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NRCC-38806

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November 1994

A version of this document is published in / Une version de ce document se trouve dans:
Noise Control Engineering Journal, 42, (6), pp. 203-208, November, 1994

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Annoyance caused by constant-amplitude and amplitude-modulated sounds containing rumble

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(Received 1994 July 05; revised 1994 October 05)

This paper reports the results of 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. 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 results indicated that annoyance is influenced by both the level and the amplitude modulation of the simulated HVAC rumble sounds. A procedure that incorporates these two factors is suggested for predicting the additional annoyance of HVAC sounds containing rumble. © *1994 Institute of Noise Control Engineering.*

Primary subject classification: 69.1, Secondary subject classification: 51.6

1. INTRODUCTION

Modern heating, ventilating, and air conditioning (HVAC) systems frequently produce noise with prominent low-frequency components. Such sounds are said to contain rumble. In many cases the level of this low-frequency sound may fluctuate over time. It is often suggested that such strong low-frequency sounds and the amplitude modulation of these sounds may cause greater annoyance than sounds with more neutral spectra. However, current noise rating schemes do not permit quantitative evaluation of the additional disturbance caused by these low-frequency rumble components.

This paper reports an initial investigation of methods to rate the annoying aspects of noise spectra with relatively high levels of both un-modulated and amplitude-modulated low-frequency sounds. Newer methods of rating indoor noise do include consideration of low-frequency sound pressure levels and the spectral balance of sounds. However, they do not lead to a single number rating that combines the effects of both level and spectrum shape on annoyance responses. In addition, they ignore the possible annoying effects of amplitude variations with time. The older, but still widely used, Noise Criterion (NC) rating system only considers sound pressure levels in the octave bands from 63 to 8000 Hz.

In 1981, Blazier[1] proposed the Room Criterion (RC) noise rating system specifically for rating the noise produced by HVAC systems. It was subsequently adopted by the American Society for Heating Refrigerating and Air Conditioning Engineers (ASHRAE)[2] for rating indoor noises from HVAC systems. Blazier found that the spectra of a large number of "acceptable" noises decreased uniformly at 5 dB per octave. He therefore created a set of rating contours with slopes of −5 dB/octave that extended from the 16-Hz to 4000-Hz octave bands. (Octave bands are referred to by the nominal center frequency of each octave band.) To evaluate noise spectra, the arithmetic average of the sound pressure levels in the three middle octaves (500, 1000, and 2000 Hz) is calculated; this average sound pressure level is the RC rating number of the noise. A letter rating of the subjective quality of the spectrum of the noise is then added. A spectrum that is close to the shape of the −5 dB/octave RC contours is termed "neutral" and is assigned an "N" rating. A spectrum with excessive low-frequency levels is assigned an "R" to indicate a spectrum containing rumble. For example, one spectrum might be assessed as RC-45 R and another RC-48 N. However, the RC system does not include a method for determining which of these two examples might be more disturbing.

More recently Beranek[3,4] developed the Balanced Noise Criterion or NCB system. The NCB procedure includes another family of rating contours that are not parallel and are closer together at low frequencies than at higher frequencies, roughly similar to the older NC and Preferred Noise Criterion (PNC) rating contours. However, the newer NCB contours extend from the 16- to the 8000-Hz octaves. Using the NCB rating contours is somewhat similar to the two-step process of using the RC system. First, a speech interference level is determined from the sound pressure levels in the 4 octaves from 500 to 4000 Hz. This speech interference level is the initial NCB value of the noise spectrum. Further calculations are then made to identify spectrum imbalance. Noise spectra with excessive levels of low-frequency sound are labeled as including "rumble." However, there is again no procedure to quantify the possible negative effects of spectral imbalance.

While the RC and NCB methods represent improvements over the older NC and PNC systems, they do not produce complete quantitative ratings of the potential annoyance of various indoor noises. The relative importance of mid-frequency sound pressure levels is ranked quantitatively, but spectrum imbalance is only qualitatively ranked. In both the NCB and the RC systems, there is no procedure for trading-off the negative effects of noise levels versus the effects related to spectrum shape. Such a more complete system is not necessary for specifying de-

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lated for the octave bands from 16 to 8000 Hz. From the same 559 sound pressure levels, L_{10} and L_{90} values were calculated as the octave-band sound pressure levels exceeded 10% and 90% of the time, respectively.

3. UN-MODULATED SOUNDS CONTAINING RUMBLE

In the first experiment, four test spectra were presented in comparison with a neutral reference spectrum. These test spectra and the reference spectra are shown in Fig. 2. The spectra are similar to typical real HVAC spectra found in a recent survey.[9] The reference spectrum decreased approximately 5 dB/octave from the 31.5-Hz octave band, and had a mid-frequency (1000-Hz) average sound pressure level of 51 dB. The test sounds with added rumble had spectra that peaked in the 31.5-Hz octave band. The comparisons also included a comparison of the neutral spectrum with itself.

Each setting of attenuator "B" was averaged over all 9 subjects and this average setting was converted to a sound pressure level change in decibels. When the subjects compared the reference spectrum with itself, the average result was a shift of −0.1 dB. Thus, subjects were able to very accurately adjust signals with the same spectrum to have the same level (i.e., with a mean error of only −0.1 dB).

The average attenuations of the four test signals were 1.5, 1.9, 3.4, and 5.9 dB. That is, for spectra with increasing low-frequency content, subjects reduced the overall level by these amounts to match the annoyance of the reference spectrum. The four test spectra and the reference spectrum are plotted in Fig. 3 with the levels of the test spectra adjusted according to the mean attenuator settings of the 9 subjects. These results showed that subjects tended to adjust the level of the test sounds until the octave band with the highest sound pressure level (31.5 Hz) just exceeded the reference spectrum and by no more than about 2 to 3 dB.

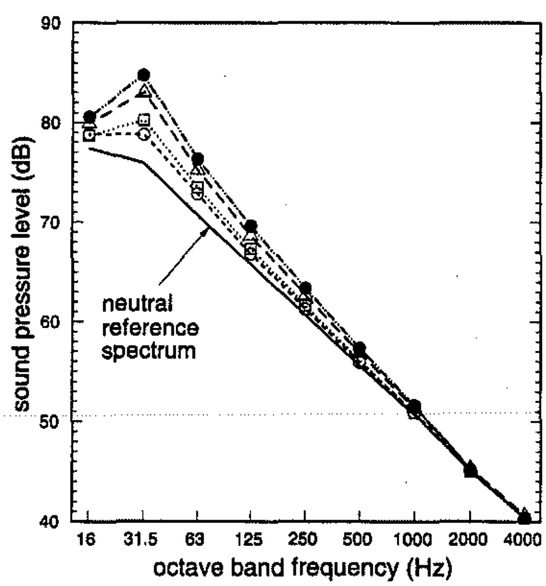

Fig. 2 – Original spectra of un-modulated test sounds.

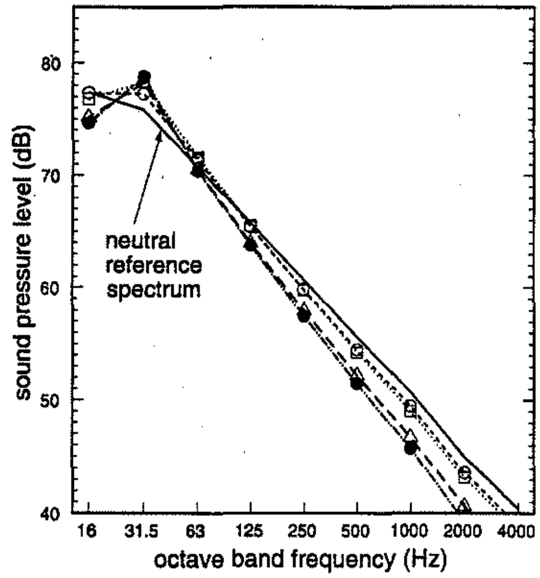

Fig. 3 – Attenuated spectra of un-modulated test sounds.

The results cannot be related to either RC or NCB ratings of these sounds because the RC and NCB ratings do not vary significantly for these spectra. Two of the test sounds were rated as RC-51 R and two as RC-51 N. The balanced-noise-criterion ratings for four spectra were NCB-48 or NCB-49. According to the NCB system, all of the spectra, including the neutral reference spectrum, would be rated as containing rumble.

The mean attenuator settings for the test sounds were also correlated with the A-, B-, C-, D-, and FLAT-weighted sound levels of the spectra. The attenuator settings were most highly correlated with the FLAT and C-weighted measures ($r=0.98$, $p<0.001$) and least highly with the A-weighted levels ($r=0.97$, $p<0.01$). (Here "r" is the correlation coefficient and "p" is the probability of this correlation occurring by chance). Plots of attenuator settings versus the frequency-weighted sound pressure levels indicated that the relationships were probably not linear and that other factors might influence the relationships.

4. AMPLITUDE-MODULATED SOUNDS CONTAINING RUMBLE

The second experiment included test sounds where the low-frequency content was amplitude modulated. The two spectra with the highest levels at 31.5 Hz in Fig. 2 were used. For each of these two base spectra, amplitude-modulated sounds were created using two different modulation depths and five different modulation frequencies. The modulation frequencies used were 0.25, 0.5, 1.0, 2.0, and 4.0 Hz. The modulation depths were 10 and 17 dB when a 1000 Hz test signal was amplitude-modulated and are referred to as "low" and "high," respectively. Because only the extra low-frequency components were amplitude-modulated, the modulation depths of the total test signals were considerably less. The un-modulated spectra were

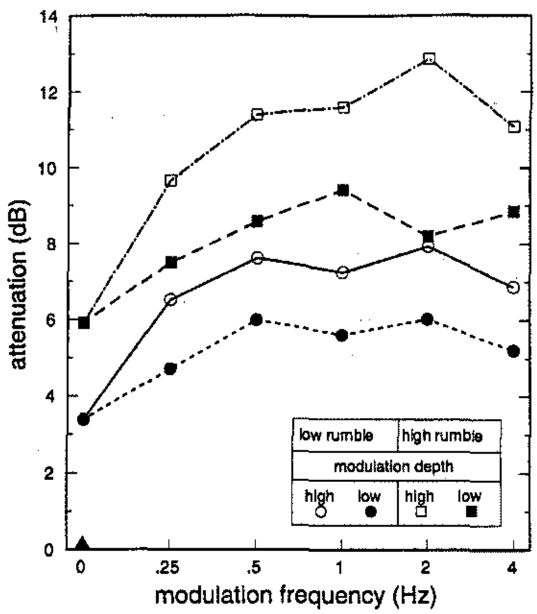

Fig. 4 – Mean attenuator settings versus modulation frequency for two different base spectra (low rumble, high rumble) and two different modulation depths (low, high). Smooth dotted lines show mean trends.

also included as a 0-Hz modulation frequency case. A total of 22 different sounds were included. These test signals were the combinations of: two base spectra, times two modulation depths, times five modulation frequencies, plus the two un-modulated spectra.

Subjects were again asked to adjust attenuator "B"until the test sound was equally annoying as the reference neutral spectrum. The mean settings of the attenuator for all 9 subjects are plotted versus modulation frequency in Fig. 4. The greater the adjustment of the attenuator, the more annoying the subjects found the particular test sound. The results in Fig. 4 show that subjects found the spectra with higher levels of low-frequency sound more annoying, found greater modulation depth more annoying, and the results varied somewhat with modulation frequency.

An analysis-of-variance test of these results showed that there were significant ($p<0.001$) main effects of modulation depth, modulation frequency, and base spectrum. There were no significant interaction effects. Thus, the results of Fig. 4 illustrate significant systematic effects of modulation depth, modulation frequency, and base spectrum on judged annoyance.

TABLE 1 – Minimum, maximum, and range of 1-min-average sound pressure levels of the test sounds.

Frequency-weighted sound pressure level (dB) A	B	C	D	FLAT	
57.6	66.6	76.0	66.4	80.3	Minimum
61.3	74.2	85.8	73.9	89.0	Maximum
3.7	7.6	9.8	7.5	8.7	Range

TABLE 2 – Minimum, maximum, and range of 1-min-average octave-band sound pressure levels and associated standard deviations of the test sounds.

Octave midband frequency (Hz) 16	31.5	63	125	250	500	1000	
1-min-average octave-band sound pressure level (dB)							
79.4	82.0	74.7	68.3	62.4	56.7	51.3	Minimum
82.3	87.6	78.2	71.2	64.7	58.4	52.4	Maximum
2.9	5.6	3.5	2.9	2.3	1.7	1.1	Range
Standard deviation (dB)							
2.4	2.3	1.8	1.3	0.9	0.7	0.5	Minimum
3.3	4.7	3.3	2.6	2.2	1.6	1.0	Maximum
0.9	2.4	1.5	1.3	1.3	0.9	0.5	Range

The analysis-of-variance results showed that the subjective evaluations were significantly related to the parameters that were systematically varied as part of the experiment. It was also desirable to obtain relationships between the subjective evaluations and standard acoustical measures. These measures included five different frequency-weighted sound pressure levels, i.e., A-, B-, C-, D-, and FLAT-weighted levels. For each octave band, values of percentile sound pressure levels L_{10} and L_{90}, and the standard deviations (σ) of the 1-min-average sound pressure levels were available. In addition, the differences (L_{10}-L_{90}) were calculated as an alternative measure of the variation of levels with time. The range of values of these acoustical measures for the 22 sound spectra are summarized in Tables 1, 2, and 3.

These data indicate that the sound spectra used in these experiments represent a reasonably wide range of realistic conditions. The C-weighted sound levels showed the greatest range. The octave-band equivalent-continuous sound pressure levels (L_{OB}) varied most in the 31.5-Hz octave. The minimum standard deviations were associated with the variation with time of the un-modulated signals.

The mean attenuator settings, that were representative of the relative annoyance of the test sounds, were significantly related to all of the measures listed in Tables 1, 2, and 3. Of the frequency-weighted sound pressure levels in Table 1,

TABLE 3 – Minimum, maximum, and range of L_{10} and L_{90} octave-band percentile sound pressure levels and the differences L_{10}-L_{90} for the test sounds.

Measure	Octave midband frequency (Hz) 16	31.5	63	125	250	500	1000	
	81.1	77.2	73.9	68.7	62.7	56.7	50.9	Minimum
L_{10}	84.2	79.9	76.8	71.7	65.4	59.2	52.7	Maximum
	3.1	2.7	2.9	3.0	2.7	2.5	1.9	Range
	74.1	73.1	69.9	64.8	59.6	54.4	49.3	Minimum
L_{90}	76.6	75.5	72.7	67.1	61.3	55.7	50.0	Maximum
	2.5	2.4	2.8	2.3	1.7	1.3	0.7	Range
	6.4	3.6	3.2	3.3	2.6	1.9	1.6	Minimum
$L_{10}-L_{90}$	8.8	4.8	4.6	5.4	4.9	4.0	2.8	Maximum
	2.4	1.2	1.4	2.1	2.3	2.1	1.2	Range

the relative annoyance was most strongly correlated with FLAT and C-weighted levels ($r=0.93$, $p<0.001$) and least strongly correlated with A-weighted levels ($r=0.90$, $p<0.001$). At lower frequencies, attenuator settings were more strongly related to the octave-band sound pressure levels L_{OB} than the L_{10} percentile sound pressure levels and more strongly related to the standard deviations σ than $(L_{10}-L_{90})$ differences. L_{10} and L_{90} values were each obtained from a single point near the extremes of the cumulative distribution of sound pressure levels. The standard deviations were calculated from the complete distribution and are a more-robust measure of level variations. In spite of the relatively high correlations with these measures, plots of mean attenuator setting versus frequency-weighted sound pressure levels exhibited substantial scatter and suggested nonlinear relationships. Further analyses were carried out to develop compound predictors of responses that included measures of both the mean levels and the temporal variations of levels.

5. COMBINED EFFECTS

In the first experiment with un-modulated sound fields, subjects tended to adjust the level of the test sound so that it just exceeded the level of the reference sound in the 31.5-Hz octave band containing the highest sound pressure levels. For the amplitude-modulated sounds, subjects tended to further attenuate the test sounds and this further attenuation could be related to the amplitude modulation of the test sounds as measured by the standard deviation of the sound levels. Figure 5 illustrates the example of the average attenuation of the test spectrum for the case of the High rumble spectrum, with a 2.0-Hz modulation frequency, and the larger modulation depth. The spectra of the reference

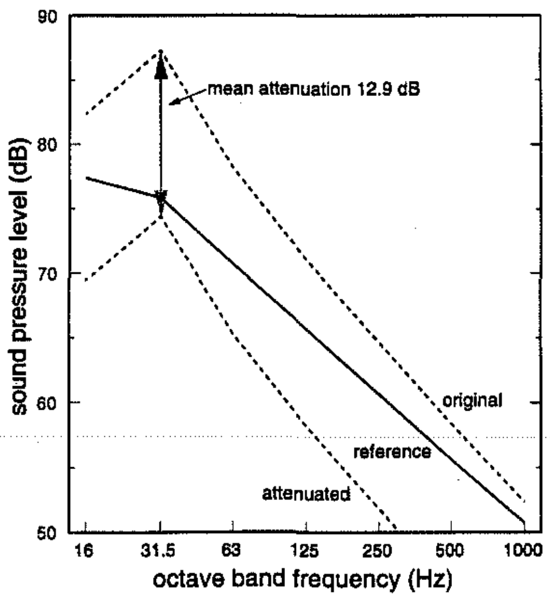

Fig. 5 – Example comparing mean attenuated spectrum with the initial spectrum and the neutral reference spectrum.

sound, the original test sound, and the attenuated test sound are compared in this figure. On average, subjects attenuated the test sound by 12.9 dB to make the annoyance equal to the annoyance of the reference sound. This example shows that rather than attenuate the test sound until it exceeded the reference spectrum at 31.5 Hz by 2 or 3 dB, it was adjusted to be 1.5 dB less than the reference sound at 31.5 Hz. Thus, there was an extra attenuation of about 4 dB in this case compared with the pattern for the unmodulated sounds. This difference can be related to the standard deviation of the test sound.

Various multiple regression analyses suggested that a number of combinations of mean sound pressure level and level variation could be used to predict the mean attenuator settings. Although statistically significant, some of these relationships were quite arbitrary in nature and were probably influenced by the particular characteristics of the test spectra used in this experiment. The most satisfactory approach for predicting the expected annoyance was obtained from an understanding of plots similar to that of Fig. 5.

The mean attenuator settings, in decibels, were predicted quite well by assuming they were related to the combination of a level matching term and a standard deviation term of the following form,

$$\text{Attenuation}=\langle \Delta L_{OB}\rangle+(K)(W)(\langle \Delta\sigma\rangle), \quad (1)$$

where $\langle \Delta L_{OB}\rangle$ is the mean difference in 1-min-average octave-band equivalent-continuous sound pressure levels between the test spectrum and the reference spectrum averaged over the four octaves from 31.5 to 250 Hz.

Similarly $\langle \Delta\sigma\rangle$ is the mean difference between the standard deviations of the sound pressure levels of the test sound and the un-modulated references sound averaged over the octaves from 31.5 to 250 Hz. K is a constant and W is a modulation-frequency-dependent weighting function.

The results of Fig. 4 suggest that the attenuator settings were approximately constant for modulation frequencies from 0.5 to 4 Hz. Subjects consistently attenuated the test sounds less for the 0.25 Hz modulation frequency cases and hence found them less annoying. A weighting function W that was 0.4 for the 0.25 Hz cases and 1.0 for all other modulation frequencies was found to successfully account for this small variation with modulation frequency.

A range of values for the constant K could give reasonable fits with the measured attenuator settings. A value of K equal to 2.5 minimized the overall scatter about the mean trend. However, a value of K equal to 4.5 seemed to better fit the majority of the data points. The agreement of the data with this relationship is illustrated in Fig. 6, which plots predicted versus measured attenuations. If the two points at the top of the graph are excluded, almost all of the measured attenuations would be within ±1 dB of the predicted values and the standard deviation of the differences between measured and predicted attenuations would be only 0.5 dB.

The results of Fig. 6 confirmed the success of the relationship of Eq. (1) above and suggested that quite simple procedures can be developed to predict the additional annoyance of sounds with strong low-frequency content and

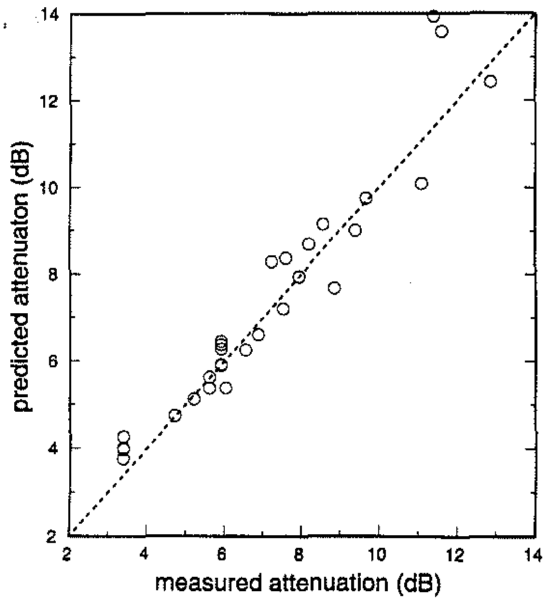

Fig. 6 – Comparison of mean measured attenuations and attenuations predicted using Eq. (1).

that may include amplitude modulation of the low-frequency components.

6. CONCLUSIONS

The results of these initial experiments suggest that the room criterion (RC) rating system could be extended to quantitatively evaluate the negative effects of sounds containing various amounts of rumble. This paper suggests a scheme to predict the extra annoyance due to rumble components that includes a level matching term and a second term relating to the amplitude variation of the sounds.

The results presented in this paper were based on an initial study with a limited range of test sounds. More comprehensive studies are now required to further explore and develop these results into improved noise rating procedures. Such experiments should include loudspeaker presentation of sounds, a greater variety of spectra, as well as consideration of the additional problems of evaluating the effects of stronger high frequency content (hiss) and pure tones. Finally, new noise rating procedures should be evaluated in actual office environments.

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