Location of Horn Speakers in a Reverberation Room

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ABSTRACT

Considerable theoretical research has been conducted in understanding the design constraints of horn speakers. Further, the locations of horn speakers in reverberation rooms had been well researched. However, most of the research methods applied simple sinusoidal source functions (tones) to evaluate the design criteria of horn speakers. The understanding of the horn speaker behaviour, when band limited random noise signatures such as pink noise and white noise are used as input sources, is still not clear. A hyperbolic horn with cut off frequency of 70 Hz was used in a medium sized reverberation room to study the horn behaviour. Some of the basic questions to be studied were the influence of horn location on the cut-off frequency, as well as the influence of the horn location on the diffuse sound field in the reverberation room. In addition, the influence of the input sound source on the room sound levels was also studied. The results of the experiment are presented in this paper.

RÉSUMÉ

D'importantes recherches théoriques ont été menées pour comprendre les contraintes de conception des enceintes à pavillon. De même, l'emplacement des enceintes à pavillon dans les salles réverbérantes a été bien étudié. Cependant, la plupart des méthodes de recherche appliquaient de simples fonctions sinusoïdales (son pur) comme source pour évaluer les critères de conception d'enceintes à pavillon. La compréhension du comportement des enceintes à pavillon quand des bruits aléatoires à bande limitée tels que le bruit rose ou le bruit blanc sont utilisés comme sources d'entrée n'est pas encore clair. Un pavillon hyperbolique avec une fréquence de coupure de 70 Hz a été utilisé dans une salle réverbérante de taille moyenne afin d'en étudier le comportement. Quelques-unes des questions fondamentales à étudier étaient l'influence de l'emplacement du pavillon sur la fréquence de coupure, ainsi que l'influence de l'emplacement du pavillon sur le champ acoustique diffus dans la salle réverbérante. Par ailleurs, l'influence de la source sonore d'entrée sur les niveaux sonores dans la salle a également été étudiée. Les résultats de l'expérimentation sont présentés dans cet article.

1 INTRODUCTION

Horn speaker design, such as the pioneering work of Beranek [1], has been well studied and reported in the literature. However all of the early research applied simple sinusoidal source functions (tones) to evaluate the design criteria of horn speakers [1,2]. In addition, the location of a source in a room is very much dependant on the expected sound field. Typical effects of locating the source in corners were highlighted in Bell [3] and Beranek [4]. The diffused sound in a reverberation room is supposed to be amplified by the factors based on source's location in the room. Waterhouse evaluated the sound power output of sources when placed against reflecting surfaces and showed that the 'Q' factors are 1, 2, 4, and 8 for the centre, single corner, double corner, and triple corner location of the source respectively [5]. However, his results, for sinusoidal sources as well as a few band-filtered random noises, were valid only when the reflecting surfaces were infinite in extent. Waterhouse concluded that the above results would hold for very large chambers even though no experimental results were provided in Reference 5. Glyn Adams, through theoretical evaluation showed that for steady sound sources, the impact of far walls, away from the reflecting surfaces near the sources, influenced the sound output of the sources [6]. Wright conducted an FEM (Finite Element Method) analysis and showed the importance of room modes on the radiated sound in enclosed spaces [7].

In addition, Cox et.al. [8] and Welti and Devantier [9] studied the relationship between low-frequency sounds, source locations, number of sources as well as the room sizes on the resulting sound level in enclosed spaces. Sevastiadis et.al., in a recent study, applied both numerical and experimental methods to evaluate the prevention of sound colouration inside rooms at low frequencies [10]. Once again, the results of References 8, 9 and 10, applied sinusoidal source functions to understand the behaviour of room sound levels. The extension of the above results, to broad-band and/or band-filtered sounds, is not clear.

The sinusoidal source functions analysis of the early research indicated that, if horn (exponential, conical or hyperbolic) speakers were used in a reverberation room as the main source, the operating frequencies can be modified based on the location of the horn. It was also hypothesized, for example, that if the horn is located in a triple corner, the cut off frequency can be reduced or the mouth size can be reduced [11]. The current investigation was undertaken to test the above hypothesis.

The main concerns with efficient horn designs are the large dimensions of the horn such as its length and mouth cross-sectional area. The understanding of the behaviour of horn speakers, when band limited random noise signatures such as pink noise and white noise are used as input sources, would aid in efficient horn designs with manageable horn mouth size as well as its length.

A hyperbolic horn with cut off frequency of 70 Hz was used in a medium sized reverberation room to study the horn behaviour. Some of the basic questions to be studied were the influence of horn location on the cut-off frequency, as well as the influence of the horn location on the diffuse sound field in the reverberation room. In addition, the influence of the input sound source on the room sound levels was also studied. The results of the above simple experiment are presented in this paper.

2 THE REVERBERATION CHAMBER

The reverberation chamber at Concordia University was used to conduct the experiment. Basic acoustic and geometrical details of the reverberation chamber are presented below. The results of the chamber evaluation can be found in Ramakrishnan and Grewal [12].

2.1 Chamber details

The reverberation chamber is located in the engineering building of Concordia University, Montreal and is used by the Building, Civil and Environmental Engineering Department (BCEE). The characteristics of the chamber are: Length, L = 6.13 m; Width = 6.96 m; Height = 3.56 m; Chamber Volume = 152.3 cu.m. The RT60 varied between 0.8 sec to 3 sec. across the frequency band.

2.2 Chamber characteristics

Reverberation rooms are special test rooms used to evaluate the sound power level of sources as well as to qualify space bound hardware such as antennae and satellites to a high intensity noise environment with levels and spectral content representative of the acoustic environment present during launch. Combinations of reverberation rooms are used to evaluate transmission properties of building materials as well as absorption characteristics of noise control products. A number of standards are available that prescribe minimum requirements of reverberation rooms [13, 14].

The main characteristics of the reverberation rooms are: i) Adequate volume; ii) Suitable shape or diffusing elements or both; iii) Suitably small sound absorption over the frequency of interest; and iv) Sufficiently low background noise levels. [13, 14].

The volume of the chamber needs to be adequate as it determines the low-frequency limit of the room. Above the low-frequency limit, the room responds to bands of noise uniformly thus assuring spatial constancy of the sound levels. There are different methods to determine the low-frequency limit. One such limit is the Schroeder frequency and is given by [15],

$$f_c = 2000\sqrt{\frac{T_{60}}{V}} \qquad (1)$$

where, T60 is the chamber's reverberation time, sec. and V is the volume of the chamber in cubic meters.

The above limit is quite restrictive and when the sound levels are bands of noise, the volume can be lower and one can still maintain adequate spatial uniformity. The results of sound levels, from both single sinusoidal tones as well as bands of noise, measured in the Concordia reverberation chamber are presented below to determine the adequacy of chamber volume.

Eq. (1) has provided a low-frequency limit which has been adopted by many standards and based on that requirement, the volume of the chamber has to be determined. As mentioned earlier, Schroeder requirement is quite restrictive.

Another empirical approach is to impose a norm of at least 20 modes per octave for acceptable uniformity. Slingerland, Elfstorm and Grün applied 20 modes/octave criterion and derived the following relationship for the cut-off frequency [16].

$$f_c = \frac{c}{\sqrt[3]{V}} \qquad (2)$$

where, c is the speed of sound.

The two different approaches produce different limits and the most commonly used Schroeder limit is too restrictive. Field measurements were conducted in the chamber to determine the most reasonable limit that is practical and can be easily implemented. The cut-off frequency as per Eq. (1) is 188 Hz and as per Eq. 2 is 64 Hz.

The chamber is rectangular in shape and the standing wave frequencies can easily be determined from basic descriptions [17] and are given by,

$$f_n = \frac{c}{2}\sqrt{\left[\frac{n_x}{L_x}\right]^2 + \left[\frac{n_y}{L_y}\right]^2 + \left[\frac{n_z}{L_z}\right]^2} \qquad (3)$$

The number of modes in each octave band was enumerated from the above equation and the results for the chamber are given in Table 1.

The results of Table 1 show that that the Chamber can be comfortably used from the 125 Hz octave band to achieve acceptable spatial uniformity. This is borne out by the cut-off frequency of 64 Hz calculated from Eq. 2. The Schroeder limit for the Chamber is 188 Hz (from Eq. 1) which is very restrictive.

Table 1. Modal Composition of the Chamber

Band No.	Lower Limit	Centre Frequency	Upper Limit	Number of Modes
1	22	31.5	44	5
2	44	63	88	38
3	88	125	177	210
4	177	250	355	340

The validity of these limiting frequencies is confirmed through measurements and is presented next.

A simple experiment was used to determine the spatial uniformity of the chamber as well as the low-frequency cut-off limit of the chamber. Simple speakers (both low-frequency speakers and a bank of high frequency tweeters) were used to generate the sound. Both pink noise and sinusoidal tones (100, 150, 200, 250, 300, 400, 500 Hz) were generated and the resulting noise levels were measured at a number of locations, - between 48 and 54. The locations were chosen randomly at two different heights. The results of the measured SPLs are presented in Tables 2 and 3.

Table 2. Sound Levels in the chamber (Broadband, 28 Samples)

1/3 Octave Band Centre Frequency, Hz	Average SPL, dB	Range, dB	Standard Deviation, dB
50	145.4	10.0	3.8
63	146.1	8.3	2.6
80	144.9	7.1	2.6
100	144.2	3.9	1.4
125	144.2	4.0	1.4

The results of Table 2 show that for a broadband signal, the chamber had good spatial uniformity from 100 Hz (1/3 octave band) and above. However, the same cannot be inferred for tones. Even for frequencies above the Schroeder frequency limit of 188 Hz, the chamber's spatial uniformity, as seen in the results of Table 3, is poor.

Table 3. Sound Levels in the chamber

Tonal Frequency Hz	Average SPL, dB	Range dB	Number of Samples	Standard Deviation, dB
100	102.5	37.1	37	9.5
150	100.1	29.3	47	7.1
200	98.0	28.6	48	8.8
250	97.6	35.1	48	7.6
300	94.4	31.1	48	7.4
400	96.3	29.8	48	7.8
500	100.7	32.6	48	8.4

The ISO Standard 3741 [14] requires a minimum of 200 cu. m. as per the Schroeder limit of 125 Hz Octave band and the maximum allowable standard deviation is 1.5 dB. The results of Table 2 show that even if one cannot meet the minimum volume requirement, the spatial uniformity of the chamber sound levels can be satisfied for broadband sound levels. For pure sinusoids, even though the volume requirements are satisfied, the results of Reference 12 indicated that the spatial uniformity cannot be assured.

3 THE HYPERBOLIC HORN

A hyperbolic horn speaker was used for the tests. The horn in a triple corner is shown in Figure 1. The horn details are: the horn length is 92.1"; the throat area is 2.1 sq. in; the mouth area 397.5 sq. in.; band width is from 68 to 219 Hz; and the horn volume is 3.7 cu. ft.

The horn was connected to an AURA NS3-193-8A speaker with frequency response from 50 Hz to 7000 Hz (±3 dB). The microphone boom that was used in the sound levels measurements is in the background.

Figure 1. The Hyperbolic horn at a triple corner (The microphone boom is in the background).

4 THE EXPERIMENT

The experiment basically consisted of driving the speaker-horn combination with single sinusoids or band filleted random noise. The diffused sound field was measured by using a microphone boom at two different heights. The equivalent sound level over a 30 second traverse of the boom was calculated. The measurements were conducted for three locations of the horn – the horn speaker in triple corner (as shown in Figure 1); the horn speaker was moved diagonally by 2 feet; and the horn speaker was moved diagonally by 4 feet. The last location would represent a double corner somewhat. Different combinations of the horn speaker locations were also tested. The results for the above triple corner and a single corner are presented in this paper. As mentioned earlier, the operating frequency of the hyperbolic horn is from 68 Hz to 219 Hz. The above band width was determined by the

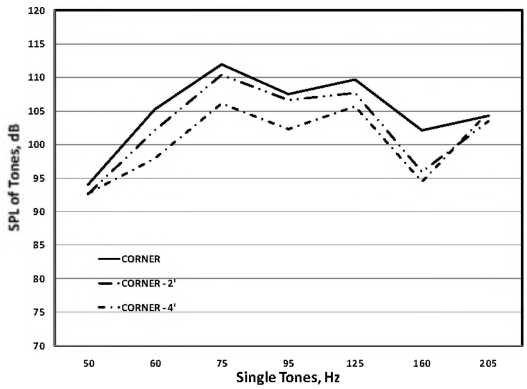

Figure 2. Room SPL variation – single tones.

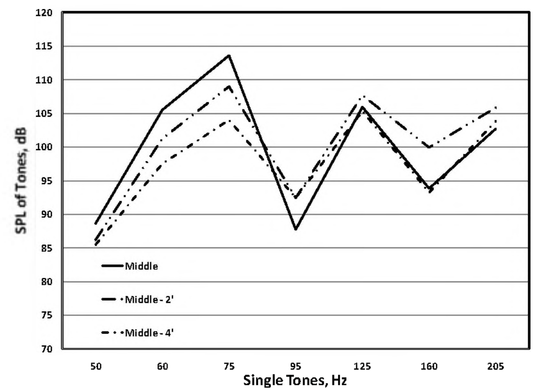

Figure 5. Room SPL variation – single tones.

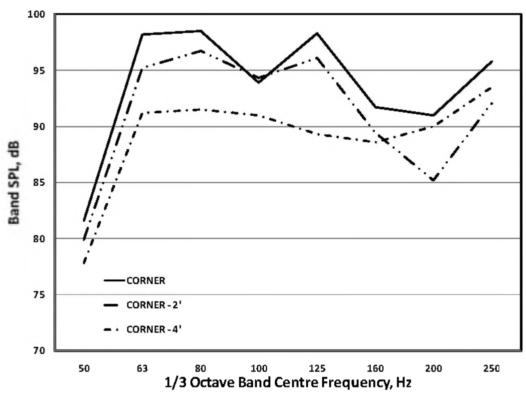

Figure 3. Room SPL variation – Band filtered noise.

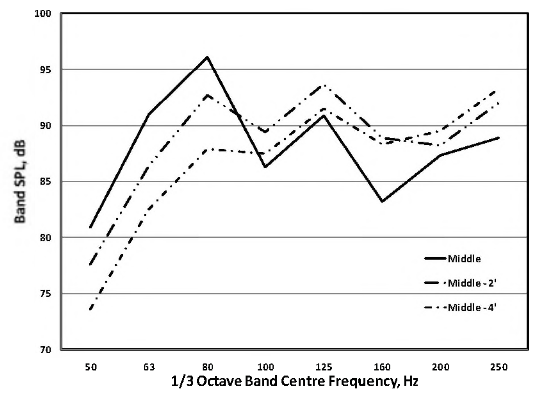

Figure 6. Room SPL variation – Band filtered noise.

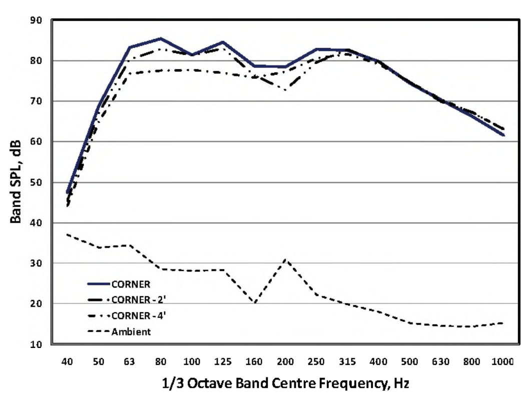

Figure 4. Room SPL variation – Pink noise (40 to 10 kHz).

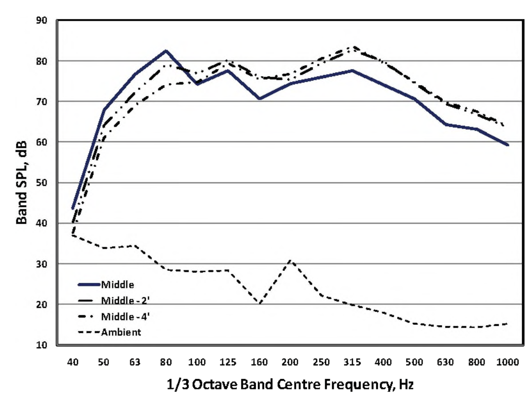

Figure 7. Room SPL variation – Pink noise (40 to 10 kHz).

manufacturer from the design of hyperbolic horn. The length and the mouth area were evaluated after fixing the cut-off frequency and the upper limit frequency of the horn design.

5 RESULTS AND DISCUSSION

The room sound pressure levels (SPL) for various conditions are shown in Figures 2, 3 and 4 below for the triple corner location. The operating condition changes from a triple corner to a somewhat pseudo-double corner.

The SPL variations in the room for sinusoidal sources are shown in Figure 2. The room SPLs between 60 Hz and 160 Hz are seen to follow the typical 'Q' factor variation of 3 to 4 dB differences. The behaviour below 60 Hz and above 200 Hz is seen to be indifferent to the speaker location. Even though a strong signal was generated at 50 Hz, the triple corner effect is non-existent. The results for band-filtered random noise are shown in Figure 3 and much broader pink noise results are shown in Figure 4. The speaker location's effect is unpredictable for the band-filtered random noise within the operating range of the horn. The speaker location had absolutely no effect when the broader pink noise was generated. No consistent 'Q' factor effect was evident in the results of Figures 3 and 4. Strong room modes may have an impact in the 100 to 200 Hz frequency range, even though there are a few modes, at least 10 in each third-octave.

The results for a single corner location, slowly changing onto a non-reflecting location, are shown in Figures 5 thru' 7.

Somewhat similar behavior to the early results can be seen. In addition, the room mode impact, particularly the coupling between the source and the room, is seen to be strong in the 100 to 200 Hz frequency range.

6 CONCLUSIONS

The effect of the location of a horn speaker in a reverberation room was tested. The effect was evident in the sinusoidal input signals. When random noise and/or broad band signals were used as input, the preliminary results show that the speaker location had no impact on the diffused sound levels of the reverberation chamber. The current work is on-going and the above experiment needs to be expanded to include higher frequency bands to test the validity of the questions that were posed.

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