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A test of proposed revisions to room noise criteria curves

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The 1995 American National Standard, *Criteria for Evaluating Noise*, presents two sets of room noise criteria curves; one termed NCB and the other RC. The two sets of room criteria curves are based on data and theory, and each is correct for specific situations. The two sets of curves depart most markedly from one another at low frequencies and low sound levels. Each set of curves is potentially inadequate for some specific situations encountered when characterizing HVAC system noise. In some circumstances the RC criteria curves can be excessively conservative (require unnecessarily low sound levels) and in other circumstances the NCB criteria curves may not provide adequate protection against noisy HVAC systems. A third set of criteria curves, the RNC curves, has been proposed as a more adequate approach to quiet HVAC system design. The proposed RNC curves and associated methodology are based on theories of hearing. In this paper the RNC methodology is tested using annoyance data that has been collected in a study of annoyance caused by HVAC system noise. Results of the RNC methodology are compared to the psycho-acoustical evaluations of the annoyance study. The comparisons reveal that the RNC curves and methodology provide improved characterization of noise in rooms.

Primary subject classification: 69.1; Secondary subject classification: 51

1. INTRODUCTION

The recent American National Standard, *Criteria for Evaluating Room Noise*,[1] presents two sets of room noise criteria curves; one termed NCB and the other RC. The NCB criterion curves are given in Fig. 1 and Table 1. They appear in the ANSI Standard only as a table of values. Beranek derived these curves from the characteristics of hearing to be consistent with equal-loudness-level contours and to be consistent with subjective responses.[2] The RC criterion curves are given in Fig. 2. They are parallel lines with a –5 dB per octave slope that goes through the stated RC value in the 1000 Hz octave band. These curves appear in the ANSI Standard only as a table of values. Blazier derived these curves from subjective responses to include the effects of slowly fluctuating low-frequency noise.[3,4]

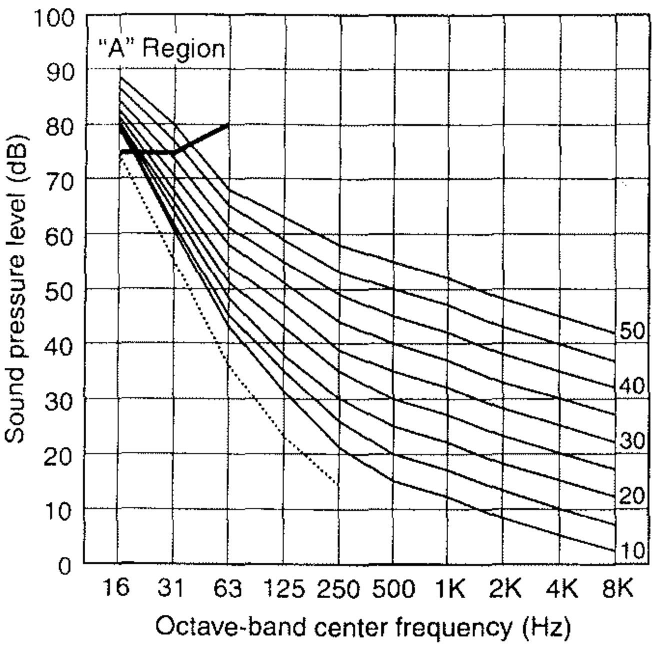

Fig. 1 – NCB room noise criteria curves—After ANSI S12.2 and Beranek. The dashed line is the approximate threshold of hearing.

The two sets of room criterion curves each are based on data and theory, and each is correct for a specific set of situations. These two sets of criterion curves depart most markedly from one another at low frequencies and low sound levels. Also, each set has its problems. The RC curves set criteria levels that are below the threshold of hearing. This is done to protect against modern, poorly designed HVAC systems that generate large turbulent fluctuation at low frequencies and can include fan surging with concomitant noise level surging of 10 dB or more. But the RC curves, strictly utilized, would "penalize" a well designed HVAC system such as the type that might be included in a concert hall design. The RC criterion could require 10 dB or more of unnecessary noise quieting at low frequencies. On the other hand, the NCB

TABLE 1 – Numerical values for the NCB curves.

Octave-band center frequency (Hz)	NCB 50	NCB 45	NCB 40	NCB 35	NCB 30	NCB 25	NCB 20	NCB 15	NCB 10
16	89	87	85	83	82	81	81	81	81
31	80	77	74	71	68	66	64	62	61
63	68	65	61	58	54	51	48	45	43
125	63	59	55	51	47	43	38	35	31
250	58	53	49	44	39	35	30	26	21
500	55	50	45	40	35	30	25	20	15
1000	52	47	42	37	32	27	22	17	12
2000	48	43	38	33	28	23	18	13	8
4000	45	40	35	30	25	20	15	10	5
8000	42	37	32	27	22	17	12	7	2

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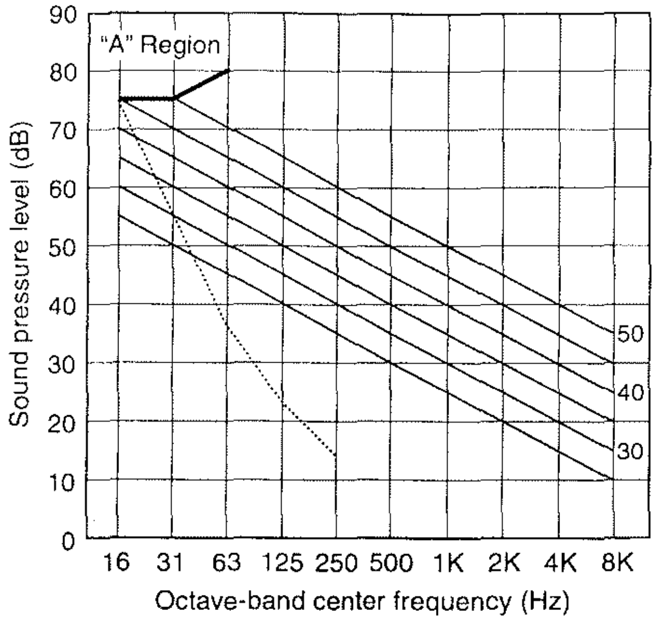

Fig. 2 – RC room noise criteria curves—After ANSI S12.2 and Blazier. The dashed line is the approximate threshold of hearing.

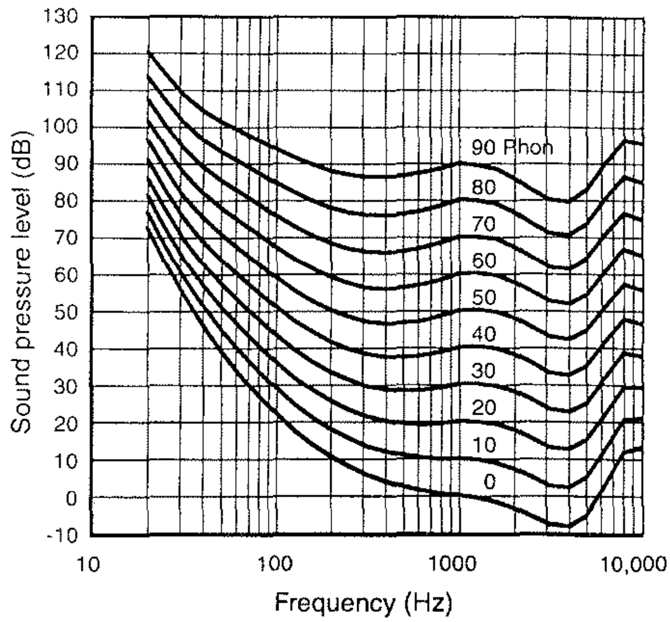

Fig. 3 – Equal-loudness-level contours (After ISO 226).

curves set criteria levels that are based on "well-behaved" HVAC systems—systems where turbulence generation is minimized and fan surging does not exist. As such, these criteria are inappropriate, alone, for a standard. They do not protect the user from a poor system (a turbulence-generating fan-surging system) that still can legally meet the standard. There can be no doubt that lawyers could and would use the NCB criteria to show that their poor system met the standard.

Schomer[5] has suggested the RNC curves and associated methodology as a means to rate room noise that bridges the gap between Beranek and Blazier. For well-designed HVAC systems, it sets criteria that are very similar to the NCB criteria of Beranek. However, if there are large turbulent fluctuations at low frequencies and/or fan surging with concomitant noise level surging, then the RNC methodology includes penalties that, in effect, reduce the criteria to those that are similar to the RC criteria of Blazier. The RNC methodology is based on theories for hearing. It makes extensive use of the equal-loudness-level contours of the ear (Fig. 3). These contours show that for a constant increase in sound pressure level, the increase in loudness is much greater at low frequencies than at frequencies above about 250 Hz, and that this effect increases with decreasing frequency. Because of this low-frequency effect, the RNC methodology incorporates two factors.

First, because of this low-frequency effect, the RNC contours are spaced more closely together at low frequencies and lower sound pressure levels than at the frequencies above 250 Hz. Second, because of this low-frequency effect, it is inappropriate to use the equivalent level (LEQ) in octave bands as the descriptor. Rather, below the 250 Hz octave band, sound must be combined into critical bandwidths and integrated over short periods that correspond to the integration time of the ear. That is, time-series of LEQ levels are developed for the combined 16, 31 and 63 Hz octave bands (the first critical band), for the 125 Hz octave band (the second critical band), and for each octave band above 125 Hz. Provisionally, Schomer suggested using the 125 ms integration time of fast-time weighting to approximate the integration time of the ear.[5] To create the time-series of LEQ levels, the fast-time-weighted level was to be sampled sufficiently fast to follow the fast-time-weighted signals. A sample rate of about 100 ms was suggested. Following generally accepted practice, it was assumed that the critical bands of the ear were about 100 Hz wide at frequencies below 500 Hz. Therefore the three lowest frequency octave bands (16, 31, and 63 Hz) are combined together when forming the time series since together they are about 100 Hz wide.[6,7] The 125 Hz octave band was used by itself when forming the time series since it is about 100 Hz wide by itself. All octave bands above 125 Hz were used each alone, since each is greater than 100 Hz wide.

Equation (1) gives the method to sum the levels from any of the time series. In Eq. 1, the parameter d reflects the sound pressure level increase required for a 10 phon increase in loudness at low to moderate sound levels (Fig. 3). For the lowest band (the combined 16, 31, and 63 Hz octave bands), d was set to 5. For the 125 Hz octave band, d was set to 8, and for all other bands, d was set to 10.

$$L_{LL} = 10\log\left[(1/N)\sum_{i=1}^{N} 10^{\left(\frac{(10/\delta)(L_i - L_m) + L_m}{10}\right)}\right]$$

$$= L_m + 10\log\left[(1/N)\sum_{i=1}^{N} 10^{\left(\frac{(10/\delta)(L_i - L_m)}{10}\right)}\right] \quad (1)$$

In Eq. (1), L_i is the *i*th value of any time series, *N* is the number of elements to that time series, L_m is the mean value for that time series, and L_{LL} is the calculated result for that time series. Note that for δ equal to 10, Eq. (1) reduces to the equation normally used to calculate LEQ. That is, for the 250 Hz octave band and above, the RNC metric reduces to octave band LEQ levels.

Bradley has studied the annoyance generated in rooms by sounds that contain various degrees of turbulence and surging at low frequencies.[8] He reports on an initial experiment to evaluate the additional annoyance caused by varying amounts of low-frequency rumble sounds from heating, ventilating, and air conditioning (HVAC) systems. HVAC noises were simulated with various levels of low-frequency sound and varying amounts of amplitude modulation of the low-frequency components. Nine subjects listened to the test sounds over headphones and adjusted the level of the test sounds to be equally annoying as a fixed neutral reference sound. The neutral test sound was random noise with a minus 5 dB per octave slope to the spectrum. Bradley used time-series of short-term LEQ levels to evaluate these sounds. The short-term LEQ levels were calculated each 0.128 s for each one-third-octave band. Thus, these data can be used to test the RNC methodology. The 0.128 s LEQ levels certainly approximate a series of fast-time-weighted levels, and the energies in the 16, 31, and 63 Hz octave bands can be combined according the RNC methodology. The resulting RNC levels can be compared with the psycho-acoustical evaluations provided by Bradley's subjects. This paper uses the Bradley data to test the RNC methodology.

2. EVALUATION OF THE BRADLEY DATA

A. The Bradley data

The Bradley data consisted of 25 test signals.[8] Five signals consisted of random noise with 5 degrees of rumble, the higher the rumble the higher the LEQ in the lower frequency octave bands. Levels were increased by increasing the gain and the standard deviation to the noise. These 5 signals had no amplitude modulation to simulate fan surging. Little could be done with the 16 Hz octave band in this experiment because it used headphones and could not reproduce energy at this low frequency. Primary use was made of the 31 Hz octave band.

Bradley used the highest two rumble signals for the modulation experiment. He designated these as the "low" and "high" rumble signals. Each rumble signal was modulated at two levels, 10 and 17 dB, which he designated as "low" and "high" modulation. For each level of rumble and modulation he used 5 modulation frequencies: 0.25, 0.5, 1, 2, and 4 Hz. Thus, in the Bradley study there were 20 modulated test signals to go with the 5 un-modulated test signals. Bradley's choice of modulation frequencies centers on the important range, since, according to Blazier, a modulation frequency of 1 Hz is typical of HVAC problems.[9] The original two un-modulated rumble spectra used for the modulation experiment and the control signal spectra are shown in Fig. 4. Further details of the original experiment can be found in Bradley.[8]

There were no analogue or digital recordings of these test signals, but digital data records of the LEQ by one-third-octave band, for every 0.128 s are available for all 20 modulated test signals and for the highest two un-modulated, rumble test signals (Fig. 4). Each digital record consists of 559 samples, each 0.128 s in duration.

Each of the 9 subjects compared separately each of the 24 test signals to the neutral, reference spectrum. To do this, the subject would adjust an attenuator that controlled the test signal until that subject judged the test signal to be equal in annoyance to the reference spectrum. Table 2 lists the average attenuator setting for the 22 test signals for which there are digital records. Note that Bradley found that the reference spectrum when compared to itself yielded an attenuator setting of just 0.2 dB showing good internal consistency for this experiment.

B. Testing the RNC methodology

In concept, testing of the RNC methodology using the Bradley data is straight forward. One would evaluate the RNC level for each of the 25 test signals, subtract the RNC level for the reference spectrum from each of the other 24 test signal RNC levels, and compare these 24 differences with the corresponding 24 mean attenuator settings. Unfortunately there are two difficulties with accomplishing this task. First, no digital record is available for the reference spectrum by 0.128 s time slices although the LEQ by one-third-octave band for the entire 71.5 s is available. However, the reference signal is described as not rumbly and it clearly is un-modulated. Therefore, for this analysis we must assume that the reference signal is non-surging and with a small enough standard deviation such that the octave band LEQs can be used to determine the RNC level without any penalties.

Second, the Bradley data are for relatively high sound levels, and they are beyond the levels given in Schomer.[5] In fact, the LEQs in the 31-Hz octave band are well into the rattle region, which is designated the "A"Region by both Beranek and Blazier and also by the RNC method. There are at least two methods to extend the RNC curves to higher levels and these are portrayed in Figs. 5(a) and 5(b). In Fig. 5(a), the RNC curves have been extended in an analytic fashion to higher levels. At

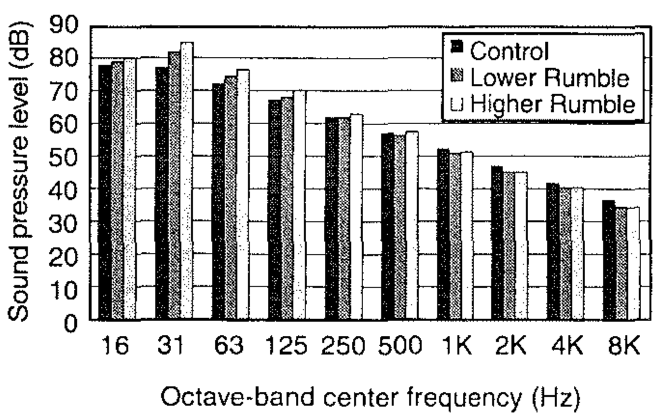

Fig. 4 – Original Bradley spectra for the higher rumble, the lower rumble and the control conditions. No modulation is present for these spectra.

TABLE 2 – Comparison between Bradley attenuator setting and the corresponding differences using RNC calculations.

Bradley Signal			Bradley Attenuator Setting	δ= 5			δ= 6.25		
Rumble	Modulation Frequency	Modulation Depth		Calculated RNC	Difference, Calculated RNC minus Control	Difference RNC Difference minus Bradley	Calculated RNC	Difference, calculated RNC minus Control	Difference RNC Difference minus Bradley
—	(Hz)	—	(dB)	(dB)	(dB)	(dB)	(dB)	(dB)	(dB)
	Control Signal		0.0	51.5	0.0	0.0	51.5	0.0	0.0
High	0	—	3.4	56.6	5.1	1.7	56.2	4.7	1.3
	0.25	Low	4.7	57.9	6.4	1.6	57.2	5.7	1.0
		high	6.5	59.6	8.1	1.5	58.5	7.0	0.4
	0.5	Low	6.0	57.4	5.9	-0.1	56.8	5.3	-0.7
		high	7.6	59.0	7.5	-0.2	58.0	6.5	-1.1
	1	Low	5.6	57.5	6.0	0.4	57.0	5.5	-0.2
		high	7.2	59.7	8.2	1.0	58.7	7.2	-0.1
	2	Low	6.0	57.7	6.2	0.1	57.2	5.7	-0.4
		high	7.9	59.2	7.7	-0.3	58.4	6.9	-1.0
	4	Low	5.2	58.4	6.9	1.7	57.8	6.3	1.0
		high	6.9	58.7	7.2	0.3	58.2	6.7	-0.2
Low	0	—	5.9	59.6	8.1	2.1	59.2	7.7	1.7
	0.25	Low	7.5	61.8	10.3	2.7	60.5	9.0	1.5
		high	9.7	65.5	14.0	4.3	63.4	11.9	2.2
	0.5	Low	8.6	61.2	9.7	1.1	60.4	8.9	0.3
		high	11.4	64.9	13.4	2.0	62.9	11.4	0.0
	1	Low	9.4	62.0	10.5	1.0	60.8	9.3	-0.2
		high	11.6	65.2	13.7	2.1	63.3	11.8	0.2
	2	Low	8.2	61.6	10.1	1.9	60.7	9.2	1.0
		high	12.9	64.5	13.0	0.1	62.8	11.3	-1.6
	4	Low	8.9	61.4	9.9	1.0	60.5	9.0	0.1
		high	11.1	63.2	11.7	0.6	62.1	10.6	-0.5
	Mean (dB) (excluding control signal)					1.2			0.2
	Standard Deviation (dB) (excluding control signal)					1.1			1.0
	Correlation Coefficient					0.92			0.92

and above the 250 Hz octave band, the curves are 5 dB apart. In the 31 Hz octave band, the curves increase by 2.5 dB in sound pressure level for each 5 unit increase in RNC. Obviously, this extension leads to curves such that the slope at low frequencies (below the 250 Hz octave band) is less than the slope above the 250 Hz octave band. Several relations and procedures suggest that this extension is not logical. First, the loudness functions (Fig. 3) never exhibit this type of slope relationship. Also, the loudness function and the Beranek curves (Fig. 1) increase in their spacing with increasing sound pressure level. The Blazier curves (Fig. 2) maintain a constant spacing, but this is a constant 5 dB at all frequencies.

Figure 5(b) shows the RNC curves extended to higher levels by adding curves that are everywhere parallel to the RNC 50 curve. This is, perhaps, the more logical extension since, firstly, it follows the Blazier lead of 5 dB parallel spacing. Second, like the equal-loudness-level contours and like the NCB curves, it increases the spacing at low frequencies and higher sound pressure levels. Third, it does not exhibit the strange reverse in slope that is evident in Fig. 5(a) but not present in equal-loudness-level contours. For these reasons, this paper extends the RNC curves to RNC 65 as shown in Fig. 5(b).

The functions represented by the curves in Fig. 5(b) are easily represented analytically for use in a spreadsheet and these functions are given in the Appendix. These are the functions that have been used to evaluate the Bradley data. In this analysis, it is assumed that rattles were not an issue because the subjects listened to the sounds through headphones, although normally, levels this high at low frequencies would have a high probability of creating rattles in building elements.

C. Results

Table 2 lists the calculated RNC levels minus the reference signal RNC for the 22 Bradley test signals that were available as digital records in the form of 0.128 s time series. As stated earlier, this table also contains the attenuator settings found for these test signals. In accordance with the RNC methodology, energies in the 16, 31, and 63 Hz octave bands were combined together after weighting each for the loudness characteristic of the ear. To do this, 14 dB were subtracted from the 16 Hz octave band levels and 14 dB were added to the 63 Hz octave band levels. There were no changes to the 31 Hz octave band levels.

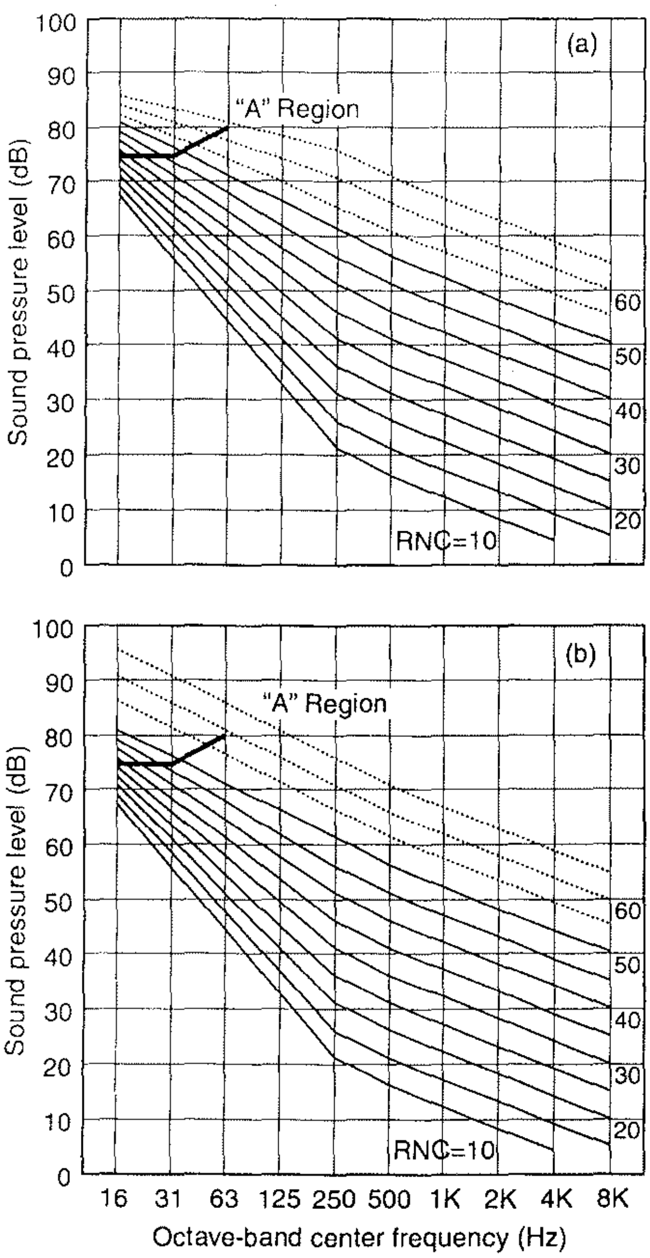

Fig. 5 – (a) The dashed lines show the extended RNC curves using analytic functions and the solid lines show the original RNC curves. (b) The dashed lines show the extended RNC curves using constant 5-dB differences and the solid lines show the original RNC curves.

3. DISCUSSION

Examination of the data in Table 2 shows that there is good correlation between the attenuator setting and the calculated RNC differences. This correlation coefficient is 0.92. More importantly, the standard deviation to the differences is only 1.1 dB. However, there is a systematic difference of 1.2 dB. If the RNC provided a perfect fit to the Bradley data, the correlation coefficient would be 1, the standard deviation would be 0 dB, and the systematic difference would be 0 dB. Part of the systematic difference may be due to a correction that should have been applied to the control signal. But we are unable to calculate any correction to the control signal because we no longer possess its time waveform. Any turbulence to the control signal will increase its RNC value and, thus, decrease this systematic offset of 1.2 dB.

Some of the standard deviation of 1.1 dB and the offset of 12 dB may result from subject bias and subject variation given that there were only 9 subjects. Most importantly, some of this variation may be due to the assumptions inherent in the RNC procedure. First, it was assumed that d equal to 5 dB was applicable to the 31 Hz band since, at low sound levels, the equal-loudness-level contours (Fig. 3) are spaced 5 dB apart for a change of 10 phon. In this experiment the 31 Hz octave band levels are between 80 and 90 dB. At these higher sound levels, the equal-loudness-level contours are spaced more like 6 dB apart for a change of 10 phon. Therefore, all the data have been reanalyzed with various values for d in the 31 Hz band. Repeated calculations in 0.25 increments have shown that δ equal to 6.25 yields the best fit to the Bradley data. These results are listed in column 6 of Table 2. With this value of δ, the standard deviation to the differences drops to 0.98 dB, the correlation coefficient remains at 0.92, and the offset drops to just 0.2 dB. As noted above, this trivial 0.2-dB offset is partly due to any minor turbulence to the control signal that has not been accounted for. Also, the subjects could only replicate their responses to 0.2 dB.

Figure 6(a) shows the Bradley attenuator settings as a function of rumble and modulation, and Fig. 6(b) shows the differences in RNC between the test signals and the control signal for these same conditions. The general similarities between these two figures can be seen. One difference is at low modulation frequencies where the RNC predicts higher differences than were measured by Bradley. No explanation can be offered for this difference. However, one important similarity is at the 4 Hz modulation frequency. The PNC predicted differences are more or less constant from 0.15 to 2 Hz and then reduce at 4 Hz. The Bradley subjective response differences peak at 2 Hz and then reduce at 4 Hz. This downward trend at 4 Hz is consistent with the use of 125 ms as the integration time, the assumed time constant of the ear. If we had assumed that the time constant was shorter than 125 ms, say 65 ms, then the PNC-predicted differences would not reduce at 4 Hz. If we had assumed a larger value for the time constant of the ear, say 250 ms, then the PNC predicted differences would start to reduce at 2 Hz and there would be a much larger reduction at 4 Hz than is shown in Figure 6(b). In either of these cases, the PNC predicted differences would correspond less well with the differences measured by Bradley. But the RNC calculated difference seems to fit the Bradley data well at 4 Hz. This implies that the selected time constant of 125 ms (fast time weighting) is about optimum.

4. CONCLUSIONS AND RECOMMENDATIONS

Based on the Bradley data, the RNC procedure is working well. The efficacy of Eq. 1 for integrating the low frequency data is clearly demonstrated. Basing the value of δ in Eq. 1 on the equal-loudness-level contours also clearly is

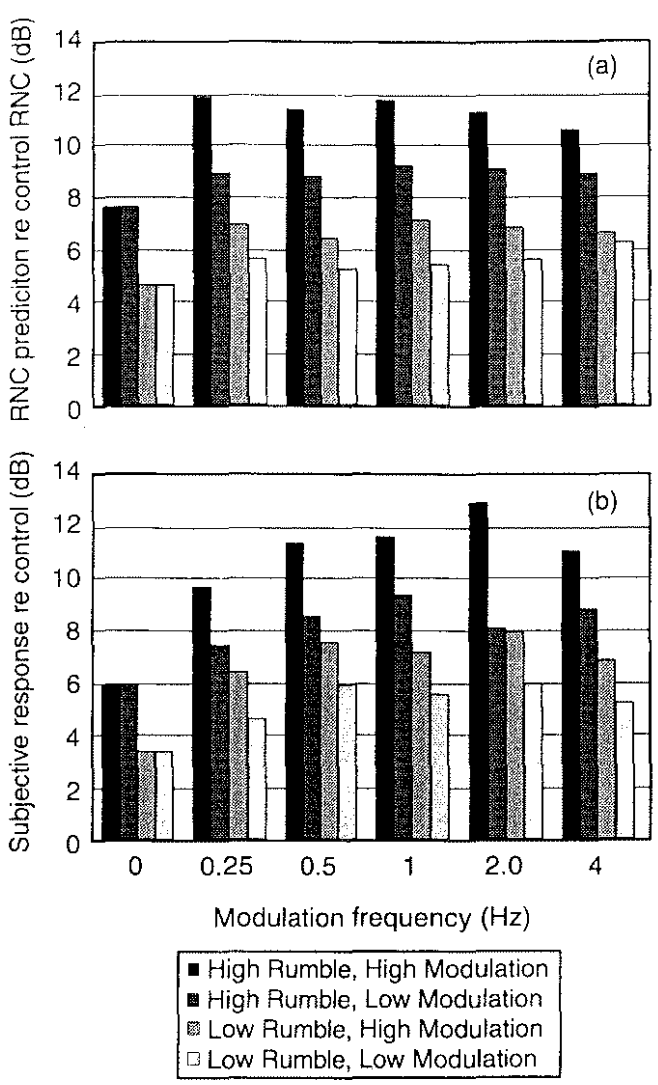

Fig. 6 – (a) RNC values re the control of 51.5 dB. (b) "Attenuator " offsets found by Bradley.

demonstrated. Finally, the use of a 125 ms time constant to approximate the time constant of the ear has been demonstrated to be a successful approximation to the time constant of the hearing system. These three are the main features that are inherent in the RNC calculation, and all have been validated by the Bradley data.

Use of the RNC procedure as described in Schomer[5] with the curves as given in the Appendix to this paper is recommended.

Although, at high levels, δ equal to about 6 provides for slightly better results, a δ equal to 5 in the 31 Hz band and a δ equal to 8 in the 125 Hz band is recommended at all sound levels. The added complexity of changing δ with sound level is not worth the increased accuracy by about 1 dB at high sound levels. Simply put, when the sound level is over 80 dB in the 31-Hz octave band, one can afford to over-predict the RNC by 1 unit.

TABLE A1 – Coefficients to the equations for calculating RNC.

Octave Band (Hz)	Sound Level Range (dB)	K1	K2
16	£ 81	64.3333	3
	> 81	31	1
31	£ 76	51	2
	> 76	26	1
63	£ 71	37.6667	1.5
	> 71	21	1
125	£ 66	24.3333	1.2
	> 66	16	1
250	ALL	11	1
500	ALL	6	1
1000	ALL	2	1
2000	ALL	-2	1
4000	ALL	-6	1
8000	ALL	-10	1

5. APPENDIX:

Equations for calculating RNC

The RNC in the *i*th octave band between 16 Hz and 8000 Hz is calculated by equations of the form:

$$RNC_i = (L_i - K1_i) * K2_i$$

Where L_i is level in the *i*th octave band. In bands at and above 250 Hz, L_i is just the octave-band equivalent sound pressure level. In bands below 250 Hz, the general RNC procedures are used. If the sound is rumbly or modulated, then Equation 1 is used to calculate levels in for use with the 31-Hz and 125-Hz equations. Table A1 gives the coefficients for use in calculating the RNC in any octave bands. For octave bands below 250 Hz, the equations are different for RNC values above and below RNC 50. The RNC procedure is a tangent method, so the reported RNC is the maximum of the RNCs calculated for the various octave bands

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