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PRECISION OF SOUND PRESSURE LEVEL MEASUREMENTS IN A REVERBERATION ROOM

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INTRODUCTION

The accuracy of a transmission loss measurement depends on the precision of sound pressure level measurements in both the source room and the receiving room and the total absorption measurement of the receiving room. It is the purpose of this Note to provide some preliminary experimental results on the assessment of the accuracy of Lubman's analysis of the precision of sound pressure level measurements in a reverberation sound field. Discussion will be limited to precision in sound pressure level measurements.

In any reverberant sound field the value of sound pressure level at any one location in a room may be very different from the average sound pressure level of that room. These variations are especially large for pure-tone or narrow-band noise excitations. As it is not practical to find the average sound pressure level exactly, it is necessary to obtain an estimate of the quantity by spatial averaging over a limited portion of the room. This estimate is subject to random error. The variance or standard deviation of this error is the primary concern here.

For a set of sound pressure level measurements, the standard deviation, σ, is given by the following formula,

$$\sigma = \left[\frac{\sum_{1}^{n} (X_i - \langle X \rangle)^2}{n} \right]^{1/2}$$

where n = total number of individual measurements X_i of the sound pressure level, assumed to be randomly distributed

$\langle X \rangle$ = arithmetic average of X_i

On the other hand, it is possible to predict the limiting values of σ analytically. Bowers and Lubman (1) suggest that the variance of sound pressure levels in a room, σ_L^2, may be computed from

$$\sigma_L^2 \simeq \frac{1}{k^2} \left(\frac{1}{N} + \frac{1}{2N^2} + \cdots\right) \qquad (2)$$

where

$k = \log_e (10)/10 = 0.2303$

N = nearest integer to $1/V_p^2$

V_p^2 = normalized variance of the mean-square pressure.

From a room excited by bands of noise, V_p^2 is given by the following expression (2)

$$V_p^2 = \begin{cases} (1 + B\eta/\pi)^{-1} & \text{(low frequency, i.e., } \eta \leqslant 1) \\ (1 + BT_{60}/6.9)^{-1} & \text{(middle and high frequencies, i.e., } \eta \geqslant 1) \end{cases}$$

where B = signal bandwidth (0.232 f for 1/3 octave signal; f is the centre frequency of band in Hz)

η = modal density

$\simeq 4\pi V f^2/c^3 + \pi s f/2c^2 + L/8c$

T_{60} = reverberation time, sec

V = room volume

s = room surface area

L = length of room edges

c = speed of sound

This note will give some comparison of the variability of measured sound pressure levels and analytical prediction obtained in the NRC facilities.

COMPARISON WITH EXPERIMENTAL RESULTS

Preliminary experimental measurements of sound pressure levels have been performed at the NRC facilities to verify analytical prediction. Figure 1 shows a schematic drawing of the layout of the facilities. Measurements have been made in both the source room (the smaller one) and the receiving room. Both rooms are equipped with fixed diffusers and a rotating diffuser. The fixed diffusers are made of 3- by 6-ft glass fibre corrugated panels. Four are hung at random in space in the source room and eight in the receiving room. Two additional panels are mounted on a rotating shaft in the source room to act as a rotating vane. They are inclined at about 45 deg to the horizontal and rotate at 8 rpm. In the receiving room the rotating vane is made of a 48 -sq ft board mounted about 30 deg to the vertical; it rotates at a rate of 12 rpm.

Sound pressure levels in 1/3 octave bands were measured by a set of eight microphones in each room. Because of space limitation the microphones in the source room are about 4 ft from the walls and about 3 ft from neighbouring microphones. In the receiving room, however, they are separated by at least 5 ft from each other and from the reflecting walls.

Spatial standard deviation (square root of the spatial variance) was calculated from these measurements taken with an averaging time of 16 sec in the source room and 32 sec in the receiving room.

At the time of these measurements, a floor specimen was installed in an opening in the ceiling of the source room and the wall opening to the receiving room was filled by a wall specimen. On the source room side, the exposed surface of the floor specimen was made of gypsum board and similary the exposed surface of the wall specimen was of gypsum board. On the receiving room side the wall opening was blocked by a heavy door.

Results for 1/3-octave bands of noise obtained in the source room are shown in Table I. The reasonable comparison with theory shown here may be fortuitous; subsequent experiments showed a significant variation in the spatial standard deviation when the room was driven by one, two or four speakers (Figure 2). Results obtained for the receiving room also showed significant variation in the spatial standard deviation at low frequencies (Figure 3). Further experiments in the receiving room showed that even for consecutive repeated measurements under identical conditions the spatial standard deviation showed substantial variation between runs at low frequencies. Table II compares mean and standard deviations for five repeated runs where four speakers were employed as driving sources. Subsequently, individual microphone data from these five repeated runs were used together to compute an over-all mean and standard deviation. Results were in much better agreement with theory, as shown in Table III and Figure 3, except for one particular point at 160 hz for which there is as yet no explanation.

Preliminary results are encouraging in showing that an analytical model might be used to predict measurement accuracy. More extensive measurements in different laboratories are needed, however, to assess the accuracy of the analytical prediction properly and to establish guidelines for measurements that will achieve such precision.

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TABLE I

COMPARISON OF ERROR ESTIMATES FOR SPL MEASUREMENTS

(small source room)

Frequency (Hz)	η	T_{60} (sec)	Experimental Sigma (dB)	Theoretical Sigma (dB)	Deviation of Observed Sigma from Theoretical Sigma (dB)
125	0.53		1.98	2.04	-0.06
160	0.79		1.65	1.41	0.24
200	>1	1.97	1.02	1.18	-0.16
250		2.66	1.06	0.92	0.14
315		2.71	0.95	0.81	0.14
400		2.56	0.55	0.74	-0.19
500		2.71	0.87	0.64	0.23
630		2.85	0.59	0.56	0.03
800		2.75	0.58	0.51	0.07
1000		2.71	0.51	0.45	0.06
1250		2.65	0.43	0.41	0.02
1600		2.51	0.39	0.37	0.02
2000		2.30	0.31	0.35	-0.04
2500		2.06	0.43	0.33	0.10
3150		1.77	0.46	0.32	0.14
4000		1.58	0.53	0.30	0.23

TABLE II

COMPARISON OF MEAN SPL AND STANDARD DEVIATION
OF CONSECUTIVE REPEATED RUNS

(large receiving room)

f	Mean (dB)					Standard Deviation (dB)				
	Run #1	Run #2	Run #3	Run #4	Run #5	Run #1	Run #2	Run #3	Run #4	Run #5
80	68.26	68.02	67.43	67.94	67.93	1.86	1.74	1.48	1.88	1.65
100	64.60	64.67	64.40	64.36	64.69	0.99	0.64	0.76	0.87	1.08
125	70.49	70.42	70.18	69.98	70.39	0.70	0.69	0.52	0.69	0.68
160	70.07	70.03	69.80	69.76	69.98	0.83	0.96	1.05	1.12	0.99
200	75.22	75.06	74.85	74.81	74.98	0.78	0.51	0.64	0.56	0.65
250	74.96	74.77	74.55	74.57	74.83	0.48	0.44	0.39	0.35	0.37
315	79.39	79.45	79.12	79.10	79.04	0.40	0.37	0.50	0.62	0.28
400	77.80	77.70	77.34	77.27	77.58	0.39	0.40	0.51	0.40	0.46
500	80.13	80.04	79.87	79.98	79.89	0.23	0.28	0.53	0.34	0.40
630	85.86	85.74	85.50	85.56	85.80	0.35	0.51	0.51	0.52	0.41
800	88.01	87.93	87.70	87.65	87.92	0.35	0.44	0.29	0.46	0.35
1000	89.88	89.73	89.50	89.64	89.76	0.30	0.39	0.23	0.38	0.33
1250	87.60	87.44	87.20	87.23	87.47	0.23	0.18	0.29	0.28	0.16
1600	89.23	89.22	88.94	88.98	89.20	0.34	0.21	0.22	0.41	0.35
2000	90.39	90.38	90.30	90.36	90.51	0.42	0.27	0.43	0.40	0.38
2500	88.89	88.84	88.84	88.83	88.87	0.40	0.58	0.55	0.37	0.52
3150	88.55	88.38	88.37	88.36	88.19	0.45	0.19	0.48	0.46	0.26
4000	86.92	87.12	86.92	86.93	87.17	0.40	0.48	0.35	0.50	0.40

TABLE III

COMPARISON OF ERROR ESTIMATES FOR SPL MEASUREMENTS

(large receiving room)

Frequency (Hz)	η	T_{60} (sec)	Experimental Sigma (dB)	Theoretical Sigma (dB)	Deviation of Observed Sigma from Theoretical Sigma (dB)
80	0.87		1.66	1.85	-0.19
100	>1	7.00	0.84	0.90	-0.06
125		8.50	0.65	0.73	-0.08
160		7.17	0.96	0.70	0.26
200		6.96	0.62	0.64	-0.02
250		7.27	0.42	0.55	-0.13
315		7.39	0.46	0.49	-0.03
400		6.66	0.46	0.46	0.00
500		6.16	0.37	0.43	-0.06
630		5.96	0.46	0.39	0.07
800		5.55	0.39	0.35	0.04
1000		5.41	0.34	0.32	0.02
1250		5.26	0.27	0.29	-0.02
1600		5.03	0.32	0.26	0.06
2000		4.53	0.37	0.25	0.12
2500		3.92	0.46	0.24	0.22
3150		3.43	0.38	0.23	0.15
4000		3.02	0.42	0.22	0.20

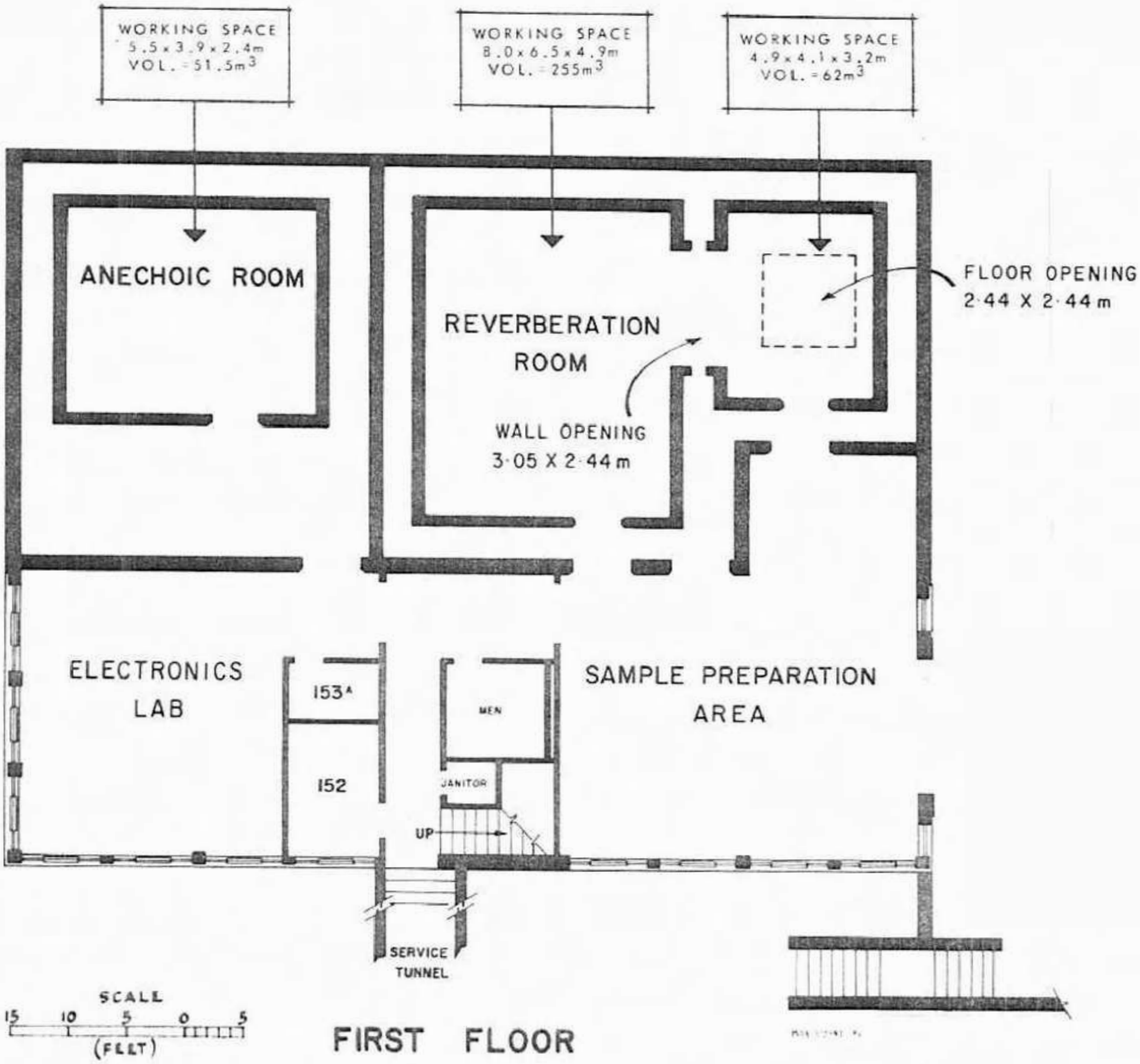

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FIGURE 1 NRC TESTING FACILITIES

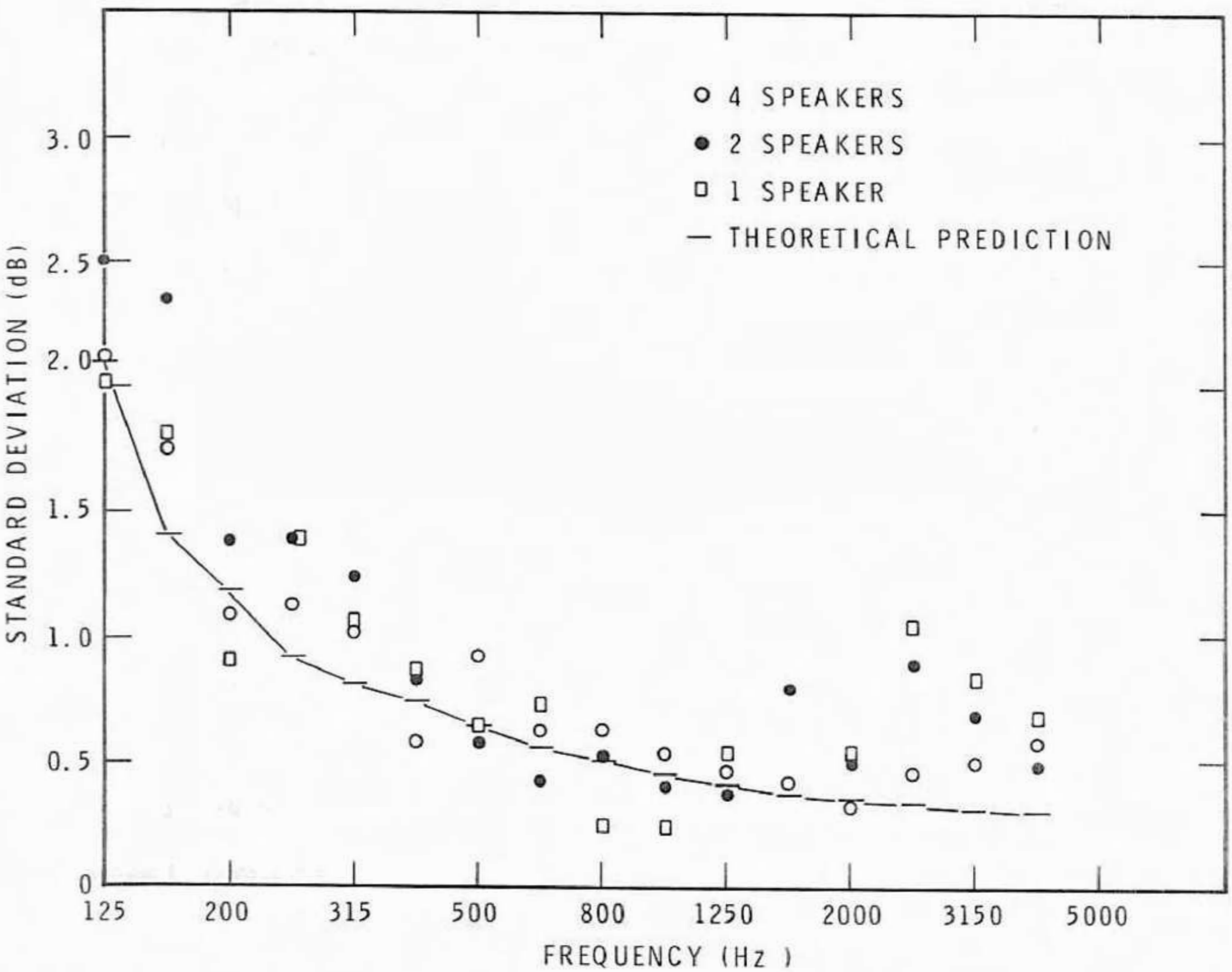

FIGURE 2

COMPARISON OF MEASURED AND PREDICTED VALUES OF SPATIAL STANDARD DEVIATION IN THE SOURCE ROOM

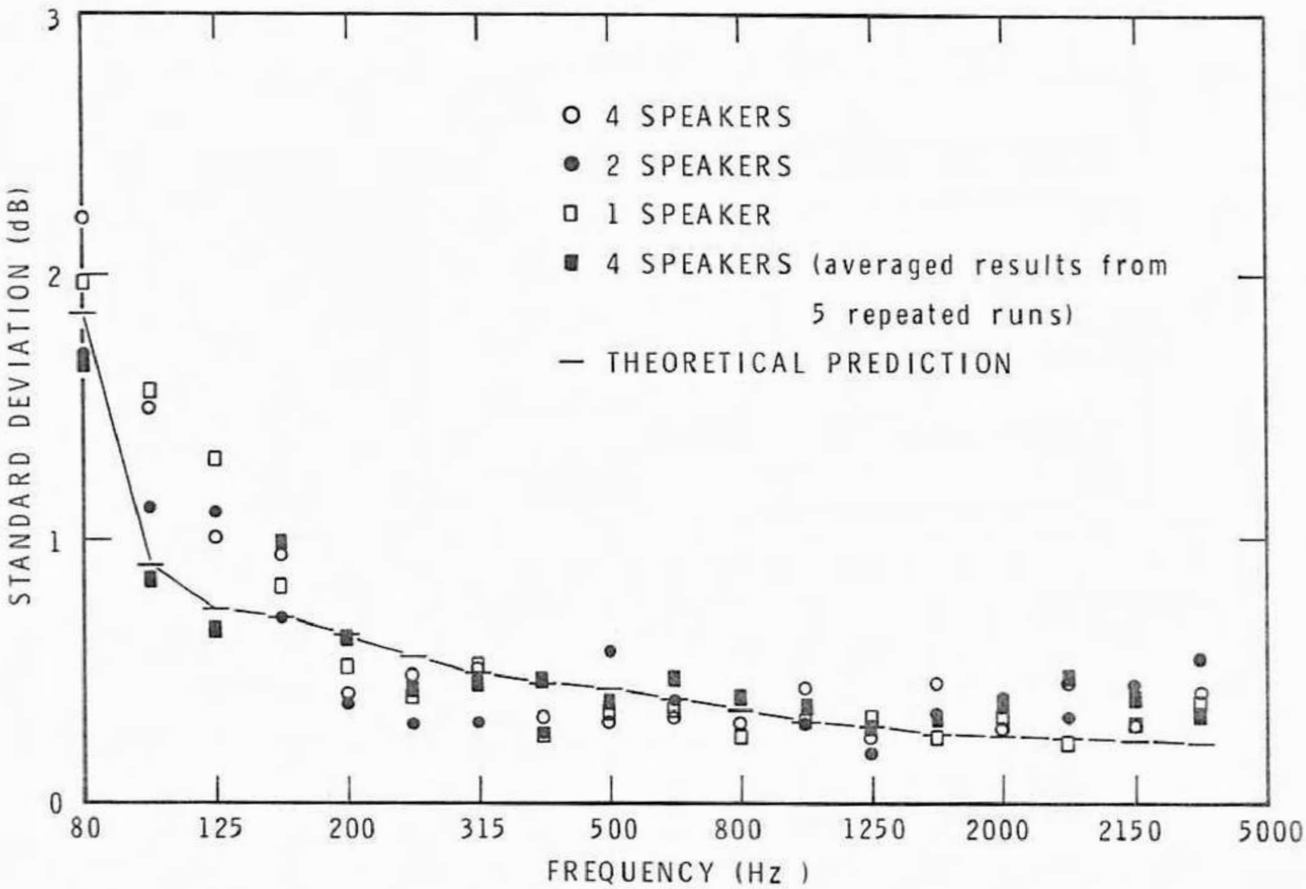

FIGURE 3

COMPARISON OF MEASURED AND PREDICTED VALUES OF SPATIAL STANDARD DEVIATION IN THE RECEIVING ROOM

APPENDIX A

DERIVATION OF EQUATION 2

As Eq. (2) has not been presented in the open literature, it may be useful to re-derive it in detail. An approximate form involving only the first term has been given by Schroeder (A-1). For N not too large, however, at least two terms in the series are required to give an accurate answer.

Consider a room excited by a band of noise with a flat spectrum. It is known that in a reverberant sound field the mean-square pressure, $\overline{p^2}$, (i.e. time-averaged value) varies with location in the room. In principle, fluctuations can be predicted from the steady-state room response, which is found as the solution to a boundary value problem. At high frequencies where many room modes are excited, however, a formal boundary value solution seems impossible and statistical approach is more appropriate. For a reverberant field that is sufficiently diffuse an ensemble of $\overline{p^2}$ measured at different locations may be considered as a continuous-parameter, stochastic process. Waterhouse (A-2) derived distributions of $\overline{p^2}$ for a room excited by a single frequency or a multitone, but the exact distribution of $\overline{p^2}$ for narrow band noise excitation is difficult to find. It has, however, been demonstrated by Lubman (A-3) that the statistics of narrow band noise excitation are about the same as those for excitation with M tones well separated in frequency and equal in power. M is taken as the nearest integer to $1/V_p^2$. The probability density function is given by the following expression (A-3):

$$\begin{aligned} P(X) &= P\,(\overline{p^2} = X) \\ &= M^M X^{M-1} e^{-MX}/(M-1)!\,, \qquad X \geqslant 0 \end{aligned} \tag{A1}$$

where, for simplicity, a unit value for the mean has been assumed, i.e. $< \overline{p^2} > = 1$. Defining

$$y = 10 \log_{10} \overline{p^2} \tag{A2}$$

for the sound pressure level, y can be rewritten as

$$y = \frac{1}{k} \log_e \overline{p^2} \tag{A3}$$

where $k = \log_e(10)/10 = 0.2303$

Knowing the statistics of $\overline{p}^2$, it is possible to estimate the variance of the sound pressure levels σ_L^2 and this is equal to:

$$\sigma_L^2 = \langle y^2 \rangle - \langle y \rangle^2 \tag{A4}$$

According to statistical theory,

$$\langle y \rangle = \frac{1}{k} \frac{M^M}{(M-1)!} \int_0^\infty (\log_e X) \quad X^{M-1} e^{-MX} \, dX \tag{A5}$$

By means of Formula 4.352.1 of Reference A-4,

$$\langle y \rangle = \frac{1}{k} \left[\psi (M) - \log_e(M) \right] \tag{A6}$$

where $\psi(M)$ is the Euler's psi function (also known as the polygama function of first order).

Similarly

$$\langle y^2 \rangle = \frac{1}{k^2} \frac{M^M}{(M-1)!} \int_0^\infty (\log_e X)^2 \, X^{M-1} e^{-MX} dX \tag{A7}$$

$$= \frac{1}{k^2} \left\{ [\psi(M) - \log_e(M)]^2 + \zeta(2,M-1) \right\}$$

according to Formula 4.358.2 of Reference A-4, where $\zeta(2,M-1)$ is the Riemann's zeta function, which can be written as

$$\zeta(2,M-1) = \sum_{n=0}^{\infty} \frac{1}{[(M-1) + n]^2} \tag{A8}$$

from Formula 9.521.1 of Reference (A-4).

Thus

$$\sigma_L^2 = \langle y^2 \rangle - \langle y \rangle^2$$

$$= \frac{1}{k^2} \sum_{n=0}^{\infty} \frac{1}{[(M-1) + n]^2} \tag{A9}$$

If $N = M-1$ is to be defined as the integer value smaller than $1/V_p^2$, Formula 8.363.8 of Reference (A-4) gives

$$\sigma_L^2 = \frac{1}{k} \psi'(N) \qquad \text{(A10)}$$

which can further be expanded for large N according to Equation 6.4.12 of Reference (A-5) to give

$$\sigma_L^2 \simeq \frac{1}{k^2}\left(\frac{1}{N} + \frac{1}{2N^2} + \frac{1}{6N^3} - \frac{1}{30N^5} + \cdots\cdots \right) \qquad \text{(A11)}$$

Equation (A11) is the same as Equation 2 of Reference 1.

It should be noted that in deriving Eq. (AII) it has been assumed that $\langle \overline{p}^2 \rangle = 1$. It can, however, easily be shown that in computing the experimental spatial variance of the sound pressure levels it is not necessary to normalize the individual mean-square pressure by the spatial mean before computing the SPL and variance.

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