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and Space Administration

Scientific and Technical
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Summary

A laboratory study was conducted to investigate the effects on subjective annoyance of simulated advanced turboprop (ATP) interior noise environments containing tonal beats. The simulated environments consisted of low-frequency tones superimposed upon a turbulent-boundary-layer noise spectrum. The variables used in the study included propeller tone frequency (100 to 250 Hz), propeller tone levels (84 to 105 dB), and tonal beat frequency (0 to 1.0 Hz). The study was conducted in a small anechoic chamber located at NASA Langley Research Center. Results indicated that propeller tones within the simulated ATP environment resulted in increased annoyance response that was fully predictable in terms of the increase in overall sound pressure level due to the tones. Neither the "tonal quality" of the noise nor the rhythmic pulsations characteristic of tonal beats were found to be an annoyance factor. The propeller tone frequency of 100 Hz was found to be significantly less annoying than the higher propeller tone frequencies (160, 200, and 250 Hz) for all test conditions. Implications for ATP aircraft include the following: (1) the interior noise environment with a propeller tone is more annoying than an environment without a tone if the tone is present at a level sufficient to increase the overall sound pressure level; (2) the increased annoyance due to the fundamental propeller tone without harmonics is predictable from the overall sound pressure level; and (3) no additional noise penalty due to the perception of single discrete-frequency tones and/or beats was observed.

Introduction

Interior noise is one of the primary factors influencing passenger acceptance of the ride environment within commercial and general aviation aircraft. It may be particularly important in the advanced turboprop (ATP) aircraft currently under development as fuel-efficient alternatives to turbofan aircraft. ATP interior noise may be higher in level and have significantly different spectral characteristics because of the presence within the cabin of high-level tones produced by the advanced design propellers. This tonal character of the interior noise and its associated higher harmonics are of special concern from the standpoint of passenger annoyance and interior noise control.

Several studies (refs. 1 to 5) have been conducted into the effects of various combinations of pure tones and broadband noise on annoyance, loudness, and noisiness. The results of these studies indicated that for equal sound pressure levels, pure tones combined with bands of noise were generally judged to be noisier than bands of noise alone. Most of these findings, however, relate to pure tone frequencies considerably higher than those expected within the ATP environment. Consequently, the applicability of the results of references 1 to 5 to the low-frequency content of ATP interior noise is uncertain.

A recent laboratory study (ref. 6) specifically addressed passenger annoyance response to simulated ATP interior noise environments. In that study annoyance penalties (called tone penalties) due to low-frequency tones were determined for a wide range of tone frequencies and tone levels superimposed on estimated turbulent-boundary-layer interior noise spectra. Tone penalty for a given metric was defined as the difference between the value of the metric without tones and the value of the metric with tones that produces the same annoyance. Defined in this manner, tone penalty reflects the inability of a noise metric to account for annoyance effects due to the presence of tones. Results presented in reference 6 showed that tone penalty was highly dependent on the choice of noise metric, and no single noise metric could be identified as best for estimating passenger annoyance. Of particular interest was the finding that tone corrections employed in the tone-corrected perceived noise level computation procedure were ineffective for the range of tone frequencies (80–315 Hz) studied.

Another factor that may influence subjective passenger reaction to ATP interior noise is the possible existence of tonal beats resulting from nonsynchronous propeller rotational speeds of multiengine aircraft. This factor was not considered in the references cited above and does not appear to have been systematically investigated in the literature. Such beating phenomena would consist of low-frequency modulation of the discrete tones corresponding to the fundamental blade passage frequency and associated harmonics. The modulation, or beat, frequency would have a value equal to the difference in blade passage frequency between two propellers (see ref. 7, p. 13, for definition of beats). The effect of such beats on passenger annoyance is unknown. A primary purpose of this study is to extend the research program described in reference 6 to include the effects of tonal beats. A second purpose is to provide additional data for use in selecting an appropriate noise metric for the assessment and prediction of passenger annoyance response to ATP interior noise. Specific goals of this research investigation were to quantify passenger annoyance response to parametric variations of tone frequency (without harmonics), propeller tone level, and beat frequency and to quantify annoyance penalties, if any, due to the beats.

Experimental Method

Test Facility

This research was conducted in a small anechoic listening room located at the Langley Aircraft Noise Reduction Laboratory. This room has dimensions of 4 by 2.5 by 2.5 m, accommodates two test subjects at a time, and is equipped with a sound reproduction system having a frequency response of 5 Hz to 20 kHz. Additional information on the Langley anechoic testing facility can be found in reference 8. A photograph of the room showing two seated test subjects and the sound system speakers is presented in figure 1.

Noise Stimuli

The noise stimuli used in this investigation consisted of either one or two tones superimposed on simulated boundary-layer noise. The boundary-layer noise spectrum shape approximated that measured in the interior of aircraft with heavy applications of noise control materials. It was generated by spectral filtering of the output of a pink noise generator. The resulting boundary-layer noise spectrum shape is given in figure 2. Pure tones having frequencies of 100, 160, 200, and 250 Hz were chosen to encompass the range of blade passage frequencies of both conventional propeller and advanced turboprop aircraft. Each pure tone was presented at three levels. For the condition representing the absence of beats, a single pure tone was added to the boundary-layer noise. To simulate the presence of beats, a second pure tone having a frequency slightly higher than the first tone was added. This resulted in audible, rhythmic pulsing of the loudness of the sound at a rate corresponding to the difference in frequency of the two pure tones. Both the temporal and spectral character of the sounds with beats are illustrated in figure 3. The differences in frequency, defined as the beat frequencies, were selected to be 0, 0.05, 0.10, 0.25, 0.50, and 1.00 Hz. Of course, a beat frequency of 0 represents the single tone condition.

The various tone and beat frequency combinations were generated by use of a computerized aircraft-noise synthesis system (see ref. 9) developed at Langley Research Center. The synthesizer produced analog magnetic tape recordings of the tones which were then used in combination with a tape containing the boundary-layer noise to generate a final program tape containing the combined stimuli. The program tape was applied as input to the power amplifier and speaker system of the anechoic room.

Experimental Design

The experimental design for this study is presented in table 1. The design is a $3 \times 4 \times 6$ factorial design with repeated measures on each factor. The factors (variables) used in this study consisted of three values of tone level, four values of tone frequency, and six values of beat frequency. The dependent variable was the subjective annoyance experienced by test subjects when exposed to the various factorial combinations of the above variables. This design resulted in a set of 72 test stimuli. Four additional test stimuli composed of boundary-layer noise only were used in order to provide a basis for determining tone penalties. These four boundary-layer noise stimuli had overall sound pressure levels (OASPL) of 84, 91, 95, and 99 dB. The equivalent A-weighted sound pressure levels (L_A) were 76, 83, 87, and 91 dB, respectively. For all test stimuli containing tones, the boundary-layer OASPL was set at 91 dB ($L_A = 83$ dB). The actual values of overall sound pressure level and A-weighted sound pressure level, measured by a microphone located at the approximate head level between the two seated subjects, are given in tables II and III for each of the conditions of the experimental design. Unweighted tone levels are given in table IV. These values represent the peak levels obtained using a "peak hold" analysis device. Sampling time was 0.5 second with 2-second exponential averaging. Each noise condition was continuously measured for 1 minute corresponding to the duration of each stimulus. The 1-minute duration allowed sufficient time for the stimuli containing the slowest beat frequencies to be adequately assessed by the test subjects. For example, a beat frequency of 0.05 Hz has a period of 20 seconds and therefore would repeat three times during the 1-minute duration of the stimuli. Approximately 15 seconds were allowed between test stimuli for the subjects to mark their evaluations. The sequence of presentation of the test stimuli was randomized. Order effects were accounted for by applying the stimuli to one-half of the test subjects in forward order, and to the remainder of the test subjects in reverse order. The subjects were tested in groups of two with the morning group receiving the stimuli in forward order and the afternoon group in reverse order. Possible bias due to time of day was not controlled, but, based on prior experiments, such effects would likely be minimal.

Subjects

The study used 48 subjects who were randomly selected from a pool of local residents. These subjects had a wide range of socioeconomic backgrounds and were paid for their participation in this study. All the test subjects were given audiograms prior to the experiment to verify normal hearing within 20 dB (ANSI, ref. 10). The subject group consisted of 20 males and 28 females who had a mean age of 40 years and median age of 35 years. The ages ranged from 20 to 60 years.

Procedure

Upon arrival at the laboratory, the subject groups were seated in the anechoic room and given a set of instruction sheets, a consent form, and a set of scoring sheets. Copies of these items are given in appendixes A, B, and C. After reading the instruction sheets the subjects completed the consent form which is required of all subjects participating in subjective response experiments within the laboratory. The subjects were then given a brief verbal explanation of the scoring sheets and asked by the test conductor whether they had any questions. Throughout the experiment the same person served as the test conductor.

Upon completing the instruction procedure, the test conductor left the anechoic room and the first of the 10 test sessions began. After completion of five sessions (approximately 45 minutes), the test conductor reentered the anechoic room, collected the scoring sheets, and allowed the test subjects to leave for a 15-minute break. After the break the test conductor issued the scoring sheets for the second half of the test which was then commenced.

The subjects made their subjective annoyance assessments using a 0 to 8 numerical category scale with the end points of the scale labeled "not annoying" and "extremely annoying." A sample scoring sheet is presented in appendix C.

Analysis

The presence (or absence) of statistically significant main effects and interactions of the independent variables with the ratings of annoyance was tested by computing a three-factor analysis of variance for the repeated measures design. It should be noted, however, that the use of a repeated measures design, although appropriate from the standpoint of efficiency and achievement of the primary goals of this paper, does result in more sensitive analysis in terms of finding statistical significance. The indication of statistical significance does not necessarily imply "practical" significance from an engineering standpoint. When appropriate in the discussion of results the practical significance of the findings is addressed.

Results and Discussion

The raw data collected in this study consisted of 3648 individual annoyance scores corresponding to evaluations of each of the 76 stimuli by 48 subjects. Thus each cell of the factorial design (table I) contained 48 annoyance scores, one for each subject. The mean annoyance responses and standard deviations of annoyance response for each cell of the design are given in table V. The results of the analysis of variance are presented in table VI. As indicated in table VI, all the main effects and interactions of the independent variables (tone frequency, tone level, and beat frequency) were statistically significant (probability < 0.05). The following sections discuss the more important of these effects in more detail.

Effect of Tone Level

The mean annoyance responses for the 72 cells of the experimental design that contain both tones and boundary-layer noise are presented in figure 4(a) as a function of the overall sound pressure level (OASPL). Since the boundary-layer noise level was held constant for all conditions containing propeller tones, any changes in OASPL were directly attributable to the varying tone levels. Thus these data reflect the highly significant tone level effect obtained from the analysis of variance. The solid line represents the best-fit linear regression line for these data. For comparison, the same data plotted as a function of A-weighted sound pressure level (L_A), tone-corrected perceived noise level (PNLT), and a specialized interior noise metric (L_I) are presented in figures 4(b) to 4(d). The metric L_I was developed during unpublished in-house research at NASA Langley Research Center and was found to be useful in quantifying annoyance response to certain other interior noise environments. The weighting for L_I falls between the conventional A and D weighting curves and is shown in figure 5. Correlation coefficients calculated between annoyance response and noise level for each metric are given in table VII. Examination of table VII indicates that all metrics except L_A correlated highly with annoyance response, but OASPL had the smallest standard error of estimate. The lowest correlation occurred for the metric L_A. Therefore, OASPL was the best and most accurate predictor of annoyance of the metrics. This was probably because OASPL, and hence the annoyance response, was dominated by the low-frequency tones whose effects could not be adequately accounted for by the other noise metrics. The data of table VII indicate that PNL and PNLT performed better than A-weighted sound pressure level but that the conventional tone correction procedure (PNLT) did not improve annoyance predictability. This finding is consistent with that of the earlier studies (ref. 6). Because of these results, the annoyance responses in the remainder of this paper are presented as a function of OASPL.

Effects of Tonal Beats

To determine whether conditions containing beats were more (or less) annoying than the conditions without beats, the data for both the no-beat and the beat conditions were fit with least-squares straight lines. The variables were mean annoyance response and OASPL. The resulting regression lines are presented in figure 6, in which the solid line represents the no-beat conditions and the dashed line the beat conditions. For clarity the actual data are not shown. A test of the equality of the two regression lines using a general linear test approach (see ref. 11) indicated that the two lines did not differ. Thus, in an overall sense, tonal beating did not introduce additional annoyance within the noise environments used in this study.

Interaction Between Beat Frequency and Tone Frequency

The significant interaction between beat frequency and tone frequency (see table VI) implies that beats differentially affected annoyance responses for various combinations of tone frequency and beat frequency. This effect, for the high tone level of the experimental design, is illustrated in figure 7. However, since tone level was not held constant across the conditions represented in figure 7, specific differential annoyance effects directly attributable to beat frequency cannot be readily obtained from this figure. To determine such effects, a differential annoyance parameter was derived from the test results.

Differential annoyance is defined as the difference between annoyance response without beats and annoyance response with beats for given values of OASPL, tone frequency, and beat frequency. Thus positive values of differential annoyance indicate conditions where annoyance without beats is greater than annoyance with beats for equivalent peak OASPL. This parameter was determined by fitting least-squares regression lines to the annoyance versus OASPL data for each tone and beat condition and using the resulting regression equations to estimate annoyance response at several selected values of OASPL. These estimated annoyance values were then used to calculate the differential annoyance values presented in figure 8 as a function of beat frequency for three values of OASPL at each propeller tone frequency. (Note that the symbols represent estimated values obtained from the regression equations, not actual data values.) The results shown in figure 8 indicate that at the higher tone frequencies (160, 200, and 250 Hz) the beat conditions were less annoying than the no-beat conditions for beat frequencies less than 0.25 Hz, as indicated by the positive values of differential annoyance. The decrease in annoyance observed for the low-frequency beats, particularly at the beat frequency of 0.05-Hz, is probably the result of inaudibility of the beating tones over a significant portion of the stimuli durations. Nondetectability of the tones occurred as the beating tone levels approached zero and/or became masked by the boundary-layer noise. As beat frequency increased, the periods of inaudibility became shorter and the beating tones were perceived over larger fractions of the stimuli durations. This resulted in increased annoyance relative to the no-beat conditions as evidenced by the overall negative sloping trend of differential annoyance with increasing beat frequency for each plot in figure 8. The above effects cannot be attributed to energy-averaged measures (such as L_{eq}) since these remained constant with beat frequency for a given tone condition.

Figure 8(a) also indicates that the results for the 100-Hz tone differed markedly from those of the other tone frequencies. The negative values of differential annoyance mean that the beat conditions were generally more annoying than the no-beat conditions at this tone frequency. This is in contrast to the data for the higher tone frequencies where differential annoyance was slightly negative only at the higher beat frequencies. Further, the data of figure 8(a) fluctuate widely and do not show the consistent trends obtained for the other conditions. The reason for this behavior is unclear at present. The implication of these results for ATP is that, for the higher tone frequencies typical of ATP blade passage frequencies, the presence of tonal beats of 1.0 Hz or less may not introduce significant annoyance penalty for the range of parameters considered in this study. For lower tone frequencies typical of conventional propeller aircraft, the presence of single tonal beats, under certain conditions, may introduce additional annoyance penalty.

Effect of Tonal Content

Figure 9 presents a comparison of mean annoyance responses obtained for the combined tone and boundary-layer noise conditions (open symbols) with mean annoyance responses obtained for boundary-layer noise without tones (shaded symbols). The best-fit linear regression line through the annoyance responses for boundary-layer noise without tones is given by the dashed line, and the corresponding regression line for the combined noise condition by the solid line. Although the actual OASPL values for the no-tone conditions range from approximately 84 to 99 dB, the line has been extrapolated (for ease of comparison) to match the range of data for the tone plus boundary-layer noise conditions. A test for differences of slope and intercept between the two lines in figure 9 indicated that they do not differ in a statistical sense. This implies that for the set of combined stimuli the growth of annoyance with increased level of propeller tone noise can be accounted for by the increase in interior noise level due to the tones. This is an important observation since it implies that the perceptual quality of the tones and beats within the ATP interior environments may not, in general, introduce an additional annoyance factor beyond that caused by an increase in noise level resulting from the presence of the tones.

Effect of Tone Frequency

Annoyance responses as a function of tone frequency for the no-beat and beat conditions are presented in figure 10. The data for the conditions containing beats (circular symbols) represent annoyance data averaged over both tone level and beat frequency, whereas annoyance data for the no-beat conditions (square symbols) were averaged over tone level only. Thus the data of figure 10 represent overall annoyance responses and do not reflect fluctuations due to individual test conditions. Examination of figure 10 shows that the statistically significant effect of tone frequency as indicated by the analysis of variance can probably be attributed to the 100-Hz tone which produced the least annoyance of the four frequencies. Annoyance responses to 160, 200, and 250 Hz differed little from one another and the fluctuations shown in figure 10 for these frequencies are not considered to be of practical significance. Thus fundamental ATP blade passage frequency may not be a crucial determiner of passenger annoyance reaction.

Discussion of Tone Penalties

This section considers the concept of tone penalties as described in the current literature (ref. 6, for example) and presents the tone penalties obtained for the various metrics discussed earlier in this paper. To accomplish this, the definition of tone penalty as given in reference 6 is used. In that reference tone penalty for a given metric and a constant level of annoyance was defined as the deviation of the regression line of a tone and boundary-layer-noise combination from the regression line of the boundary-layer noise alone. This definition is illustrated by the hypothetical regression lines in figure 11. For a given tone and boundary-layer combination this definition implies that annoyance increases without an accompanying increase in metric level would produce positive tone penalties. If the increases in annoyance are perfectly matched by increases in metric level, then no tone penalty results. Based on this definition, it is clear that the metric giving the smallest tone penalties would be most appropriate for quantifying annoyance within the ATP environment since it would best account for the effects of tones. A "best" metric is very useful for quantifying annoyance within noise environments and for specification of criteria limits.

The tone penalties for each metric of the present study are presented in figure 12. The solid curves in figure 12 represent the linear regression lines through all the data points containing combined tones and boundary-layer noise. The dashed lines represent the linear regression lines for boundary-layer noise only. These results show that OASPL produced the smallest tone penalties and, hence, was the most appropriate for quantifying annoyance response within the simulated ATP environments of the present study. This finding, together with the fact that the two regression lines of figure 12(a) did not differ statistically, implies that the "tonal character" of the sound did not contribute additional annoyance effects beyond those attributable to increased OASPL.

Concluding Remarks

In terms of the advanced turboprop (ATP) environment the preceding results lead to the implication that passenger annoyance within ATP aircraft may be greater, for a given level of boundary-layer noise, when tones are present at levels sufficient to increase the overall sound pressure level within the cabin. In particular, annoyance response to the 100-Hz tone was significantly less than the responses to tones at frequencies representative of ATP blade passage frequencies (160–250 Hz). For the present study, which used a single boundary-layer-noise level, the increases in annoyance were fully explained by the increases in overall sound pressure level caused by the tone and beat conditions. Additional annoyance factors due to the perceived tonal character of the tones and/or beats were not observed. In fact, in many instances where beats were present, the annoyance decreased, especially for the very low beat frequencies. Thus, for a noise environment containing single tones with no harmonics, the noise control engineer may not have to be concerned with the tonal nature or beating quality of the sound, although effort may be required to bring the overall sound pressure level to within acceptable limits. Blade passage frequency for the range of frequencies considered representative of ATP aircraft had only minor effects on passenger annoyance. This would imply that the exact value of fundamental blade passage frequency of single-rotating advanced design propellers for ATP may not be crucial to passenger annoyance. This result, however, was obtained for no propeller harmonics within an anechoic environment and should be considered tentative pending future verification within a more realistic reverberant environment with harmonics present.

Several noise metrics were investigated for possible use in quantifying passenger annoyance within the simulated ATP interior noise environments, and OASPL was found to correlate best with the annoyance response data of this study and to have the least error of prediction. The conventional tone correction metric, tone-corrected perceived noise level (PNLT), was ineffective in accounting for effects of the propeller tones. Additional research to study the effects of propeller harmonics and alternate propeller designs (counter-rotating, for example) is highly desirable.

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Appendix A

Instructions

You have volunteered to participate in a research program to investigate the acceptability of noises that may occur in cabins of certain aircraft. Specifically, we wish to identify the types of sounds which people find the least and most annoying.

The sounds that you will hear today are representative of sounds that people may experience in an airplane. You are to make yourself as comfortable and relaxed as possible while the selected sounds are applied to the chamber. During the test you will, at all times, be in two-way communication with the test conductor.

You have the option at any time and for any reason to terminate the test in either of two ways: (1) by voice communication with the test conductor or (2) by exiting the chamber. Because of individual differences in people, there is always the possibility that someone may find the sounds objectionable and may not wish to continue. If this should happen to you, please do not hesitate to stop the test by one of the above methods.

Test Instructions

The task you will be required to perform is to evaluate the annoyance associated with various sounds called ride segments. There will be 10 sessions, 9 of which contain 8 rides, and one session which contains 4 rides. Each ride segment, to be evaluated by yourself, will be presented to you for approximately one minute. Listen to all of the sound before making your judgment. There will be several seconds between successive ride segments to allow you to mark your evaluation.

You should record your evaluation of the annoyance associated with each ride segment by placing a checkmark (√) upon the scale. For example, a sound causing little annoyance should be scored towards the "0 not annoying" end of the scale. Similarly, if you judge a sound to cause a large amount of annoyance, you would place your checkmark towards the "8 extremely annoying" end of the scale.

There are no right or wrong answers. Your ratings should reflect only your own opinion of the sound.

Are there any questions?

Appendix B

Voluntary Consent Form

VOLUNTARY CONSENT FORM FOR SUBJECTS
FOR HUMAN RESPONSE TO AIRCRAFT NOISE AND VIBRATION

I understand the purpose of the research and the technique to be used, including my participation in the research, as explained to me by the Principal Investigator (or qualified designee).

I do voluntarily consent to participate as a subject in the human response to aircraft noise experiment to be conducted at NASA Langley Research Center on_________________.
date

I understand that I may at any time withdraw from the experiment and that I am under no obligation to give reasons for withdrawal or to attend again for experimentation.

I undertake to obey the regulations of the laboratory and instruction of the Principal Investigator regarding safety, subject only to my right to withdraw declared above.

I affirm that, to my knowledge, my state of health has not changed since the time at which I completed and signed the medical report form required for my participation as a test subject.

____
Printed name

____
Signature

Appendix C

Sample Scoring Sheet

SUBJECT NO. ________ DATE ___________

AGE ________ SEAT ___________

SESSION 1

NOISE

NOT ANNOYING — EXTREMELY ANNOYING

NOISE									
1	0	1	2	3	4	5	6	7	8
2	0	1	2	3	4	5	6	7	8
3	0	1	2	3	4	5	6	7	8
4	0	1	2	3	4	5	6	7	8
5	0	1	2	3	4	5	6	7	8
6	0	1	2	3	4	5	6	7	8
7	0	1	2	3	4	5	6	7	8
8	0	1	2	3	4	5	6	7	8

Table I. Experimental Design

Tone level	Tone frequency, Hz	Beat frequency, Hz, of —					
		0	0.05	0.10	0.25	0.50	1.00
Low	100						
	160						
	200						
	250						
Medium	100						
	160						
	200						
	250						
High	100						
	160						
	200						
	250						

Table II. Overall Sound Pressure Level for Each Test Condition

Tone level	Tone frequency, Hz	OASPL, dB, at beat frequency, Hz, of —					
		0	0.05	0.10	0.25	0.50	1.00
Low	100	92.0	92.2	92.2	91.4	92.0	92.2
	160	91.9	92.0	92.2	91.7	91.9	92.1
	200	92.0	92.1	91.8	92.2	91.9	92.4
	250	92.2	92.4	92.7	92.8	92.4	93.1
Medium	100	96.7	97.0	96.1	97.1	95.8	97.2
	160	96.8	96.8	96.7	96.5	96.9	97.0
	200	96.9	97.4	96.6	96.4	95.7	96.9
	250	98.9	97.0	97.8	97.0	97.2	97.1
High	100	100.4	101.6	101.2	101.0	100.5	100.6
	160	105.3	105.7	103.6	104.9	105.2	105.1
	200	105.0	103.5	103.5	104.6	104.2	104.3
	250	104.2	104.8	104.4	103.8	105.1	103.5

Table III. A-Weighted Sound Pressure Level for Each Test Condition

Tone level	Tone frequency, Hz	L_A, dB, at beat frequency, Hz, of —					
		0	0.05	0.10	0.25	0.50	1.00
Low	100	82.7	82.8	83.0	81.9	82.6	82.7
	160	82.7	83.0	83.1	82.8	82.9	83.0
	200	83.2	83.1	83.0	83.3	83.1	83.5
	250	84.5	84.0	84.0	84.2	84.0	84.8
Medium	100	83.4	83.4	82.8	83.5	83.2	83.7
	160	85.6	85.5	85.8	85.7	85.6	85.8
	200	86.9	87.5	86.8	86.7	86.3	87.1
	250	90.6	88.7	89.5	88.8	88.9	88.9
High	100	84.7	85.8	85.1	85.0	84.9	85.0
	160	92.8	93.2	91.2	92.5	92.8	92.7
	200	94.7	93.2	93.3	94.4	94.0	94.1
	250	96.0	96.4	96.1	95.5	96.8	96.0

Table IV. Unweighted Tone Levels for Each Test Condition

Tone level	Tone frequency, Hz	Tone level, dB, at beat frequency, Hz, of —					
		0	0.05	0.10	0.25	0.50	1.00
Low	100	87.1	87.2	86.7	86.3	87.1	87.6
	160	87.0	86.9	87.2	86.3	86.6	87.3
	200	87.0	87.7	87.1	87.4	86.2	87.8
	250	88.4	88.2	88.5	89.5	87.7	88.7
Medium	100	95.7	96.0	95.0	95.9	94.4	96.2
	160	95.4	95.4	94.9	94.6	95.4	95.8
	200	95.5	96.5	95.2	95.0	94.3	95.7
	250	98.0	95.9	96.8	95.8	95.9	95.8
High	100	100.1	101.0	101.0	100.7	100.2	100.2
	160	104.9	105.4	103.1	104.4	104.8	104.7
	200	104.8	103.2	103.2	104.3	103.9	104.0
	250	103.9	104.1	104.1	103.5	104.7	103.5

Table V. Annoyance Response for Each Test Condition

(a) Mean

Tone level	Tone frequency, Hz	Mean annoyance response at beat frequency, Hz, of —					
		0	0.05	0.10	0.25	0.50	1.00
Low	100	2.08	2.12	2.32	2.27	3.17	2.51
	160	3.11	2.22	2.21	2.30	2.15	2.57
	200	2.33	2.72	2.03	2.32	2.28	2.79
	250	2.56	2.21	2.76	2.79	2.74	3.30
Medium	100	3.71	3.34	3.93	3.84	3.73	4.66
	160	4.38	3.17	3.48	3.86	4.82	4.78
	200	4.84	3.83	3.59	3.99	4.54	5.30
	250	4.94	3.35	4.13	4.32	4.23	4.75
High	100	4.93	5.26	4.94	5.03	5.18	6.29
	160	7.19	7.00	6.01	6.28	6.66	7.04
	200	7.05	5.65	6.15	6.44	6.74	6.96
	250	6.62	6.37	6.53	6.59	7.12	6.69

(b) Standard Deviation

Tone level	Tone frequency, Hz	Standard deviation at beat frequency, Hz, of —					
		0	0.05	0.10	0.25	0.50	1.00
Low	100	1.61	1.51	1.52	1.96	1.89	1.38
	160	1.97	1.66	1.47	1.33	1.45	1.57
	200	1.32	1.57	1.40	1.65	1.72	1.43
	250	1.56	1.65	1.60	1.73	1.47	1.78
Medium	100	1.56	1.69	1.86	1.68	1.52	1.57
	160	1.81	1.53	1.42	1.28	1.65	1.50
	200	1.79	1.54	1.57	1.53	1.67	1.39
	250	1.94	1.61	1.62	1.37	1.43	1.54
High	100	1.84	1.81	1.66	1.49	1.39	1.32
	160	1.07	1.23	1.31	1.38	1.64	1.28
	200	1.44	1.56	1.60	1.40	1.05	1.14
	250	1.46	1.43	1.65	1.65	.99	1.22

Table VI. Analysis of Variance

Source of variation	Sum of squares	Degrees of freedom	Mean square	F
Tone frequency	251.45	3	83.816	39.539*
within cells	298.90	141	2.120	
Tone level	8340.40	2	4152.200	418.880*
within cells	931.79	94	9.913	
Beat frequency	312.23	5	62.445	34.292*
within cells		235	1.821	
Tone frequency × tone level	206.30	6	34.383	26.351*
within cells	367.96	282	1.305	
Tone frequency × beat frequency	92.94	15	6.196	4.830*
within cells	904.46	105	1.283	
Tone level × beat frequency	70.46	10	7.046	5.322*
within cells	622.18	470	1.324	
Tone frequency × tone level × beat frequency	182.10	30	6.070	
within cells	1618.11	1410	1.148	5.289*

*Probability < 0.05.

Table VII. Correlation Coefficient for Various Metrics

Metric	Correlation coefficient	Standard error of estimate
Overall sound pressure level (OASPL)	0.9652	0.4367
Perceived noise level (PNL)	.9462	.5419
Tone-corrected perceived noise level (PNLT)	.9462	.5416
A-weighted sound pressure level (L_A)	.9235	.6423
I-weighted (fig. 5) sound pressure level (L_I)	.7827	1.0420

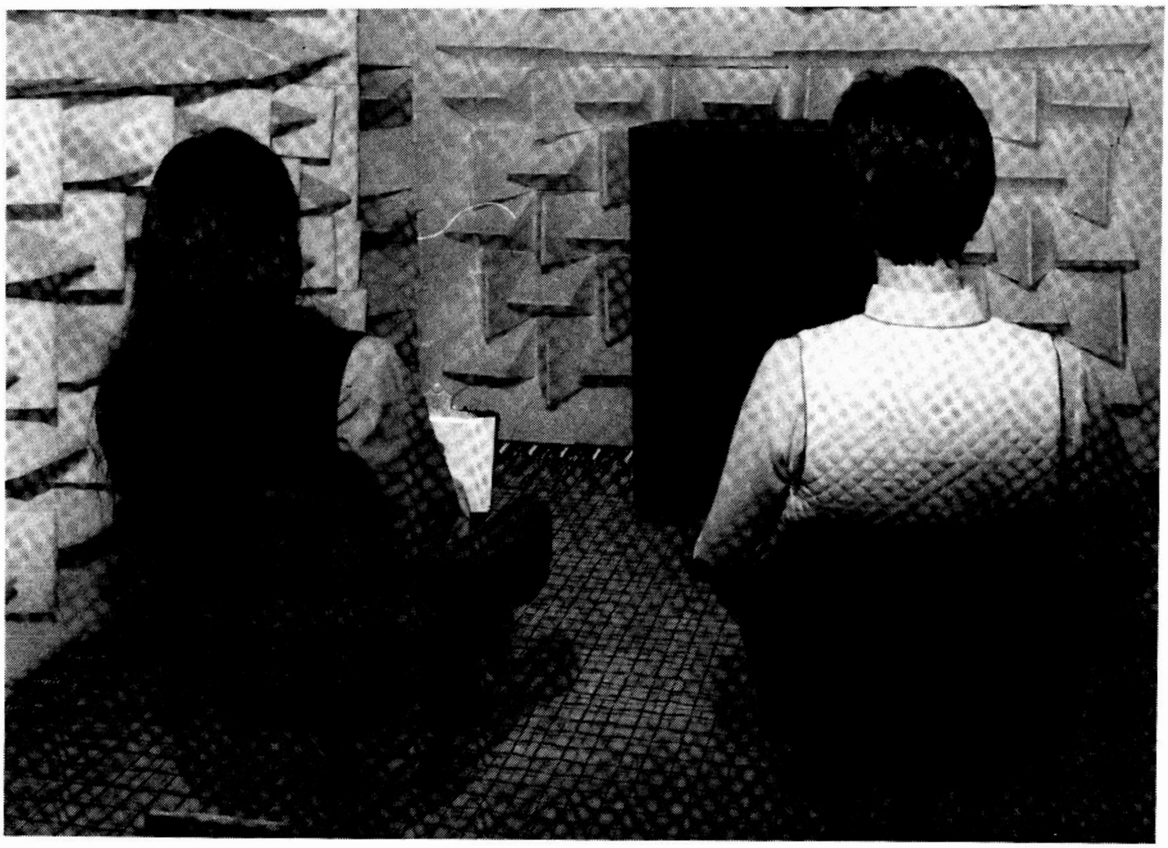
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Figure 1. Anechoic listening facility.

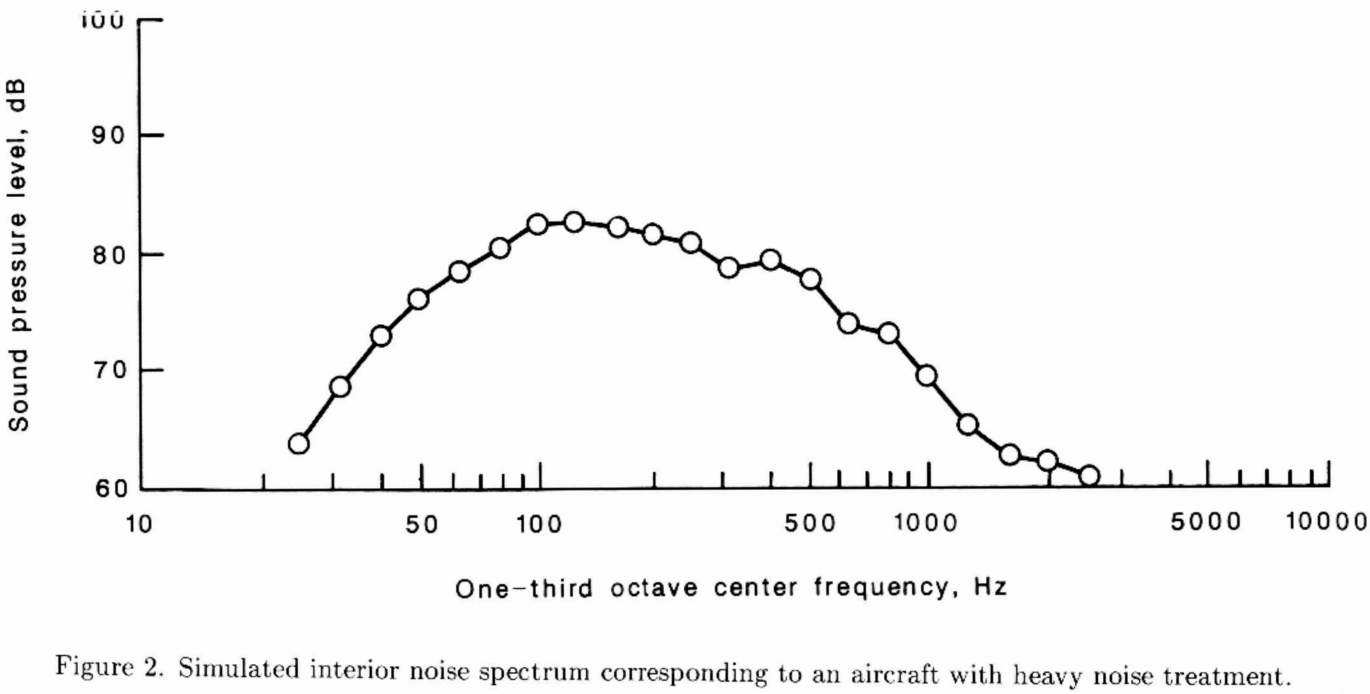
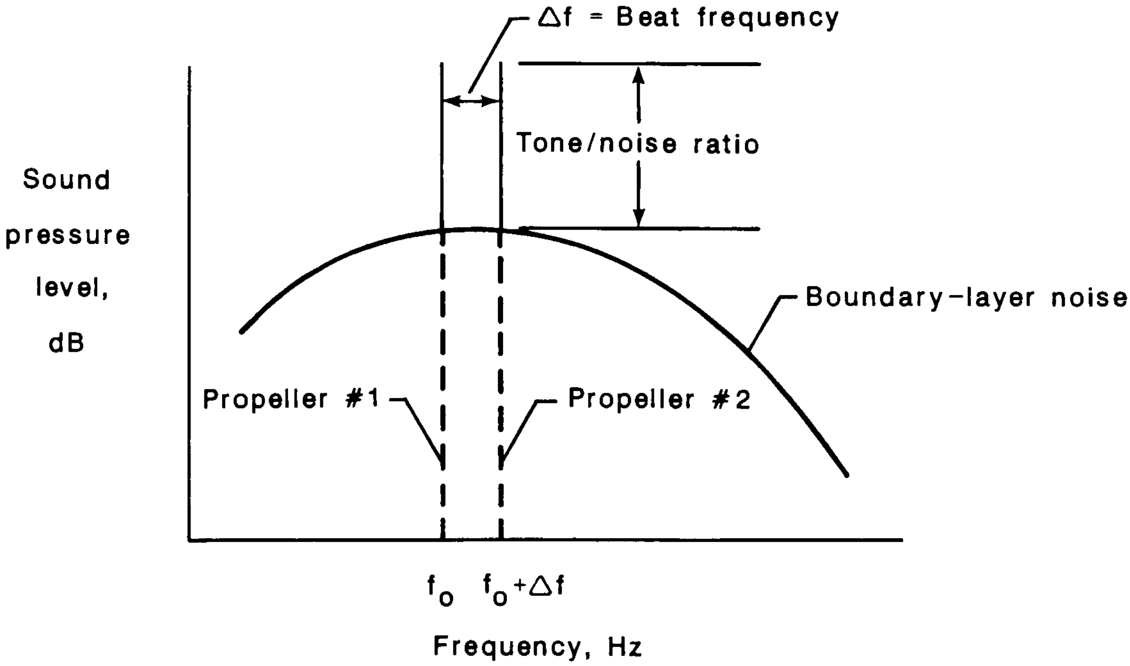
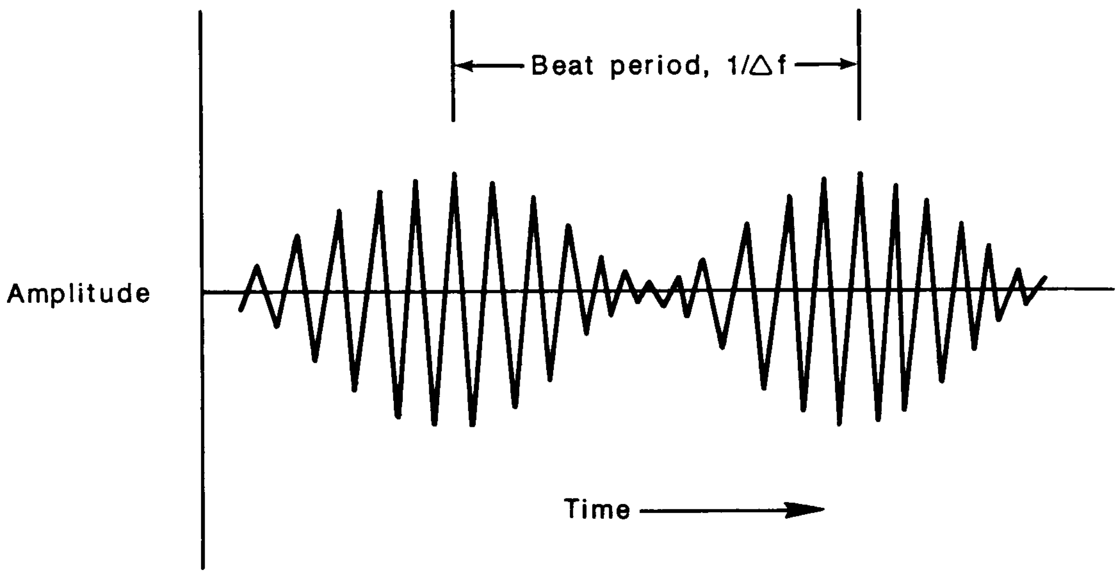


Figure 2. Simulated interior noise spectrum corresponding to an aircraft with heavy noise treatment.

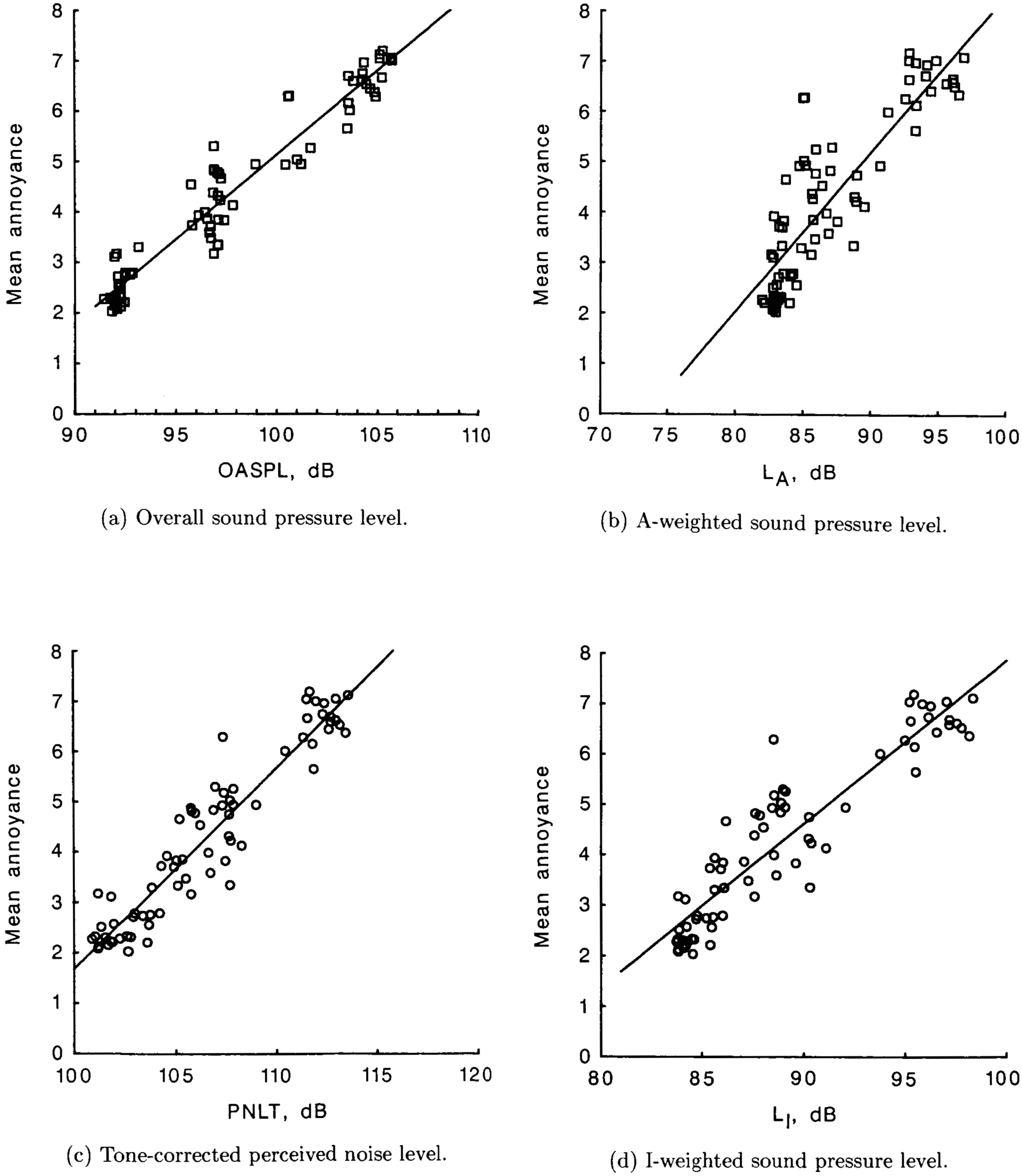


(a) Hypothetical spectrum that produces a single beat frequency.



(b) Hypothetical beat time history.

Figure 3. Spectral and temporal character of the simulated ATP beats.



(a) Overall sound pressure level.

(b) A-weighted sound pressure level.

(c) Tone-corrected perceived noise level.

(d) I-weighted sound pressure level.

Figure 4. Mean annoyance response as a function of level for various noise metrics.

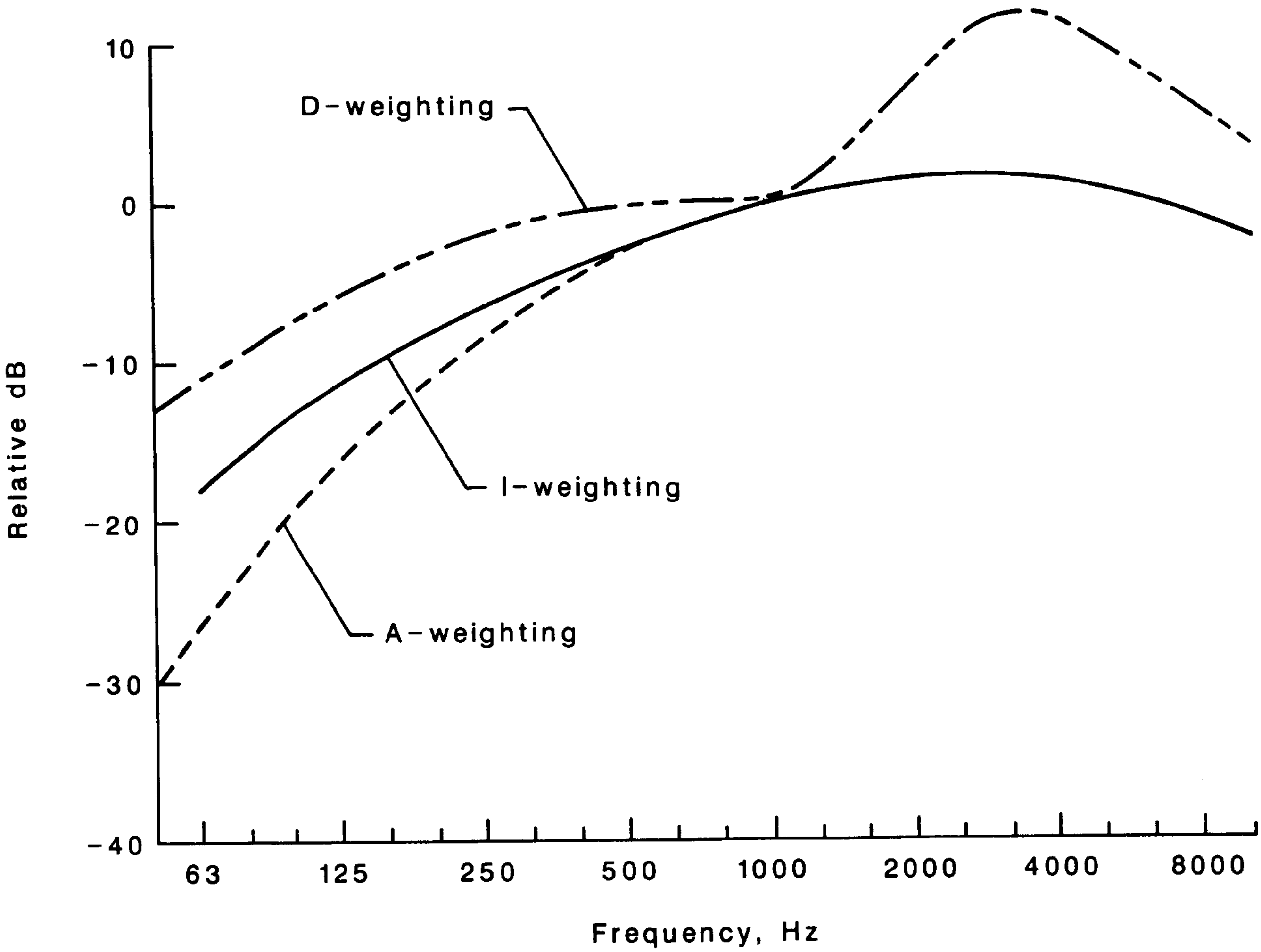


Figure 5. Comparison of A, D, and I frequency weightings.

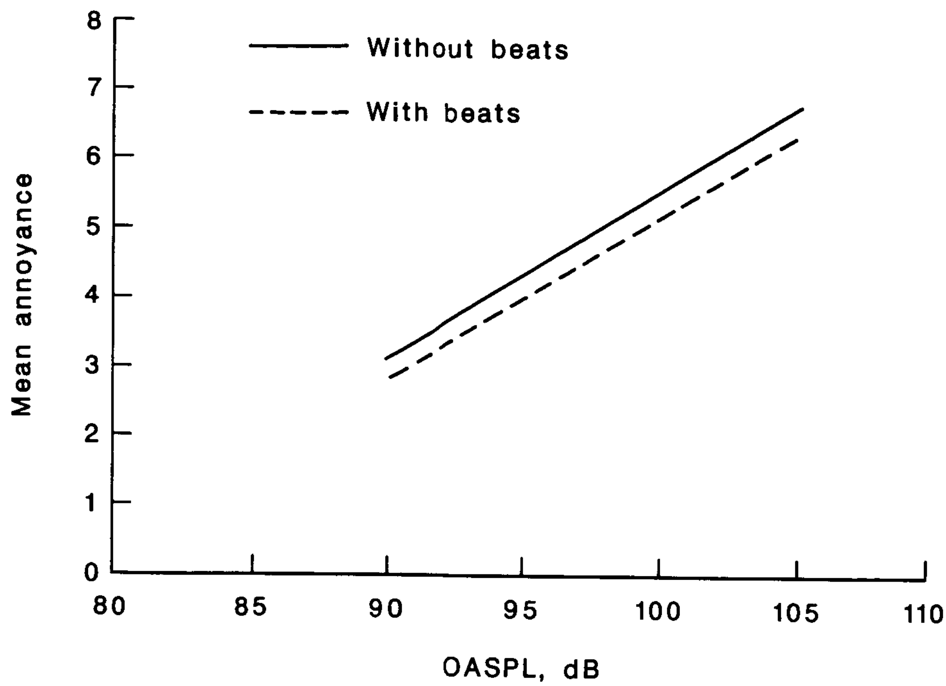


Figure 6. Comparison of annoyance responses to tonal stimuli with and without bea

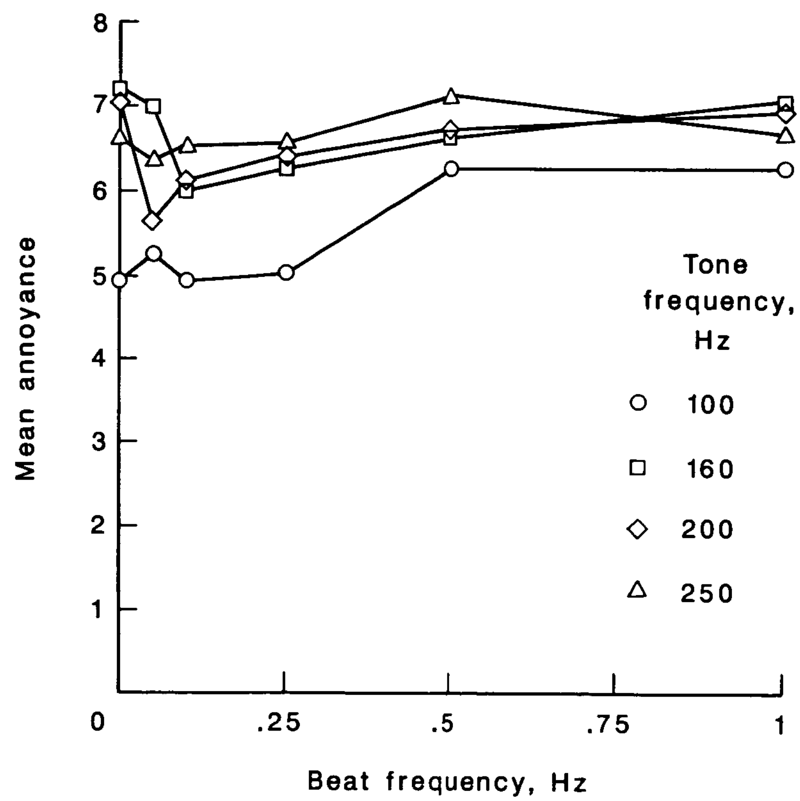
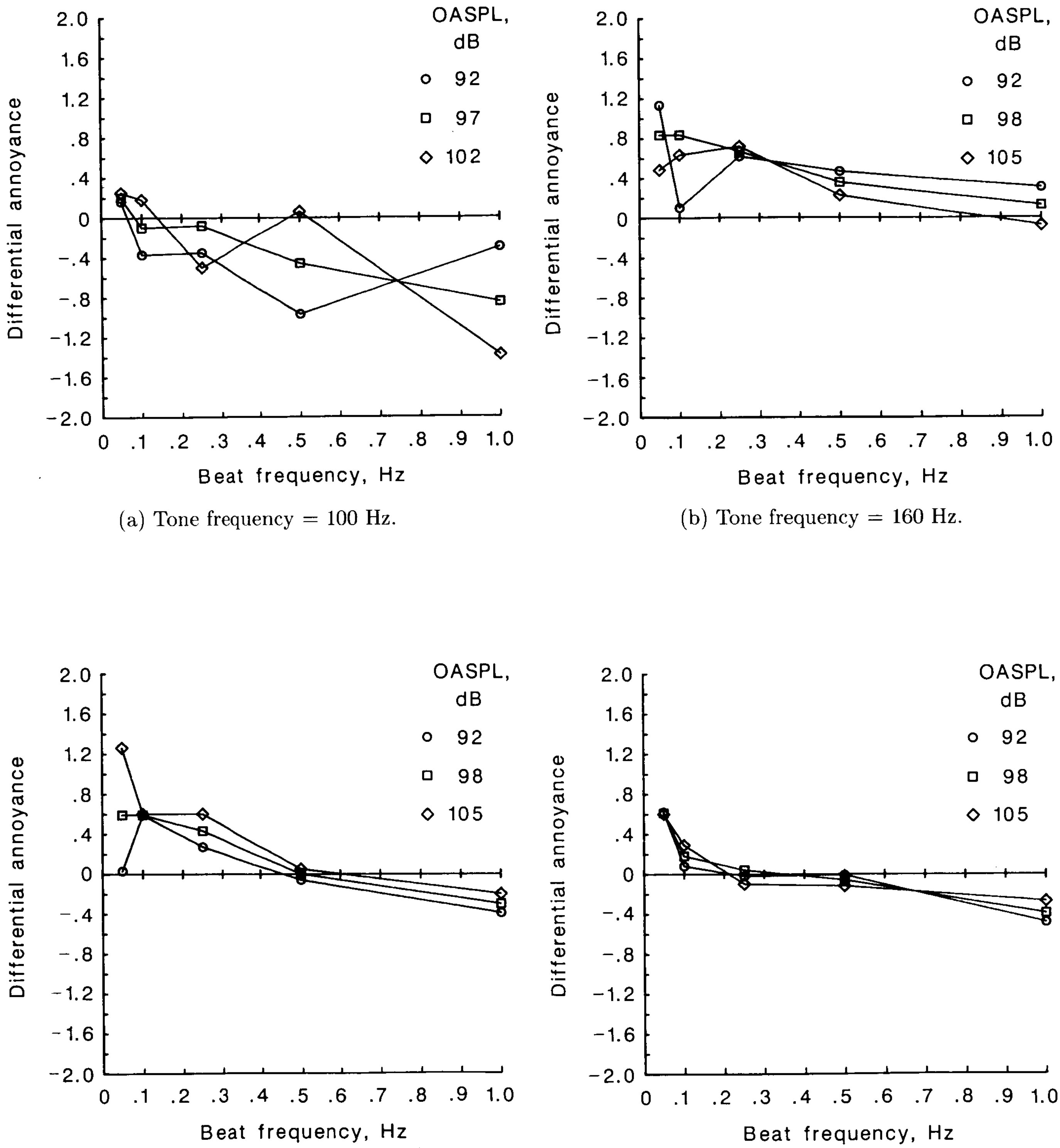


Figure 7. Interaction of tone frequency and beat frequency for the high tone level.



(a) Tone frequency = 100 Hz.

(b) Tone frequency = 160 Hz.

(c) Tone frequency = 200 Hz.

(d) Tone frequency = 250 Hz.

Figure 8. Differential annoyance as a function of beat frequency and tone frequency for constant values of OASPL.

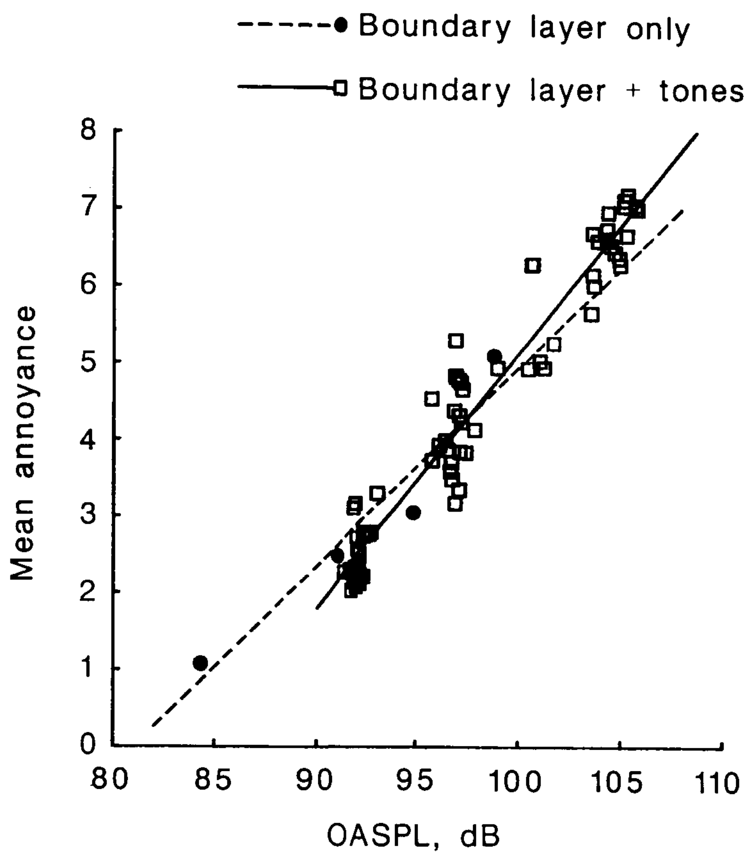


Figure 9. Annoyance due to boundary-layer noise alone and annoyance due to combined boundary-layer noise and tones (for all beat conditions).

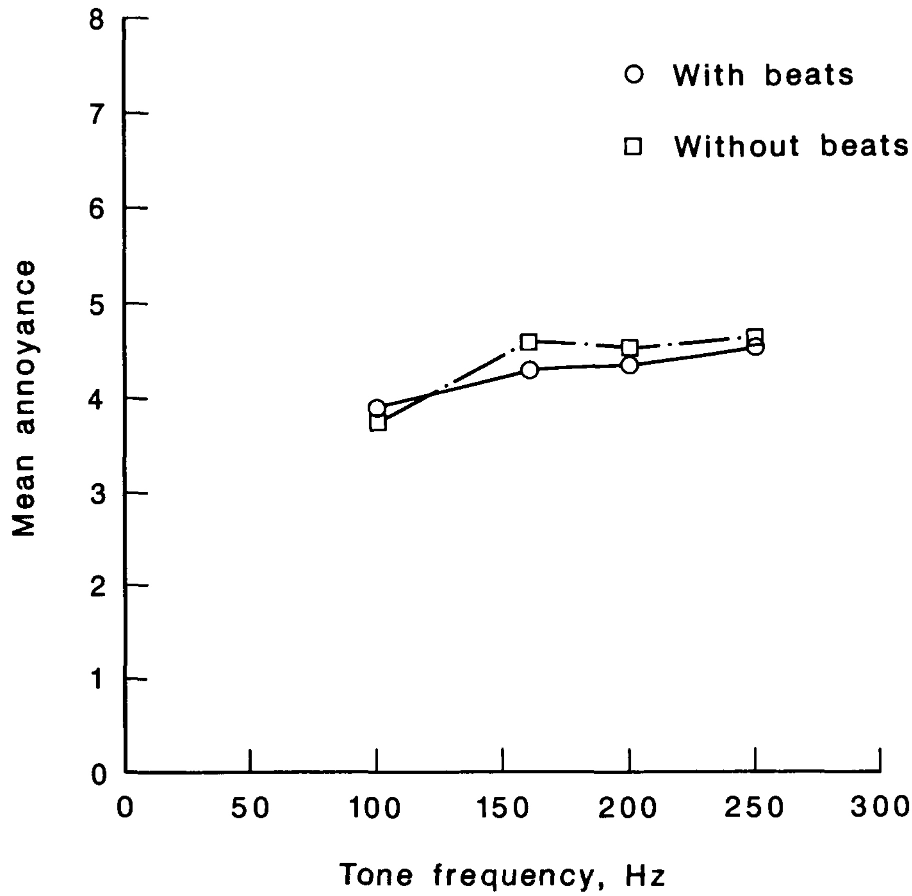


Figure 10. Overall effect of tone frequency on annoyance for the beat and no-beat test conditions.

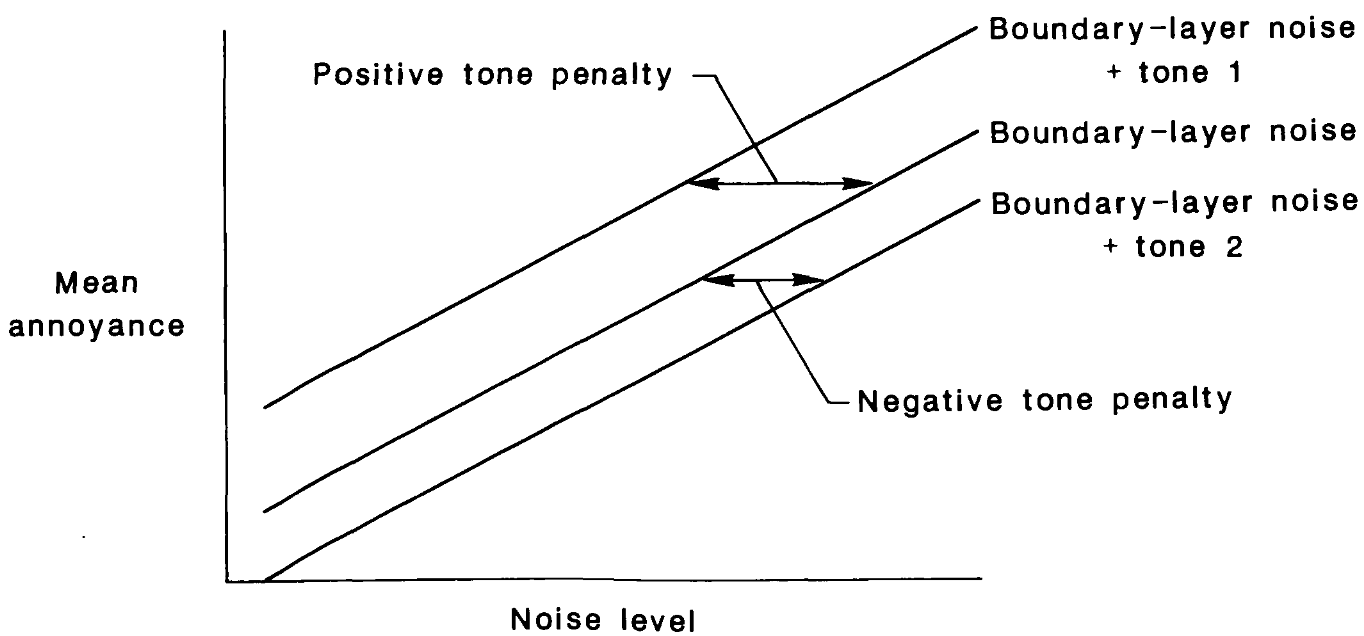
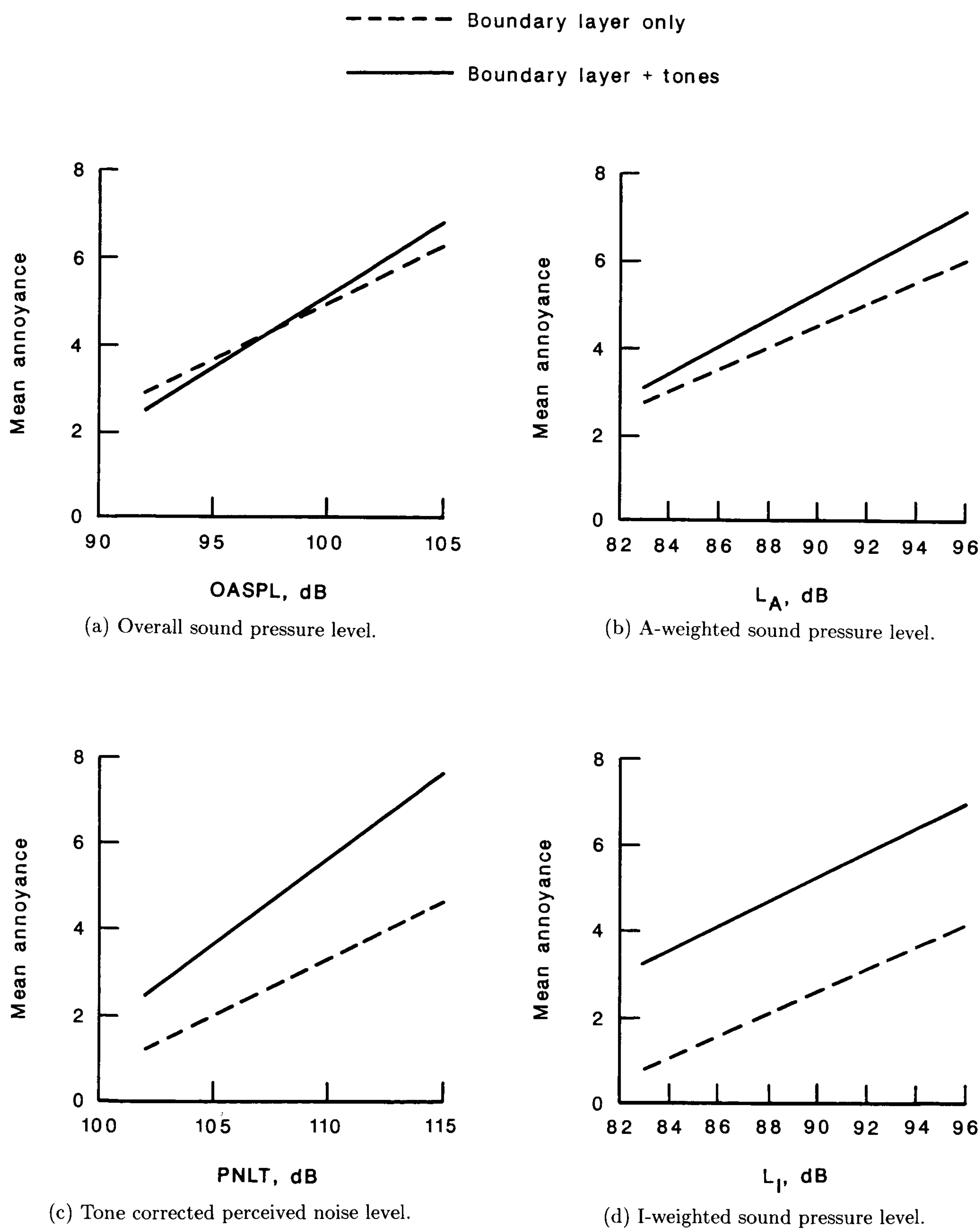


Figure 11. Definitions of tone penalties.



(a) Overall sound pressure level.

(b) A-weighted sound pressure level.

(c) Tone corrected perceived noise level.

(d) I-weighted sound pressure level.

Figure 12. Tone penalties for various metrics.

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15. Supplementary Notes

16. Abstract

A laboratory study was conducted to investigate the effects on subjective annoyance of simulated advanced turboprop (ATP) interior noise environments containing tonal beats. The simulated environments consisted of low-frequency tones superimposed on a turbulent-boundary-layer noise spectrum. The variables used in the study included propeller tone frequency (100 to 250 Hz), propeller tone levels (84 to 105 dB), and tonal beat frequency (0 to 1.0 Hz). Results indicated that propeller tones within the simulated ATP environment resulted in increased annoyance response that was fully predictable in terms of the increase in overall sound pressure level due to the tones. Neither the "tonal quality" of the noise nor the rhythmic pulsations characteristic of tonal beats were found to be an annoyance factor. Implications for ATP aircraft include the following: (1) the interior noise environment with propeller tones is more annoying than an environment without tones if the tone is present at a level sufficient to increase the overall sound pressure level; (2) the increased annoyance due to the fundamental propeller tone frequency without harmonics is predictable from the overall sound pressure level; and (3) no additional noise penalty due to the perception of single discrete-frequency tones and/or beats was observed.

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