in the following.
2.1 \( L_p \) – Indoor Steady-State Sound Pressure Level at a Distance \( r \) from the Sound Source

In order to analyze the utmost hearing distance in a lecture hall under natural phonation condition, the human hearing discrimination threshold \( \Delta I \) is selected as a reference value (see Table 1) for calculation [2,6]. Assuming that the indoor background noise is at the upper limit of the specified value by the State, i.e., \( L_A = 50 \text{ dB} \) [3].

<table>
<thead>
<tr>
<th>Age group</th>
<th>( \Delta I ) (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 20</td>
<td>0.23 ± 0.10</td>
</tr>
<tr>
<td>20 ~ 29</td>
<td>0.29 ± 0.13</td>
</tr>
<tr>
<td>30 ~ 39</td>
<td>0.44 ± 0.29</td>
</tr>
<tr>
<td>40 ~ 49</td>
<td>0.52 ± 0.41</td>
</tr>
<tr>
<td>50 ~ 59</td>
<td>1.00 ± 1.36</td>
</tr>
<tr>
<td>&gt; 59</td>
<td>1.55 ± 1.40</td>
</tr>
</tbody>
</table>

The data of the age group 20-29 were selected for calculation. The indoor minimum steady-state sound pressure level for the receiver at utmost hearing distance from the speaker is:

\[
L_p = 50 + 0.29 = 50.29 \text{ (dB)}
\]

2.2 \( L_W \) – Sound Power of the Sound Source

The indoor sound power of human under natural phonation is very small. According to some experimental data, the average sound power for a person talking for more than 60 s (including natural pauses) is 34 \( \mu \text{W} \) for men and 18 \( \mu \text{W} \) for women [1]. Taking the average sound power \( W \) of the speaker to be 34 \( \mu \text{W} \), then the sound power level is [3]:

\[
L_w = 10 \log \frac{W}{W_0} = 75.32 \text{ (dB)}
\]

where \( W_0 \) is benchmark sound power (\( 10^{-12} \) \( W \)).

2.3 \( Q \) – Directional Factor of the Sound Source

Most of the single sound sources radiate sound in all directions, but there are also some sources that radiate sound with a greater intensity in a particular direction; the human voice is a typical example [3], the directional factor of human \( Q = 2.5 \) [5].

2.4 \( R \) – Room Constant

Room constant \( R \) depends on the total inner surface area \( S \) (\( \text{m}^2 \)) and the average indoor sound absorption coefficient \( \bar{\alpha} \) as:

\[
R = \frac{S\bar{\alpha}}{1 - \bar{\alpha}}
\] (3)

It seems that \( R \) cannot be determined. However, some literature had reported that the optimum reverberation time for a lecture hall is 1.0 s [7]. Also, through analyzing the size scale of a large number of halls with good acoustic fidelity, it has been found that the ratio of volume to total inner surface area of the hall is 3.7 [8], i.e., \( V/S = 3.7 \). Putting it into Sabine’s formula [3] would give the indoor sound absorption coefficient:

\[
\bar{\alpha} = \frac{3.7K}{T_{60}}
\] (4)

where \( K \) and \( T_{60} \) are the constant (0.161) and reverberation time respectively.

Note that when the optimum value of the above parameter is put into equation (1), the utmost hearing distance between the speaker and the audience \( r \) becomes a function of the total inner surface area \( S \), i.e.:

\[
r = f(S)
\] (5)

3. CURVE-FITTING OF HEARING DISTANCE \( r \) AND TOTAL INNER SURFACE AREA \( S \)

From equation (1),

\[
r = \sqrt{\frac{Q}{4\pi \cdot R}} \cdot \frac{1}{n \cdot R - 4}
\] (6)

where

\[
n = 10^{\frac{L_p - L_{w0}}{10}}
\]

Therefore, equation (5) becomes:

\[
S = \frac{2.714r^2}{0.00314r^2 - 0.1989}
\] (7)

From equation (7), since the value of the inner surface area \( S \) cannot be negative, so \( S > 0 \); from \( 0.00314r^2 - 0.1989 \geq 0 \), the minimum value of \( r \)
can be derived as 7.96 m.

Based on the fact that the ratio of height, width and length of a hall satisfies the law of Golden Section [8], the relationship between the total inner surface area $S$ and the distance $r$ between the speaker and the audience (corresponds to curve 2 in Fig. 1) can be obtained.

$$S = 2.472r^2$$

(8)

Based on equation (7), curve 1 is drawn in Fig. 1. Curve 1 and curve 2 intersects at point A.

From Fig. 1, it can be observed that:

- For curve 1, $\lim_{S \to \infty} r = 7.96$ (m). When $S$ approaches infinity, i.e. both the speaker and the audience are under free sound field, since there is no boundary, the sound received by the audience is the sound directly from the speaker, that value agrees with everyday experience, which also agrees with the recommended value of 8 m for lecture halls by the State [5].

- It seems that $r$ in curve 1 can approach infinity, however, bear in mind that there is another limitation for lecture halls with good acoustic fidelity, i.e., the ratio of height, width and length has to satisfy the law of Golden Section [8]; therefore, $r$ has a boundary.

- The equation of curve 2 represents the geometry ratio of a lecture hall with good acoustic fidelity. It provides the boundary condition for curve 1, so the value of $r$ that corresponds to point A where curve 2 intersects with curve 1 is the maximum value, $r = 20.32$ m.

Summing up the above, it can be concluded that the utmost hearing distance in a lecture hall under natural phonation is 20.32 m.

4. CONCLUSION

The utmost hearing distance in a lecture hall is a useful information for the architects in designing such buildings. That value was calculated based on the optimum values of the parameters. The utmost hearing distance decreases with the increase in age (decrease in hearing discrimination threshold $\Delta I$) and the increase in indoor background noise. Obviously, among the various factors that affect hearing, only the problem of background noise can be tackled technically.
REFERENCES


