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Potential Subjective Effectiveness of Active Interior Noise Control in Propeller Airplanes

Clemans A. Powell and Brenda M. Sullivan
Langley Research Center, Hampton, Virginia

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National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

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Summary

Active noise control technology offers the potential for weight-efficient aircraft interior noise reduction, particularly for propeller aircraft. However, there is little information on how passengers respond to this type of interior noise control. This paper presents results of two experiments which used sound quality engineering practices to determine the subjective effectiveness of hypothetical active noise control (ANC) systems in five different propeller airplanes. Binaural recordings were made of the sounds inside the airplanes at passenger head positions under typical steady flight conditions. Digital filtering and reduction of the propeller tones at blade passage frequency and higher harmonics provided simulations of hypothetical reductions in interior sound levels which could be obtained with active noise control systems. The original recordings and simulated active noise control sounds were presented to the test subjects using electrostatic headphones to preserve the realism of the airplane interior sounds. The two experiments differed by the type of judgments made by the subjects: pair comparisons based on preference in the first and numerical category scaling of noisiness in the second. Although the results of the two experiments generally showed that the hypothetical active control measures improved the interior noise environments, the pair comparison method appears to be more sensitive to subtle changes in the characteristics of the sounds which are related to passenger preference. Subject preference increased with decreases in the level of propeller tones and with increases in the number of tones reduced by the simulated ANC conditions. The subjective effectiveness of the simulated ANC conditions was highly dependent on the spectral content and relative levels of the tonal and broadband components in the original airplane interior sounds. However, the reductions in subjective response due to the ANC conditions were predicted with reasonable accuracy by reductions in measured loudness level. Inclusion of corrections for the sound quality characteristics of tonality and fluctuation strength in multiple regression models improved the prediction of the ANC effects.

Introduction

The National Aeronautics and Space Administration currently is conducting a research program in aircraft interior noise reduction for commercial transport, business and general aviation airplanes and rotorcraft. As part of this activity, a program has been initiated to address passenger response to the interior noise of these aircraft. The goal of the activity is to develop tools that are responsive to passenger preference and can be used to guide design decisions for interior noise treatments. The ideal tool would be a passenger response model with a metric or scale that adequately accounts for all of the many characteristics of cabin noise for a wide range of aircraft. The designers or noise control engineers could then use this model to insure that changes in the noise characteristics would be reflected by appropriate changes in passenger acceptance or preference. Such a model would thereby provide guidance towards the necessary compromises between weight, costs and treatment effectiveness.

Several investigations on passenger response to aircraft cabin noise were conducted in the mid 1970s, (refs. 1, 2, and 3). These studies concluded that since common noise metrics were so highly correlated with each other, none of the metrics could be clearly identified as being a substantially better predictor of passenger satisfaction. In reference 3, however, it was found that summing contributions from different sound sources provided improvement over models that considered the noise as a whole with only a single metric. More recent studies (ref. 4 and 5) have used simulated interior noise with both broadband and tone components. In reference 4, it was found that the tone correction in the metric which is used to certify aircraft for community noise was ineffective in predicting subjective response to sounds that contained audible tones in combination with broadband interior sounds. In reference 5, however, it was found that a model combining loudness (ref. 6) and tonality (ref. 7) predicted subjective annoyance better than either unweighted or A- weighted sound level.

Active noise control offers the potential of very weight-efficient aircraft interior noise reduction, particularly for propeller aircraft. The interior noise of a propeller airplane is usually dominated by tonal components resulting from acoustic loads on the fuselage from the propeller(s) and from structurally transmitted vibration from the engine(s). These include components at the blade passage frequency (BPF), at multiples of the BPF, and occasionally at subharmonics of the BPF and multiples of those subharmonics. The number and relative amplitudes of these components in the interior sound field vary considerably between different airplanes and determine the general character of the interior noise. An appropriately designed active noise control system can significantly reduce the sound level of the lowest of these components. However, there is neither a validated model nor a sufficient experimental database for predicting how passengers would respond to this type of interior noise control. The two experiments described in this paper were conducted to determine the subjective effectiveness of hypothetical active noise control (ANC) systems in a range of propeller airplanes.

Recently, an experimental test technique commonly referred to as “Sound Quality (SQ) Engineering” has been used to determine the sound characteristics of automobile interiors and consumer products which are preferred by customers (ref. 8 and 9). A number of metrics have been developed for quantifying the effects that acoustic characteristics have on people’s response and preference to different sounds. Such characteristics include loudness (ref. 6), tonality (ref. 10), sharpness (ref. 11), roughness (ref. 12), and fluctuation strength (ref. 13). The SQ technique typically uses an acoustic mannequin, with microphones located at the entrance of the ear canals, and a digital audio recorder (DAT) to record sounds in which the binaural amplitude and phase characteristics of the sounds as presented to the human auditory system are preserved. These sounds, as recorded or after some manipulation, are then played back to human test subjects using very high quality stereo headphones. Through this process, the spatial and temporal characteristics of the sounds as heard in situ are largely preserved, thus providing an auditory realism that is not ordinarily achieved in laboratory listening tests. An additional benefit of this type of subjective testing is that multiple test subjects can be simultaneously exposed to acoustic stimuli that are more nearly the same than can be achieved in a reverberant or anechoic laboratory facility using loudspeakers. The experiments to be described in this paper used the binaural presentation and some of the other SQ practices to maintain realism and to reduce variability in sounds presented to the test subjects. In addition, this methodology was expected to enhance the discrimination of sound characteristics that affect human responses such as annoyance and preference of one sound over another.

The sections to follow will describe the facility and equipment, the experimental design and test procedures, and the data analysis methods for two experiments which were conducted to quantify changes in sounds representative of the application of active noise control systems in propeller airplanes. The primary difference between the two experiments is that in the first the subjects indicated their preferences, if any, for the ANC sounds over the original uncontrolled sounds, whereas in the second the subjects rated the noisiness character of the sounds. The magnitude of the subjective effects and correlation with changes in the measured physical characteristics of the sounds will also be discussed. In addition, differences between the results of the two tests and findings relative to the application of previously defined sound quality metrics to the propeller airplane interior sounds will be presented.

Abbreviations and Symbols

A/C	Aircraft
AL	A-weighted sound level (ref. 14), dB
ANC	Active noise control
BPF	Blade passage frequency
CESL	Corrected equivalent subjective level, dB or phon
DAT	Digital audio tape recorder

DL	D-weighted sound level (ref. 14), dB
ESL	Equivalent subjective level, dB or phon
f_0	Propeller tone fundamental frequency, Hz
FS	Fluctuation strength (ref. 13), vacil
L_S	Binaurally summed level, dB or phon
L_L	Level of sound presented to left ear, dB or phon
L_R	Level of sound presented to right ear, dB or phon
LL_Z	Loudness level calculated using the procedures of Zwicker (ref. 6), phon
LL_{MG}	Loudness level calculated using the procedures of Moore and Glasberg (ref.15), phon
R	Roughness (ref. 12), asper
S	Sharpness (ref. 11), acum
l_L	Loudness of sound presented to left ear, sone
l_R	Loudness of sound presented to right ear, sone
SQ	Sound quality
SPL	Sound pressure level
T	Tonality (ref. 10)
Δ	Difference in the quantity that follows the Δ symbol

Experimental Method

Test Facility

An aircraft interior simulator, which uses interior trim and seats from Boeing 727, 737 and 757 airplanes to provide the visual ambiance of a aircraft interior, was assembled in an acoustically isolated room within the NASA Langley Acoustics Research Laboratory. A photograph of the simulator is shown in figure 1. The simulator is approximately 24 feet long and 11.5 feet wide and provides tourist class seating for 45 passengers. Noise stimuli for the subjective judgment tests were presented to the test subjects through electrostatic headphones to preserve the directivity and spatial information afforded by the binaural recording system.

Figure 1. Aircraft interior simulator test facility.

Acoustic Recording, Presentation, Analysis and Safety System

A schematic diagram of the system used to record and modify the noise stimuli, to present the stimuli to the test subjects and to ensure that excessive noise levels are not presented to the test subjects is shown in figure 2. Sound recordings were made with a commercially available binaural recording system inside the cabins of five propeller driven airplanes. Details of these recordings will be presented in the next section. The sounds were recorded on a digital audio tape recorder (DAT). A computer workstation was used to process the digital representations of the recorded sounds. Commercially available sound quality analysis software was used to calculate a wide range of conventional noise metrics and sound quality (SQ) metrics. Modifications to simulate the hypothetical ANC conditions from the original recorded interior sounds were also performed with the sound quality analysis software. In-house developed software was used to control the level, timing and sequence of the stimuli for playback to the test subjects. The digital representations of the stimuli were converted to analog electrical signals by the computer workstation and passed through a limiter circuit to a series of electrostatic headphone amplifiers and finally to six sets of very high quality electrostatic headphones. Five sets of headphones were used to present the stimuli to the test subjects. The sixth set was positioned on an acoustic mannequin, the microphones of which were connected to sound level meters. The sound level meters were programmed to output a trip indication signal if an acoustic signal from either the left or right ear channel exceeded a preset A-weighted sound level (AL). The trip indication signals were fed to the dual channel limiter that terminates the input to the headphone amplifiers upon receipt of a trip signal. The test protocol for human testing in the laboratory requires that the sound level not exceed an AL of 95 dB.

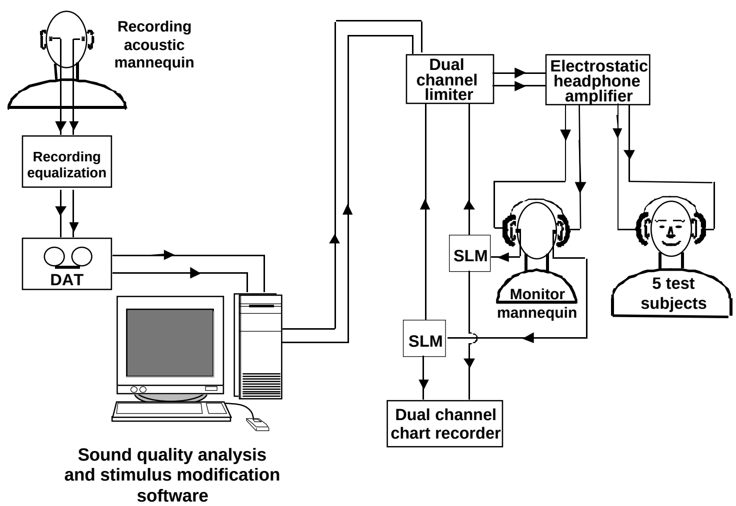


Figure 2. Schematic diagram of the binaural acoustic recording, analysis, presentation and safety system.

Noise Stimuli

Stimuli preparation. Recordings made in five different propeller airplanes during cruise operations were used to create modified stimuli with spectra approximating sounds that could be achieved by ANC technology with three levels of sophistication and three levels of effectiveness. The five propeller airplanes were:

A/C 1. single turboprop engine, 15 passenger cargo

A/C 2. twin turboprop engine, 7-10 passenger business

A/C 3. single 4-cylinder piston engine, 4 place general aviation

A/C 4. twin turboprop engine, 30 passenger commuter

A/C 5. single 6-cylinder piston engine, 6 place general aviation

The SQ software was used to modify the duration and propeller tone content of the original sound recordings to produce the hypothetical ANC stimuli. A recording made in a twin engine conventional jet transport airplane during cruise was used to create comparison and reference stimuli for the two tests. This sound consisted of broadband boundary layer and engine jet noise with no discernable tone content. Each stimulus had a rise and fall time of 0.3 sec and a total duration of 3.6 sec.

Tone modifications. The range of propeller tone reductions for the hypothetical ANC treatments is shown in figure 3. The modified spectra for each airplane type were obtained by reducing the levels of tonal components within each signal by amounts indicated in the graph. Three levels of reduction (7 dB, 14 dB and 21 dB) for the fundamental propeller tone of each aircraft were selected to represent the effectiveness of hypothetical ANC systems. For all aircraft except A/C 5, the blade passage frequency (BPF) was chosen as the propeller tone fundamental frequency, f_0. For A/C 5, one-half the BPF (54 Hz) was chosen to be the fundamental frequency, since a strong tone which existed at 1.5 times the BPF would not be affected by reductions of multiples of the BPF. Three numbers of harmonics (3, 7 and 15 multiples of the fundamental) were reduced in the ANC stimuli to represent the complexity of the ANC systems. These levels and numbers of harmonics affected resulted in nine modified spectra for each airplane type. The level of reduction for each tonal component above f_0 decreased linearly with the multiplier of f_0. Reductions in sound levels for tone components in the spectra with 3 components controlled are given in figure 3 by the solid black symbols on the straight lines. Reductions in components for spectra with 7 components controlled are given by the solid and shaded symbols. Reductions in components for spectra with 15 components controlled are given by all the symbols on the line. A-weighted, 1/24-octave spectra of the original and most modified stimuli for each airplane type are given in appendix A. The spectrum for the jet noise stimulus is also given in appendix A.

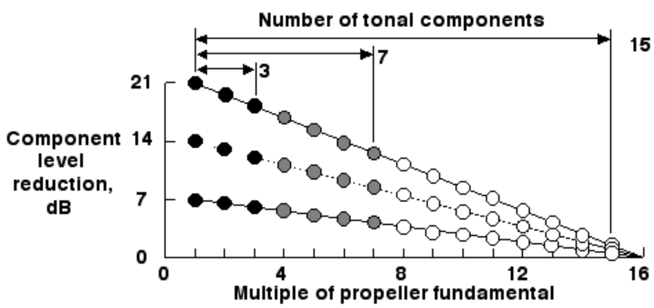


Figure 3. Number and reductions in level of contolled tonal components.

Acoustic analysis. A computer workstation and commercially available software were used to determine the acoustic characteristics, in terms of conventional and SQ noise metrics, of the stimuli used in both tests. Table 1 presents a summary of results from these analyses in terms of unweighted sound pressure level (SPL), A-weighted and D-weighted sound levels (AL and DL, ref.14), and two variations of loudness levels (LL_Z and LL_{MG}). LL_Z is normally referred to as the Zwicker Loudness Level and has been incorporated into an international standard (ref. 6). LL_{MG} is a more recent development by Moore and Glasberg (ref. 13) to more accurately reflect the loudness of partially masked sounds and changes in loudness with level and frequency. In table 1, levels are presented for the original propeller airplane interior sounds and for the ANC sounds with the greatest reduction in number and level of the tones. For the conventional jet airplane interior sound, only a single level of presentation is presented. A full listing of levels for all propeller airplane stimuli are given in appendix B. Sounds presented at more than one level, such as the jet airplane interior sound and the original uncontrolled sounds, which were used as comparison and reference sounds, are represented in the table by only a single level. The levels presented in table 1 and appendix B were based on the signals presented over the headphones to each ear of the test subjects as measured with the acoustic mannequin, computer workstation, and commercial analysis software, except for LL_{MG} which was computed from one third octave band levels calculated from the computer sound file. For the two loudness metrics, the loudness in sones was summed across left and right ears, and converted to phons. These values are presented in the table as combined sones.

Table 1. Measured and Calculated Levels of Original Propeller Airplane Interior Sounds and Sounds with the Greatest Reduction of Harmonic Tone Components

Airplane	Number of harmonics reduced	Reduction in fundamental tone level, dB	SPL, dB		AL, dB		DL, dB	
			Left ear	Right ear	Left ear	Right ear	Left ear	Right ear
1	0	0	96.3	97.4	84.3	84.4	91.1	91.8
	15	21	91.0	91.5	82.1	82.4	88.4	89.0
2	0	0	96.9	95.2	81.6	77.2	90.2	87.4
	15	21	81.3	78.1	71.4	66.3	77.1	73.1
3	0	0	92.5	95.8	78.7	82.9	86.2	90.5
	15	21	89.6	90.1	73.8	75.5	81.9	83.4
4	0	0	100.4	98.4	80.4	77.8	90.9	88.8
	15	21	88.7	85.9	75.6	72.1	83.1	79.9
5	0	0	91.5	90.7	78.7	82.3	86.8	89.1
	15	21	84.5	86.2	76.1	80.5	83.5	87.4
Jet	-		89.2	88.3	82.6	81.1	87.7	86.5

Airplane	Number of harmonics reduced	Reduction in fundamental tone level, dB	LL_Z, phon			LL_{MG}, phon		
			Left ear	Right ear	Combined Sones	Left ear	Right ear	Combined Sones
1	0	0	101.9	102.4	112.2	102.0	102.6	110.2
	15	21	100.2	100.8	110.5	100.6	101.0	109.0
2	0	0	98.1	95.1	106.7	98.7	95.4	105.3
	15	21	90.1	85.2	97.9	93.0	89.4	99.8
3	0	0	95.4	97.9	106.7	97.1	99.3	106.4
	15	21	92.3	93.4	102.9	94.7	95.8	103.7
4	0	0	97.2	95.6	106.5	99.4	98.2	107.0
	15	21	92.6	90.8	101.7	94.9	94.0	102.9
5	0	0	97.7	100.0	108.9	98.4	100.5	107.7
	15	21	95.2	98.5	107.0	96.8	99.3	106.3
Jet	-	-	97.9	97.3	107.6	98.9	98.5	106.3

Experiment Design

Preference test. The first test was conducted using the paired comparison method. To determine the subjective effectiveness of the ANC treatments relative to changes in measured noise characteristics and levels for each aircraft type, the noise stimulus with the original spectrum was used as the standard or reference stimulus for the modified (target) stimuli. The presentation levels used for the target stimuli were those that would have occurred in flight had the hypothetical ANC treatments been achieved in practice. For each target stimulus, the loudness level, LL_Z, was determined. Each target stimulus was compared with the reference stimulus presented at levels -6, -2, +2 and +6 dB relative to this level.Similarly, to determine the subjective differences in level between the original stimuli for all aircraft types, the interior noise of the commercial jet aircraft was used as a reference stimulus for comparison with the original stimulus of each propeller aircraft type, when presented at its recorded level. A total of 200 pairs of sounds was required to cover all conditions. The pairs were randomly assigned to 4 sessions of 50 pairs. An additional set of 4 sessions was prepared which had the order of pairs in the sessions and the order of stimuli within each pair reversed to provide balance in presentation order of pairs within sessions and A-B and B-A orders of presentation for the target and reference stimuli. Time between stimuli in a pair was one second and time between pairs was 5 seconds. Subjects were tested in groups of five, four groups exposed to the four original sessions and four groups exposed to the reverse order sessions. The order of presentation of the sessions was balanced across the groups. The subjects were asked to *"indicate which member of the pair you preferred"* by circling A or B on a response score sheet. An example score sheet is given in appendix C.

Noisiness test. The second test was conducted using the numerical category scaling method. The test subjects made noisiness judgments on the same set of ANC and original stimuli presented at the same levels as the target stimuli in the first test, a complete repeat of the set at those levels and complete repeats presented at three additional loudness levels. In addition, the same jet aircraft interior noise as in the first test was presented at 10 levels over a range of loudness levels slightly exceeding the range of loudness levels of all the propeller aircraft interior noises. These 260 stimuli were randomly assigned to four sessions of 65 stimuli each. An additional set of 4 sessions was prepared which had the order of stimuli in the sessions reversed to provide balance in presentation order. As in the first test, subjects were tested in groups of five, four groups exposed to the four original sessions and four groups exposed to the reverse order sessions. The order of presentation of the sessions was also balanced across the groups. The judgments were made on a graphical scale with equal intervals labeled 0 to 10. The subjects were asked to *"indicate how noisy you judge the sounds to be by placing a slash mark along the scale"*. Arrows on the scale indicated the *"Less noisy"* and *"More noisy"* directions of the scales. An example score sheet is given in appendix D.

Test Subjects

Eighty test subjects, 40 for each experiment, were randomly selected from a pool of local residents with a wide range of socioeconomic backgrounds, and were paid to participate in the experiments. All subjects were given audiograms prior to testing to verify normal hearing, i.e. within 40dB of ISO threshold values.

Preference Test. Fourteen of the subjects were males, age range 18-65 years with a mean age of 33.1 years. Twenty-six were females, age range 18-65 with a mean age of 33.9 years. Thirty-three of the subjects had flown in airplanes and 17 had flown in propeller airplanes within the previous 10 years.

Noisiness test. Sixteen of the subjects were males, age range 18-66 years with a mean age of 30.2 years. Twenty-four were females, age range 19-72 with a mean age of 47.5 years. Only one of the females and 4 of the males had participated in the preference test. Thirty-six of the subjects had flown in airplanes and 18 had flown in propeller airplanes within the previous 10 years.

Test Procedures

Very similar procedures were used for both tests. Upon arrival at the laboratory a group of test subjects was escorted into the aircraft interior acoustic simulator and seated. The test conductor then gave each subject a clipboard with a set of general instructions and information, consent forms, specific instructions and scoring sheets. After reading the general instructions and information, the safety features and procedures of the simulator were described and the subjects were requested to sign the voluntary consent form. The test conductor then described the specific test procedures and method of responding on the scoring sheets, and helped the subjects in placing and adjusting the headphones for a good fit. The subjects heard a sample of five of the sounds used in the test and then responded to a short practice test of either six pair of sounds for the preference test or six individual sounds for the noisiness judgment test. After the practice session the test conductor again asked if there were any questions and then left the subjects to begin the first session. Each session lasted 10 to 12 minutes. To help the subjects keep track of the stimuli presented, voice cues were given over the headphones before the presentation of the first and each succeeding fifth pair of stimuli (preference test) or individual stimulus (noisiness test). Complete instructions and scoring sheets are given in appendix C for the preference test and in appendix D for the noisiness test.

Subjective Response Conversions

In the following sections the procedures used to convert the preference and noisiness judgements into an ordinal scale with decibel like properties are described. The regression analyses used for the conversions and all other statistical analyses for this report were conducted using the commercially available statistical analysis package, SPSS for Windows™.

Preference judgments: The paired comparison responses were converted to percentage of subjects preferring the target ANC stimuli (modified spectra) to the comparison (original unfiltered) stimuli. Equivalent subjective levels (ESL), for each aircraft type and ANC condition and for each metric, were determined by calculating the levels at which 50% preferred the ANC stimulus. This was accomplished using logit regressions of the percent preferring the ANC stimulus on the measured levels of the comparison stimuli as indicated in figure 4. For one target stimulus, each of the four data points indicates the percentage of judgements preferring the target (ANC) stimulus over the comparison (original spectrum) stimulus when the comparison stimulus was presented at one of the four loudness levels. A logit regression analysis was conducted for the set of data for each aircraft type and ANC condition, for each noise metric considered. From these analyses the level of the comparison was calculated for which

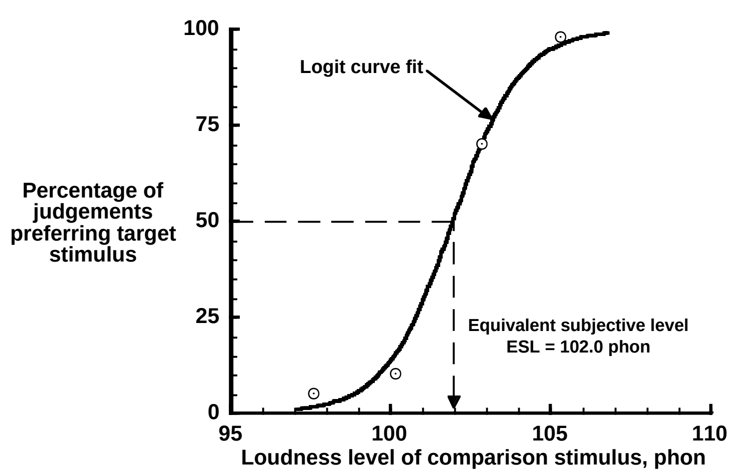


Figure 4. Use of logit regression analysis to convert preference judgements to equivalent subjective levels (ESL).

there was equal likelihood that the ANC stimulus or the comparison would be preferred. This level was considered to be the equivalent subjective level, ESL, of each ANC stimulus. Since each ANC stimulus was compared only with its original unmodified sound, it was not possible to compare the ESL values directly for the different aircraft. However similar analyses were made for the data sets where the original stimuli were compared to the conventional jet aircraft interior sound. These ESL values provided a means of directly comparing the original sounds of the different aircraft, and an indirect means of comparing all sound as will be described in a later section.

Noisiness judgments: In the second test, the mean of the judgements over subjects and repeats for each stimulus was calculated. The mean noisiness judgements of the ANC stimuli were converted to ESL values based on the mean noisiness judgements of the conventional jet aircraft stimuli. For each noise metric, a least-squares third order polynomial regression was made of the measured levels of the ten jet stimuli on the mean noisiness judgements of the jet stimuli. An example for Zwicker loudness level is shown in figure 5. For each ANC stimulus, the mean noisiness judgement was transformed into an ESL value using the regression equation found in the polynomial fit. In the example shown in figure 5, a mean noisiness judgement of 5.8 corresponds to an ESL of 96.5 phons. Thus an ANC stimulus that received a mean noisiness judgement of 5.8 was deemed to have a perceived noisiness equivalent to the jet aircraft interior sound at an LL_Z of 96.5 phons.

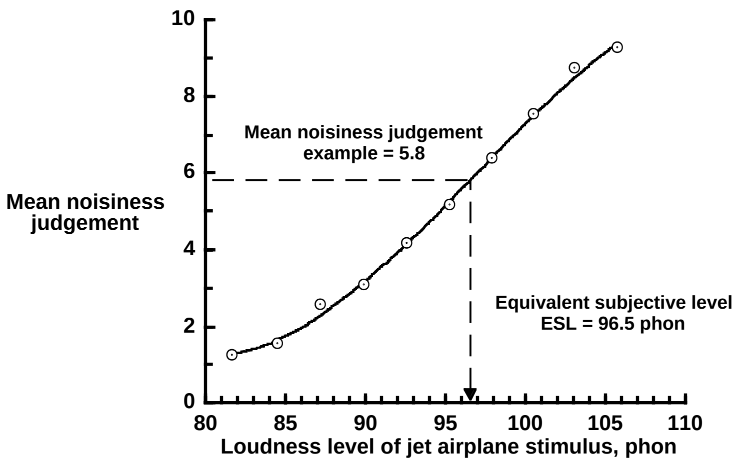


Figure 5. Use of polynomial regression analysis of loudness on mean noisiness for the jet aircraft interior sounds to determine equivalent subjective levels for the ANC sounds.

Results and Discussion

Preference Test

Since the primary objective of the study was to determine the benefits or subjective reductions in interior noise afforded by the hypothetical reductions in propeller tones, it was necessary to examine the differences between the ESL of each ANC sound and the ESL of the original or unmodified sound. The ESL of the original sound is assumed to be the same as its measured level. For a given modified stimulus the difference in equivalent subjective level is given by

$$\Delta ESL = ESL(\text{ANC sound}) - ESL(\text{original sound}) \quad (1)$$

and is dependent on which metric is used to describe the ESLs. Linear regression analyses of ΔESL were conducted on the difference between the measured levels of the modified (ANC) stimuli and the original stimuli for several different sound level metrics. Results of these analyses are given in table 2 for the metrics: unweighted sound pressure level (SPL), A-weighted sound level (AL), D-weighted sound level (LD), loudness level using the Zwicker calculation method (LL_Z) (ref. 6), and loudness level as more recently proposed in reference 15 (LL_{MG}). These analyses also considered four methods of combining the levels presented to the two ears of the subjects, i.e., binaural summation.

The arithmetic average method is the simple average of the dB or phon levels presented to the two ears

$$L_S(\text{average}) = \frac{1}{2}\left(L_L + L_R\right) \qquad (2)$$

where L_S is the combined level, L_L is the level presented to the left ear, and L_R is the level presented to the right ear.

The energy summation method adds the relative acoustic power or energy presented to the two ears and converts the resultant to a sound level by the relationship

$$L_S(\text{energy}) = 10\log_{10}\left(10^{L_L/10} + 10^{L_R/10}\right) \qquad (3)$$

The pressure summation method adds the weighted acoustic pressure presented to the two ears and converts the resultant to a sound level.

$$L_S(\text{pressure}) = 20\log_{10}\left(10^{L_L/20} + 10^{L_R/20}\right) \qquad (4)$$

The loudness summation method adds the loudness, in sones, at the two ears and converts the resultant to a loudness level in phons. For LL_Z, the conversion formula is

$$L_S(\text{loudness}) = 40 + 10\log_2\left(l_L + l_R\right) \qquad (5)$$

where l_L and l_R are the loudness of the sound in sones presented to the left and right ears, respectively. For LL_{MG},, the conversion is performed from a table look-up procedure. Only the two loudness level metrics could be combined in this manner.

Table 2 Coefficients of Determination (Square Of Correlation Coefficients) for ΔESL and Measured Level for Various Metrics; Preference Judgements

Binaural summation method	Noise metric				
	SPL, dB	AL, dB	DL, dB	LL_Z, phon	LL_{MG}, phon
Arithmetic average	0.654	0.878	0.838	0.893	0.864
Energy summation	.671	.858	.846	.898	.864
Pressure summation	.663	.869	.843	.896	.865
Loudness summation (Combined Sones)				.895	.869

The analyses in table 2 indicated that differences in equivalent subjective level were slightly more correlated with differences in measured LL_Z than with changes in AL or any of the other metrics considered. Because of this performance and since this method of loudness prediction is calculated by an international standard, the results in the following sections will be described primarily in terms of ΔLL_Z. The arithmetic average method was found to provide slightly lower correlation than the other summation methods for most metrics. Very little difference in correlation was found for the other summation methods. This result is not unexpected since the sounds presented to the two ears differed by only 1 to 2 dB, except for A/C 2. The loudness summation method is generally accepted as being appropriate to account for binaural loudness summation (ref. 13). However, there is some evidence that binaural loudness summation, particularly at high sound levels, may be less than complete, i.e., the loudness of the same sound presented at equal levels to both ears appears somewhat less than twice as loud as when presented to either ear alone. Such a small effect would not be expected to significantly affect the results of the present study. Therefore the results in the following section will be described in terms of loudness summation and will be designated in tables as *combined sones.*

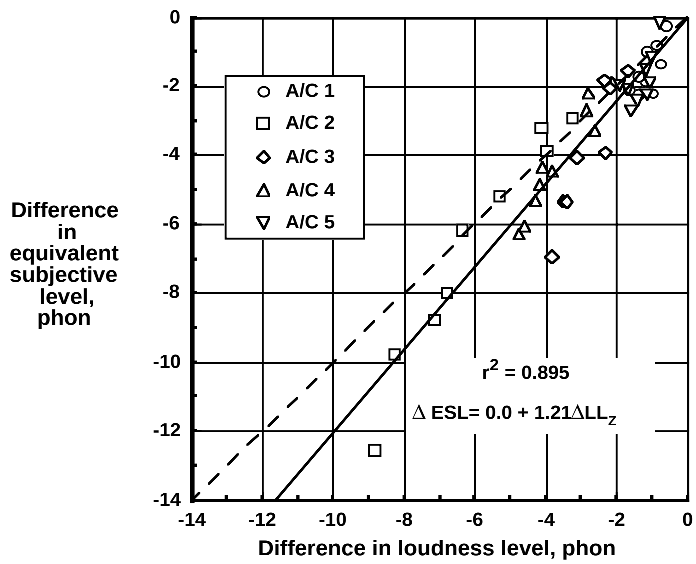


Figure 6. Reductions, based on preference judgments, in equivalent subjective levels of the propeller aircraft interior sounds provided by the hypothetical ANC conditions as compared with measured loudness level reductions.

Effects of ANC conditions. The changes in equivalent subjective level and in LL_Z with changes in harmonic content associated with the hypothetical ANC conditions are given in table 3. There is a generally consistent trend for an increase in preference (decrease in ΔESL) with an increase in attenuation of the level of the tones and with an increase in the number of harmonics reduced. The effectiveness of the reductions in tones was greatest for A/C 2 and least for A/C 1 and A/C 5. These results are not unexpected since it is very apparent from the figures in appendix A that the low frequency tones dominate the A-weighted spectrum of A/C 2 but are comparable to components in the 400 Hz to 1000 Hz range for A/C 5.

Correlation of ANC effects with objective measures. Differences in equivalent subjective level associated with the differences in loudness level, LL_Z, for the hypothetical ANC conditions are shown in figure 6. The maximum reduction in LL_Z for A/C 1 was 1.8 phon; for A/C 5, 1.9 phon; for A/C 4, 4.8 phon; for A/C 3, 3.8 phon; and for A/C 2, 8.8 phon. While the equivalent subjective level differences for A/C 1 and A/C 5 are comparable to the measured differences in loudness level, the equivalent subjective differences for the other aircraft and particularly for A/C 2 were somewhat greater than the measured differences in loudness level. This is reflected by the slope determined in a linear least-squares regression analysis of the differences in ESL on measured differences in LL_Z. This analysis yielded a slope of 1.2 phon of subjective change per phon of change in loudness level across all conditions and aircraft.

Table 3. Changes in Equivalent Subjective Levels with Reduction in Harmonic Tone Content: Preference Judgments

Airplane	Reduction in fundamental tone level, dB	Number of harmonics reduced					
		3		7		15	
		ΔLL_Z, dB	ΔESL, dB	ΔLL_Z, dB	ΔESL, dB	ΔLL_Z, dB	ΔESL, dB
1	7	-0.6	-0.3	-0.8	-1.4	-0.9	-0.8
	14	-1.0	-2.2	-1.2	-1.9	-1.4	-2.2
	21	-1.1	-1.0	-1.4	-1.7	-1.7	-2.1
2	7	-3.3	-2.9	-4.0	-3.9	-4.1	-3.2
	14	-5.3	-5.2	-6.8	-8.0	-7.2	-8.8
	21	-6.4	-6.2	-8.3	-9.8	-8.8	-12.6
3	7	-1.7	-1.5	-2.2	-2.1	-2.4	-1.8
	14	-2.2	-1.9	-3.1	-4.1	-3.4	-5.3
	21	-2.3	-3.9	-3.5	-5.3	-3.8	-6.9
4	7	-2.6	-3.3	-2.8	-2.2	-2.9	-2.7
	14	-3.8	-4.5	-4.1	-4.3	-4.2	-4.8
	21	-4.3	-5.3	-4.6	-6.1	-4.8	-6.3
5	7	-0.8	-0.2	-1.0	-1.2	-1.2	-1.5
	14	-1.1	-1.9	-1.4	-2.4	-1.7	-2.1
	21	-1.2	-2.2	-1.6	-2.7	-1.9	-2.0

Correlation of equivalent subjective level with objective measures. The regression analysis in the previous section provided information only on the prediction of the effect of changes in the sounds from their unmodified state and not on the ability to predict response to the individual stimuli across the different aircraft. Based on the paired comparisons of the unmodified propeller aircraft interior noise stimuli with the commercial jet aircraft interior noise stimulus, it was found that the response to the different propeller aircraft interior sounds were underestimated by LL_Z by 0.6 phon to 4.5 phon relative to the jet interior sound. Corrections for these under-estimations were made to the ESL values for each modified propeller aircraft stimulus so that an overall prediction ability could be assessed.

Table 4. Coefficients of Determination (Square Of Correlation Coefficients) for CESL and Measured Level for Various Metrics; Preference Judgements

Binaural summation method	Noise metric				
	SPL, dB	AL, dB	DL, dB	LL_Z, phon	LL_{MG}, phon
Arithmetic average	0.540	0.829	0.885	0.819	0.853
Energy summation	.534	.820	.884	.801	.848
Pressure summation	.537	.825	.885	.810	.851
Loudness summation (Combined Sones)				.814	.858

Table 4 presents the results of linear regression analyses of the corrected equivalent subjective level, CESL, on measured sound level for the different metrics and binaural summation methods. Some differences in results of the analyses for CESL are noted, as compared to the results in table 2 for changes in subjective response with reductions in propeller tones. The highest correlations were found for DL and both LL_{MG} and LA were more highly correlated with CESL than was LL_Z. However, except for DL, the correlations for all metrics were less than those in table 2. The relationship and scatter for all corrected equivalent subjective levels, CESL, with measured LL_Z are shown in figure 7. Except for A/C 4, loudness level appears to predict the subjective loudness for all of the different propeller aircraft interior sounds with reasonable accuracy. The deviations from the dashed line, which represented perfect prediction, are generally less than 2 phon for all aircraft except A/C 4.

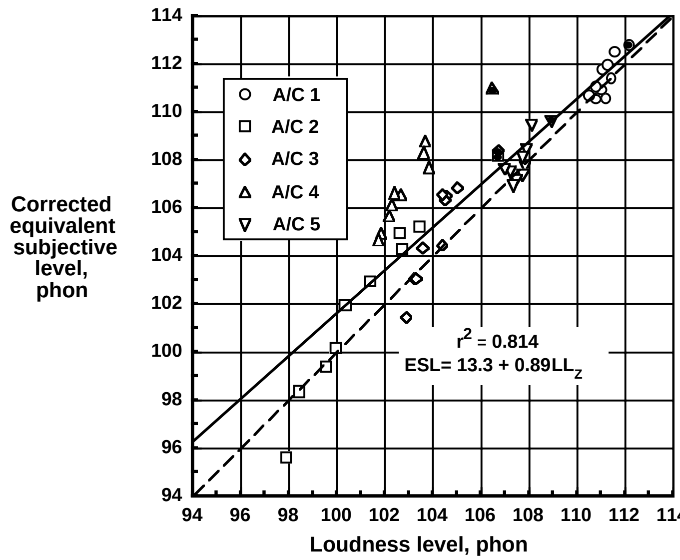


Figure 7. Correlation between corrected equivalent subjective level and measured loudness level. Equivalent subjective levels have been corrected based on differences between measured levels of the unmodified propeller aircraft interior sounds and conventional jet interior sounds when they were equally preferred. Filled sybols are for unmodified sounds.

Noisiness Test

It was anticipated that the inclusion of some of the other sound quality attributes of the stimuli, which will be considered later in this report, could reduce scatter and provide guidance on the prediction of subjective reactions to measured or predicted sound characteristics in a propeller airplane. However, since the correction factors were based solely on judgements of the unmodified sounds relative to the jet sounds, it is possible that one relatively large random error could bias the corrected equivalent subjective levels for all of the modified sounds of that aircraft type. Because of this potential bias, it was decided to run an additional test in which the equivalent subjective levels were determined directly. The use of the paired comparison method presented two options for using preference between sounds as the subjective correlate. Each sound could be compared with different levels of a single reference sound or each sound could be compared with all of the unmodified sounds. It was thought that using a single reference sound, particularly the jet aircraft interior sound, could overemphasize the tonal quality of the propeller aircraft interior sounds. As a consequence, the subjects could be biased towards less tone being preferable regardless of other characteristics of the propeller airplane interior sounds. The latter option was thought not to introduce a bias but would require many more comparisons that could introduce significant test subject fatigue or loss of diligence. The use of category scaling was thought to offer advantages over the options for pair comparisons in that testing time would not be increased and emphasis on tone level would be minimized. It was not possible to use preference as the subjective scale, since it is a comparative descriptor related to different conditions rather than one that could easily be used to describe a single sound. It was hoped that the descriptor noisiness, which has frequently been used in subjective tests for single event aircraft community noises, would elicit an equivalent response due to the unwanted character of the interior sounds as would preference. That is, a sound that was judged preferable to another sound would also be judged less noisy.

The subjective results were examined in much the same way for the noisiness test as was done for the preference test. The exception was that all of the ESL and CESL values were determined by comparing the noisiness judgements of the propeller aircraft interior sounds against the relationship between judgements and presented sound levels of the jet aircraft interior sound. This procedure was described in the previous section on subjective response conversion.

Effects of ANC condition. Table 5 presents results of linear least-squares regression analyses of the difference in equivalent subjective level, ΔESL, on the difference in measured sound level between the original propeller aircraft interior sounds and the ANC sounds for various metrics and binaural summation methods. The differences for the two loudness measures, LL_Z and LL_{MG}, were found to be slightly more correlated with differences in equivalent subjective levels than were the differences for the simple frequency weighted measures, AL and DL, and considerably more correlated than the differences for the unweighted measure, SPL. In contrast to the results of the preference test, ΔLL_{MG} was found to be slightly more correlated than ΔLL_Z. Little difference in results was found for the different binaural summation methods. Since differences between the loudness calculation procedures and binaural summation methods are so small and since LL_Z is an international standard, further results will be presented primarily in terms of LL_Z using the loudness summation method.

Table 5. Coefficients of Determination (Square Of Correlation Coefficients) for ΔESL and Measured Level for Various Metrics; Noisiness Judgements

Binaural summation method	Noise metric				
	SPL, dB	AL, dB	DL, dB	LL_Z, phon	LL_{MG}, phon
Arithmetic average	0.612	0.864	0.831	0.859	0.878
Energy summation	.630	.853	.846	.881	.883
Pressure summation	.621	.860	.840	.871	.881
Loudness summation (Combined Sones)				.867	.895

The changes in equivalent subjective level and changes in LL_Z with changes in harmonic content associated with the hypothetical ANC conditions for the noisiness test are given in table 6. There is a generally consistent trend for a decrease in ΔESL with an increase in attenuation of the level of the tones and with an increase in the number of harmonics reduced. The effectiveness of the reductions in tones was greatest for A/C 2 and least for A/C 1 and A/C 5. The reductions in equivalent subjective level based on noisiness are generally about the same or slightly less than the reductions in loudness level for the different ANC conditions. This effect is examined more closely in the next section.

Correlation of ANC effects with objective measures. Based on the noisiness judgements, the differences in equivalent subjective level, associated with ΔLL_Z for the hypothetical ANC conditions are shown in figure 8. The maximum reduction in ΔLL_Z for A/C 1 was 1.7 phon; for A/C 5, 1.9 phon; for A/C 4, 4.8 phon; for A/C 3, 3.8 phon; and for A/C 2, 8.8 phon. While the equivalent subjective level differences for A/C 3, A/C 4 and A/C 5 are comparable to the measured differences in loudness, the equivalent subjective differences for A/C 1 and particularly for A/C 2 were somewhat less than the measured changes in loudness level. A linear least-squares regression analysis of the differences in ΔESL on ΔLL_Z yielded a slope of 0.78 phon of subjective change per phon of change in measured loudness across all conditions and aircraft. The deviation from unity slope resulted primarily from the results for A/C 2.

Table 6. Changes in Equivalent Subjective Levels with Reduction in Harmonic Tone Content: Noisiness Judgments

Airplane	Reduction in fundamental tone level, dB	Number of harmonics reduced					
		3		7		15	
		ΔLL_Z, dB	ΔESL, dB	ΔLL_Z, dB	ΔESL, dB	ΔLL_Z, dB	ΔESL, dB
1	7	-0.8	-1.0	-0.8	-0.6	-1.1	-1.2
	14	-1.2	-0.9	-1.2	-1.1	-1.6	-1.0
	21	-1.3	-0.5	-1.4	-1.0	-1.8	-1.0
2	7	-3.3	-2.4	-4.0	-2.6	-4.1	-3.3
	14	-5.3	-2.9	-6.8	-4.9	-7.2	-5.5
	21	-6.4	-4.2	-8.3	-7.5	-8.8	-7.4
3	7	-1.8	-2.0	-2.2	-2.3	-2.4	-3.2
	14	-2.3	-2.4	-3.1	-4.1	-3.5	-3.6
	21	-2.5	-2.5	-3.5	-3.9	-3.9	-4.1
4	7	-2.6	-2.3	-2.8	-3.1	-2.8	-3.2
	14	-3.8	-4.4	-4.1	-3.6	-4.2	-4.1
	21	-4.3	-4.0	-4.6	-4.9	-4.7	-4.5
5	7	-0.8	-1.0	-1.0	-1.1	-1.2	-1.3
	14	-1.1	-1.4	-1.4	-1.1	-1.8	-2.1
	21	-1.2	-1.7	-1.6	-2.1	-2.0	-1.6

Correlation of equivalent subjective level with objective measures. Table 7 presents the results of linear regression analyses, based on the noisiness judgements, of the equivalent subjective level on measured sound level for the different metrics and binaural summation methods. Some differences in results of these analyses, as compared to the results in table 5 for ΔESL, are noted. The correlations for all metrics except SPL were higher for ESL than for ΔESL; the correlation for SPL was much less for ESL than for ΔESL. As was found for ΔESL, the highest correlations were for LL_{MG}, and both LL_Z and LA were more highly correlated with ESL than was DL. The correlation between ESL and any of the metrics was slightly greater for the arithmetic average binaural summation than for the other summation methods. Again, the differences between the two loudness metrics and between the binaural summation methods are small enough to be of little practical significance. Therefore only LL_Z and the loudness summation procedure will be considered for further discussion of results.

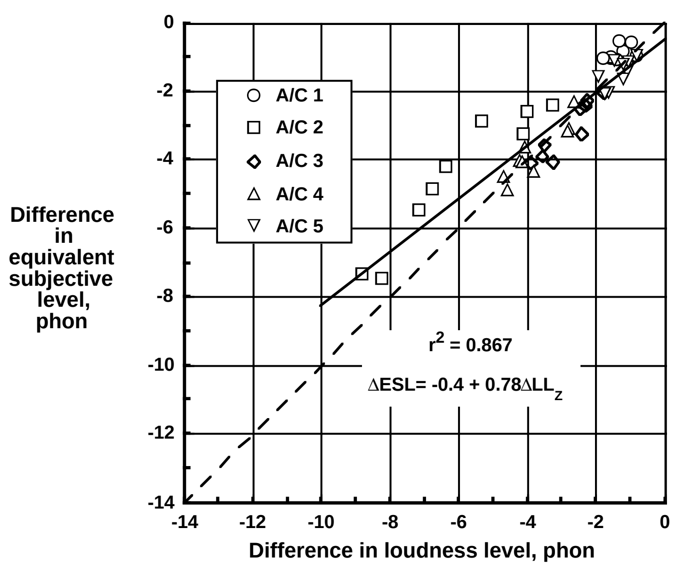


Figure 8. Reductions, based on noisiness judgments, in equivalent subjective levels of the propeller aircraft interior sounds provided by the hypothetical ANC conditions as compared with measured loudness level reductions.

Table 7. Coefficients of Determination (Square Of Correlation Coefficients) for ESL and Measured Level for Various Metrics; Noisiness Judgements

Binaural summation method	Noise metric				
	SPL, dB	AL, dB	DL, dB	LL_Z, phon	LL_{MG}, phon
Arithmetic average	0.376	0.953	0.892	0.966	0.981
Energy summation	.362	.946	.888	.956	.978
Pressure summation	.369	.950	.890	.961	.980
Loudness summation (Combined Sones)				.963	.982

The relationship and scatter for the equivalent subjective levels, ESL, with measured loudness, LL_Z, based on the noisiness judgements, are shown in figure 9. The explained variance (r^2) of the regression analysis is 0.96 and loudness level appears to predict the subjective loudness of all of the different propeller aircraft interior sounds with reasonable accuracy. The deviations from the regression line and from the unity slope (dashed) line, are generally less than 2 phon for all aircraft.

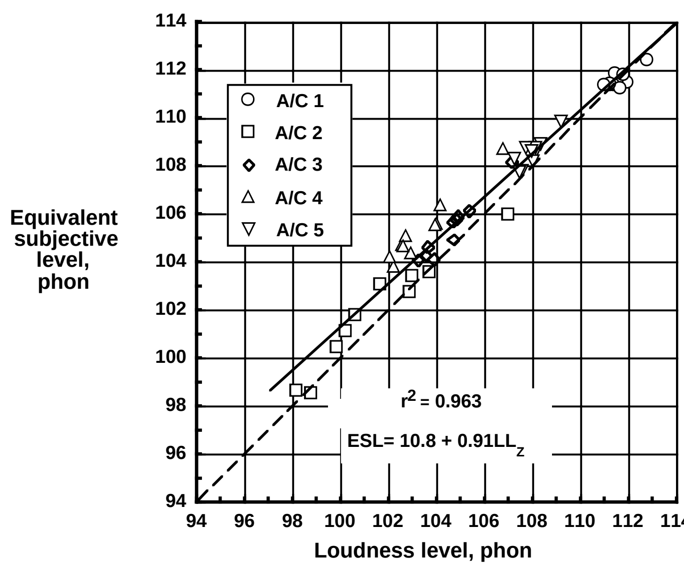


Figure 9. Correlation between equivalent subjective levels, based on noisiness judgements and measured loudness levels.

Comparison of Preference and Noisiness Results

Examination of the results of the two different tests indicated many consistencies but also several inconsistencies. The inconsistencies could either be due to the different test methodologies, i.e., pair comparisons versus numerical category scaling, or could be due to differences in response based on preference or noisiness. The following two sections will address the inconsistencies between the two tests in more detail.

Relative preference and noisiness of original sounds. In the first test the only way to compare the relative difference in preference for the interior sounds of the different aircraft types was indirectly through comparisons of the unmodified propeller aircraft interior sounds with the jet aircraft interior sound. In a previous section it was noted that the preference responses to the different propeller aircraft interior sounds were underestimated by LL_Z by 0.6 phon to 4.5 phon relative to the jet interior sound. A similar comparison was made based on the results of noisiness test. A comparison of the results from the

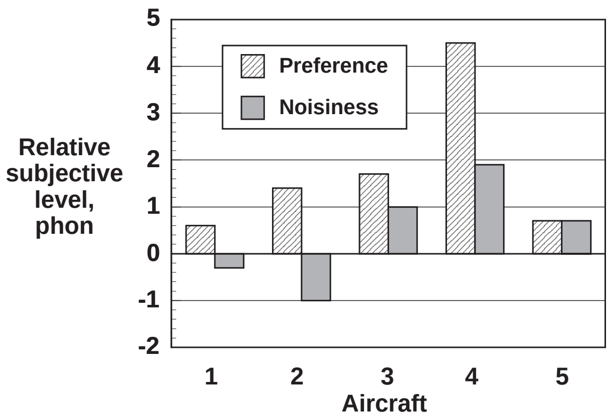


Figure 10. Subjective level of original airplane interior sounds relative to Zwicker loudness level, LL_Z.

two tests is shown in figure 10. In the preference test, all of the original propeller interior sounds were judged less preferable than the jet interior sound when presented at equal values of LL_Z. In the noisiness test, the interior sounds of aircraft 1 and 2 were judged slightly less noisy than the jet interior sound for equal LL_Z. While these relatively small differences could be due to random error, the general trends with aircraft type indicated in figure 10 are also reflected in figure 9 for the original and modified sounds. The ESLs for A/C 2 generally lie below the regression line. Similarly the ESLs for A/C 1 generally lie below the line but the effect is not as pronounced. The ESLs in figure 9 for A/C 4, on the other hand, all lie somewhat above the regression line. However, the subjects in the preference test indicated that A/C 4 was much less preferable than the other sounds. Thus it appears that the subjects are indicating that preference may not be adequately represented by noisiness judgements.

Effects of ANC conditions. Comparisons of the results for the two tests related to the effects of the hypothetical ANC conditions for each of the different aircraft types are shown in figure 11. For both tests, the previously mentioned general trends for reduction in equivalent subjective level with reduction in the fundamental tone level, and with an increase in number of tones reduced, are readily apparent. The smallest changes with the ANC conditions, for both the preference and noisiness test, occurred for A/C 1 and A/C 5. Reduction in tone level had a slightly greater effect on the preference judgements than on the noisiness judgements. The number of tones reduced appears to have very small effects on either type of judgement for these two airplanes. Reduction in tone level had larger effects on noisiness and preference for A/C 3 and A/C 4 than for A/C 1 and A/C 5. The magnitude of these effects was about the same for A/C 3 and A/C 4. However, the number of tones reduced had a very small effect on preference for A/C 4 but a larger effect on A/C 3. Reduction in the

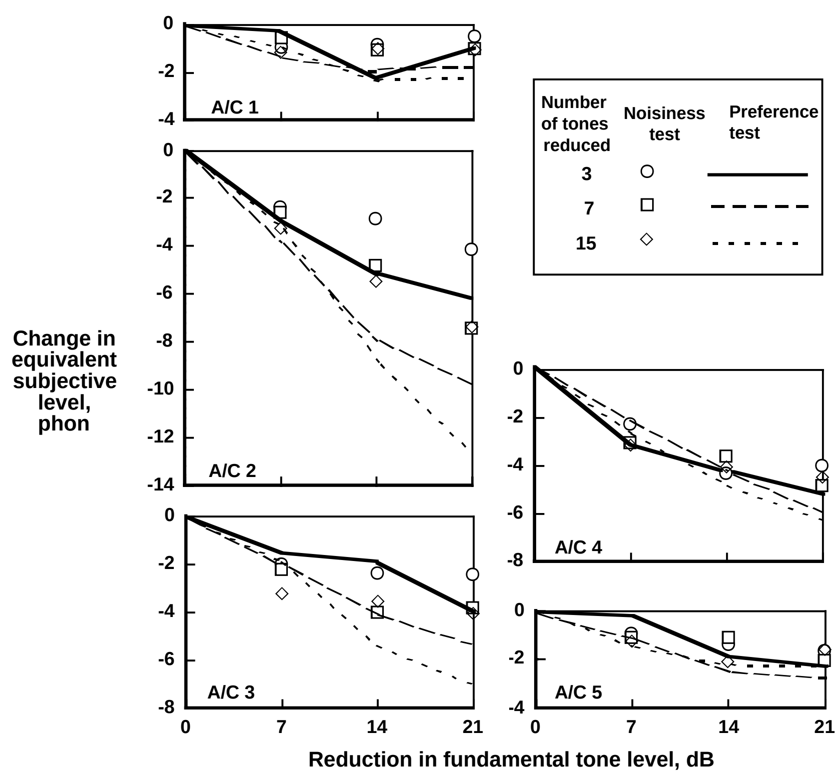


Figure 11. Effects of hypothetical ANC conditions on preference and noisiness judgements.

level of tones, and the number of tones reduced, had more effect for A/C 2 than for any of the other aircraft, particularly in the preference judgements. Thus the subjects' preference for the hypothetical ANC conditions tended to be greater than indicated by either the measured loudness or subjective judgements of noisiness.

Applicability of Sound Quality Measures

A number of different metrics, in addition to loudness, have been developed (refs. 10-13) to quantify some of the characteristics of sounds that have been shown to be related to subjective response and that may help predict preference for some sounds over others. The fluctuation strength, roughness, sharpness and tonality of the original and ANC modified propeller airplane and jet airplane interior sounds were calculated (table B3, appendix B), and their relevance to the subjective response to the sounds is examined in the following sections. Models which considered inclusion of these variable as corrections to simple loudness models are also examined.

Correlation between SQ measures. Ideally a set of metrics for quantifying characteristics of sounds related to human response should be independent or orthogonal. Pearson Product-Moment correlation coefficients and level of significance for the sound quality metrics for the particular set of sounds used in the present experiments are given in table 8. The interrelationships between these metrics are also

Table 8. Correlation between Sound Quality Metrics.

	Fluctuation Strength (FS)	Roughness (R)	Sharpness (S)	Tonality (T)
Loudness Level (LL_Z)	-0.181	0.311*	0.679**	-0.300*
Fluctuation Strength (FS)		.028	-.192	.084
Roughness (R)			.539**	-.850**
Sharpness (S)				-.683**

* indicates significant at the 5% level. ** indicates significant at the 1% level

indicated in the scatterplots in figure 12. For each scatterplot, the abscissa is the metric identified by the label in that column and the ordinate is the metric identified by the label in the row. From the first row, it can be seen that loudness has a weak negative relationship with fluctuation strength. Although the correlation coefficient between loudness and fluctuation strength for all data combined (table 8) is not significant, based on the groupings in figure 12 and the data in tables B2 and B3, appendix B, there does seem to be a negative relationship within each aircraft type. Based on the correlation coefficient, loudness is positively related to roughness. Examination of the scatter plot confirms this trend except for A/C 2 and A/C 4 (see tables B2 and B3, Appendix B). For these two aircraft a strong negative relationship is indicated. Although the correlation between loudness and tonality is negative and significant, the scatterplot and tables B2 and B3 indicate that within each aircraft type, the relationship between loudness and tonality is positive. From the second row in figure 12, fluctuation strength does not appear to be related to roughness but does have a weak positive relation ship with sharpness and a weak negative relationship with tonality. The correlation coefficients in table 8, however, are all not significant and the trends again are only within aircraft types. From the third and fourth rows, respectively, roughness is strongly but negatively related to tonality and there appears to be a strong negative relationship between sharpness and tonality. These trends are confirmed by highly significant correlation coefficients. Also from the third row a significant positive relationship between roughness and sharpness is indicated. Based on the data in table B3, A/C 1 and A/C 5 form one group and A/C 2, A/C 3, and A/C 4 form another that can be distinguished by sharpness. This is because A/C 1 and A/C 5 have relatively more broadband high frequency content than do the other aircraft interior sounds and sharpness is related to the high frequency content.

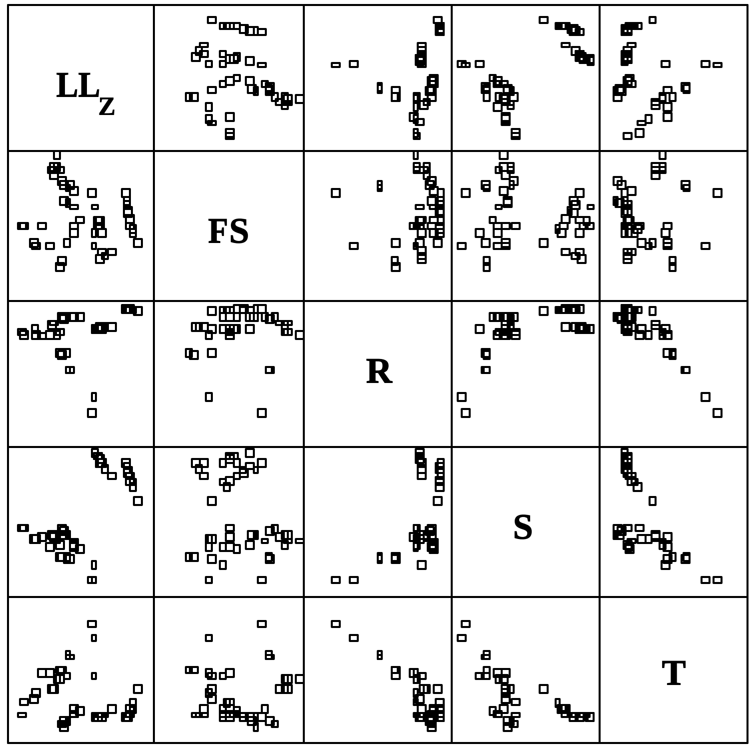


Figure 12. Scatter plots of interrelationship between sound quality metrics.

Multiple regression models. Step-wise linear multiple regression analyses were conducted on the preference and noisiness data for both equivalent subjective level, ESL, and difference in equivalent subjective level, ΔESL. Both loudness metrics, LL_Z and LL_{MG} were considered separately with fluctuation strength, FS; roughness, R; sharpness, S; and tonality, T, as additional independent variables. The coefficients for the linear multiple correlation models developed by the analyses are presented in table 9. None of the analyses indicated any significant improvement by the inclusion of the roughness or sharpness sound quality metrics in the models.

Difference in preference with ANC condition. Differences in equivalent subjective level, ΔESL, for the effects of the ANC conditions were generally predicted better by models using ΔLL_Z than ΔLL_{MG}. The inclusion of a positive correction for tonality, T, made a slight improvement in the model; however because of the negative correlation of LL_Z and T, the coefficient for ΔLL_Z increased relative to the single variable model. The greatest relative difference in correction in ΔESL for T was 3.0 phon. The inclusion of a negative correction for fluctuation strength also made a slight improvement in the model. The relative difference in correction to ΔESL by FS was no greater than 1.0 phon even though the FS coefficient was very large. The actual fluctuation strengths of the sounds used in these tests were quite small and may be of no practical significance in actual magnitude or difference between the sounds. The best fit model for ΔESL using ΔLL_Z, T and FS is shown in figure 13. The reduction in scatter for this multiple regression model over the single regression model for ΔLL_Z in figure 6 is apparent.

Equivalent subjective level for preference. The corrected equivalent subjective levels based on the preference judgements were predicted slightly but not significantly better by LL_{MG} than by LL_Z. The inclusion of a positive correction for tonality made a substantial improvement in the models for both

Table 9. Multiple Regression Models with Loudness and Sound Quality Measures

Zwicker Loudness, Average headphone SQ measures					
Test	B_0	B_L	B_{FS}	B_T	r^2
	Constant	Loudness	Fluctuation strength	Tonality	
Differences in equivalent subjective level					
Preference	0.00	1.21			0.90
	-0.86	1.30		10.08	0.93
	1.31	1.30	-60.15	10.92	0.95
Noisiness	-0.38	0.78			0.87
	1.56	0.78	-49.67		0.89
Corrected equivalent subjective level					
Preference	13.29	0.89			0.81
	0.93	0.98		18.53	0.91
	-5.77	1.01	104.65	18.22	0.93
Noisiness	10.81	0.91			0.96
	6.83	0.91	78.28		0.97
	4.93	0.93	80.85	2.87	0.98

Moore and Glasburg Loudness, Average headphone SQ measures					
Test	B_0	B_{LL}	B_{FS}	B_T	r^2
	Constant	Loudness	Fluctuation strength	Tonality	
Differences in equivalent subjective level					
Preference	0.23	1.32			0.87
	-0.57	1.51		10.61	0.94
Noisiness	-0.14	0.84			0.90
	-0.46	0.91		4.16	0.92
Corrected equivalent subjective level					
Preference	10.55	0.91			0.86
	-0.20	1.00		12.79	0.95
Noisiness	9.95	0.91			0.98
	9.00	0.91	21.57		0.98
	7.66	0.92	22.62	1.65	0.99

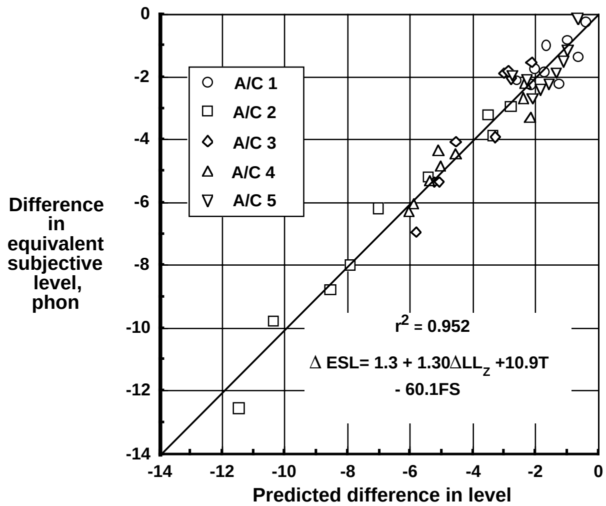


Figure 13. Multiple regression model for predicting effect of hypothetical ANC conditions on subjective response based on preference judgements.

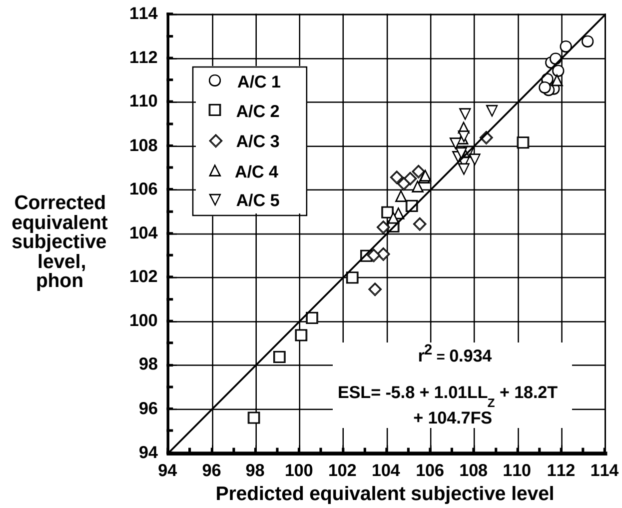


Figure 14. Multiple regression model for predicting subjective response based on preference judgements.

loudness metrics and increased the coefficients for the loudness metrics to very near unity. The greatest relative differences in corrections in ESL for T were 5.2 phon and 3.7 phon for LL_Z and LL_{MG}, respectively. While the inclusion of a positive correction for fluctuation strength made a slight improvement in the LL_Z model, the addition for a correction to the LL_{MG} model was not verified by the stepwise regression analysis. The best-fit model for corrected ESL using LL_Z, T and FS is shown in figure 14. The reduction in scatter for this multiple regression model over the single regression model for LL_Z in figure 7 is clearly noticeable.

Difference in noisiness with ANC condition. In contrast to the results for the preference judgements, the stepwise regression analyses did not find tonality a significant variable along with LL_Z for predicting difference in noisiness due to the ANC conditions. However, a slight improvement in correlation was found by the inclusion of fluctuation strength. This result is shown in figure 15 as compared with figure 8. In effect, the inclusion of the fluctuation strength improved the alignment of A/C 2 with the other aircraft. The stepwise regression analyses, however, found a slight improvement to the model with LL_{MG} by including tonality but no improvement by including the fluctuation strength. These very slight improvements probably indicate that the inclusion of either sound quality metric is of little practical significance in improving the prediction of differences in noisiness for interior noise treatments for a given aircraft type.

Equivalent subjective level of noisiness. Although the correlations of the noisiness judgements with LL_Z and LL_{MG} were very high, the stepwise regression analyses found that the addition of positive corrections for FS and T were significant. The inclusion of these factors, however, had very little effect on the coefficients for loudness. Figure 16, as compared with figure 9, indicates the improvement was primarily a result of correcting the underprediction of noisiness for A/C 4.

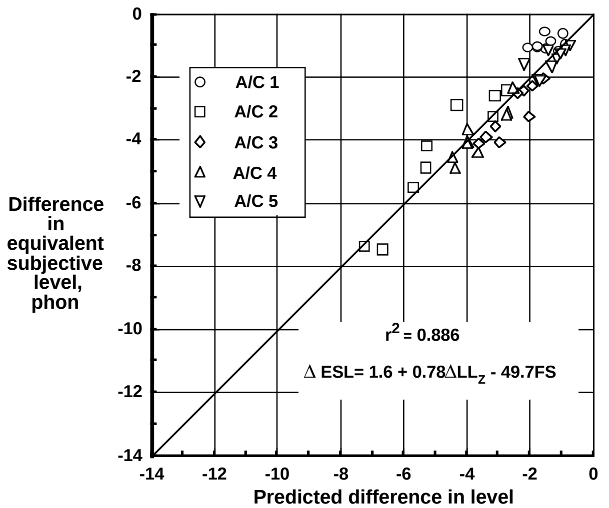


Figure 15. Multiple regression model for predicting effect of hypothetical ANC conditions on noisiness judgements.

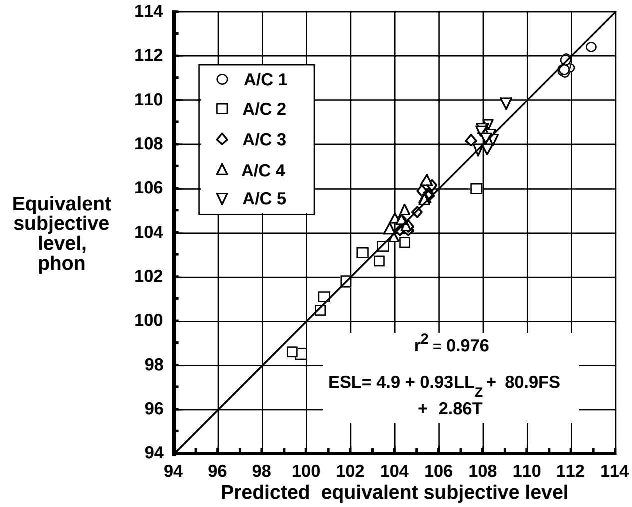


Figure 16. Multiple regression model for predicting subjective response based on noisiness judgements.

Conclusions

Two experiments were conducted, which used sound quality engineering practices to determine the subjective effectiveness of hypothetical active noise control (ANC) systems in five different propeller airplanes. Binaural recordings were made at passenger head positions of the sounds inside the airplanes under typical steady flight conditions. Digital filtering and reduction of the propeller tones at blade passage frequency and higher harmonics provided simulations of hypothetical reductions in interior sound levels which could be obtained with active noise control systems. The two experiments differed by the type of judgments made by the subjects: pair comparisons based on preference in the first and numerical category scaling of noisiness in the second. The following conclusions were noted:

1. The results of the two experiments were in general agreement that the hypothetical active noise control measures improved the interior noise environments.

2. Subject preference increased with decreases in the level of propeller tones and with increases in the number of tones reduced by the simulated ANC conditions.

3. The subjective effectiveness of the simulated ANC conditions was highly dependent on the spectral content and relative levels of the tonal and broadband components in the original airplane interior sounds.

4. The reductions in subjective response due to the ANC conditions were predicted with reasonable accuracy by reductions in measured loudness level.

5. Inclusion of corrections for the sound quality characteristics of tonality and fluctuation strength in multiple regression models improved the prediction of the effects of the hypothetical ANC conditions.

6. Although the results of the two tests are in general agreement, the pair comparison method based on subject preference appears to be more sensitive to subtle changes in the characteristics of the sounds which are related to passenger preference than is the numerical category method based on noisiness.

Appendix A
Spectra of Noise Stimuli

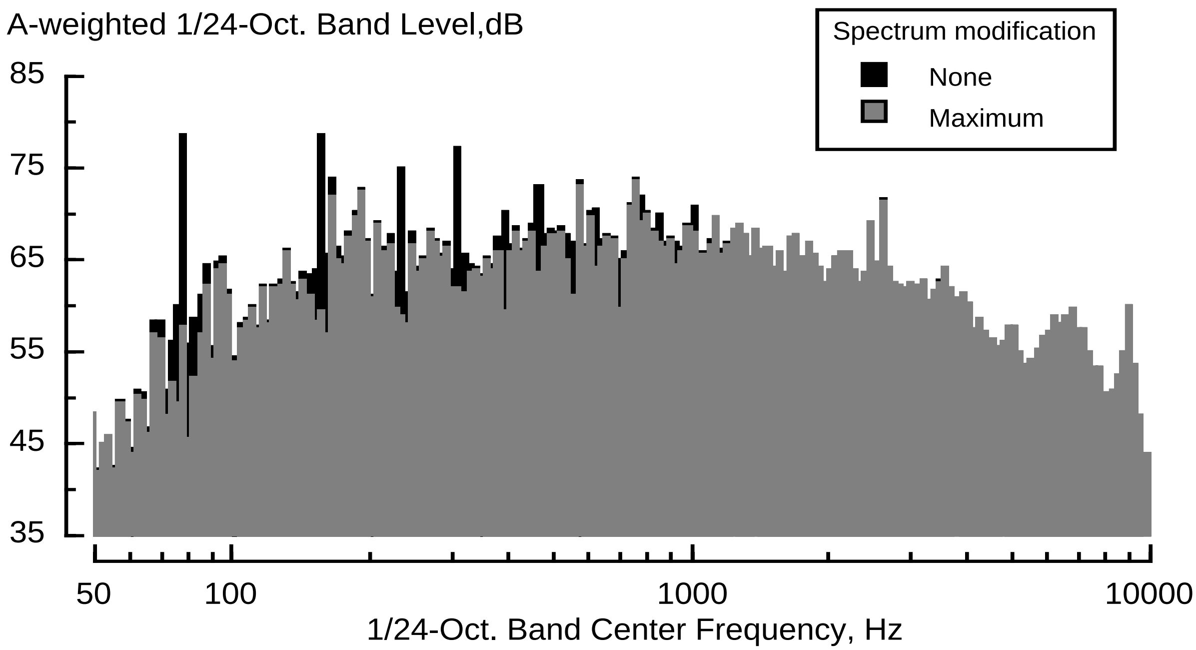


Figure A1. Spectra of noise stimuli for A/C 1, original spectrum and spectrum with the greatest reduction in tonal components illustrated.

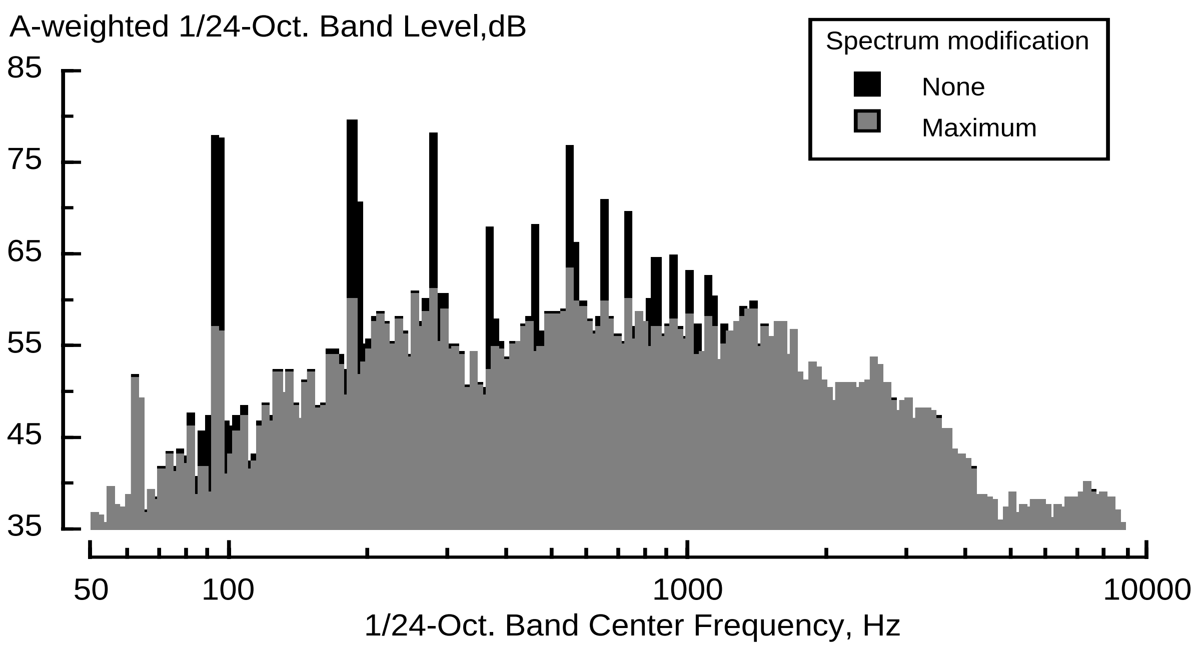


Figure A2. Spectra of noise stimuli for A/C 2, original spectrum and spectrum with the greatest reduction in tonal components illustrated.

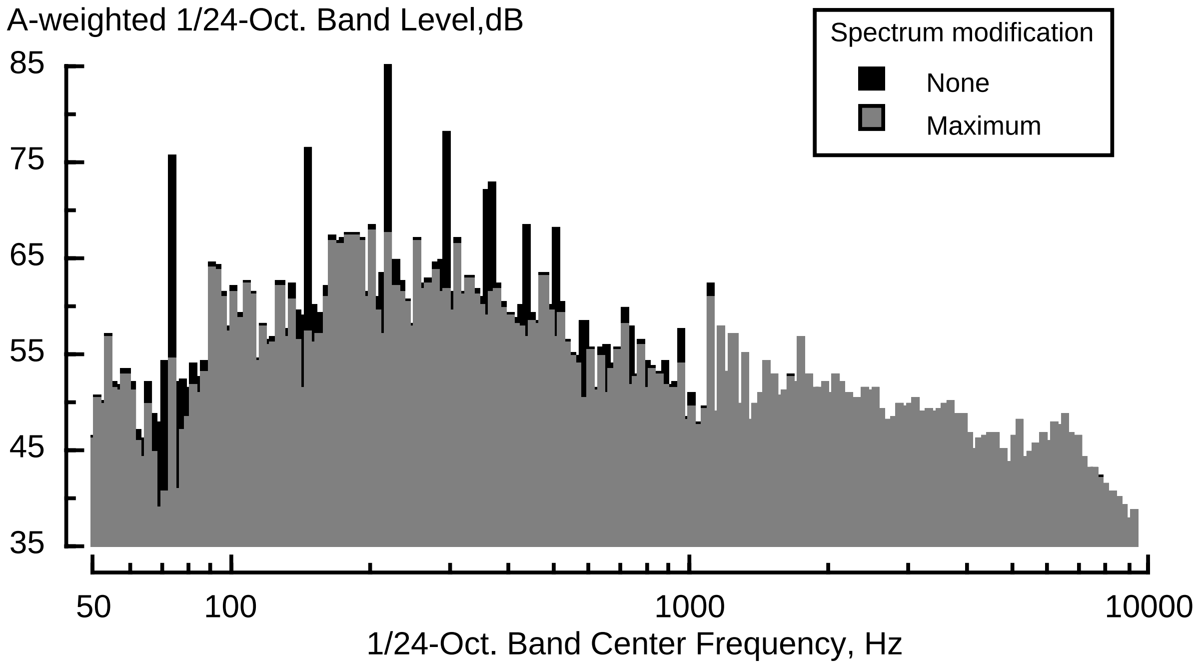


Figure A3. Spectra of noise stimuli for A/C 3, original spectrum and spectrum with the greatest reduction in tonal components illustrated.

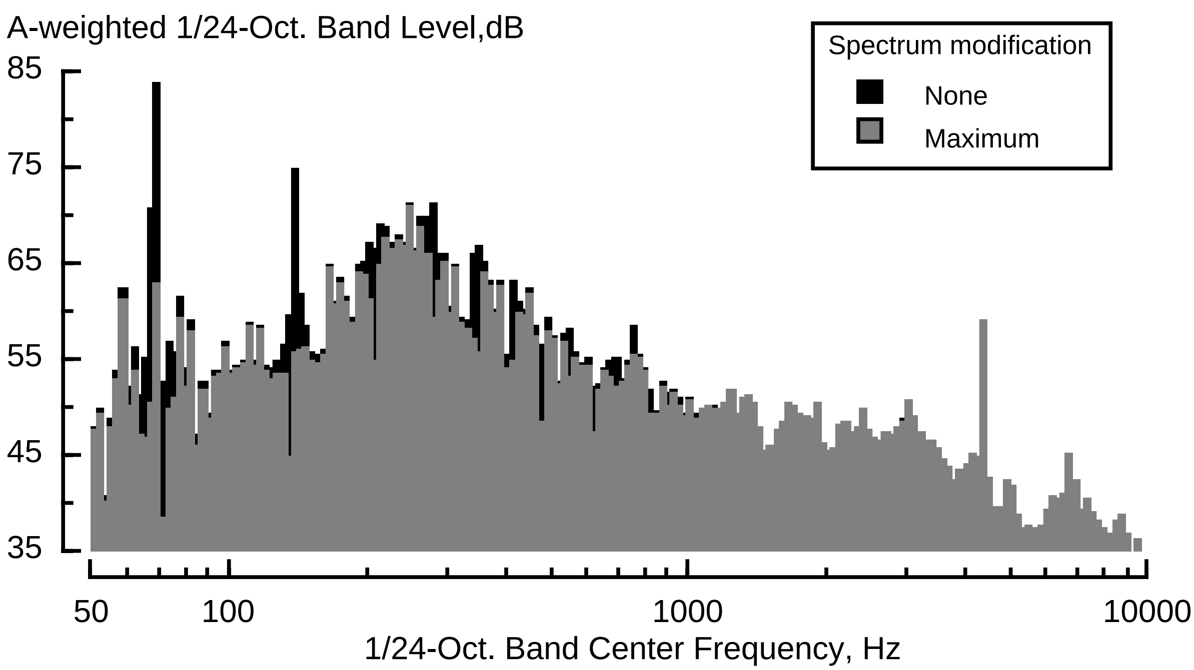


Figure A4. Spectra of noise stimuli for A/C 4, original spectrum and spectrum with the greatest reduction in tonal components illustrated.

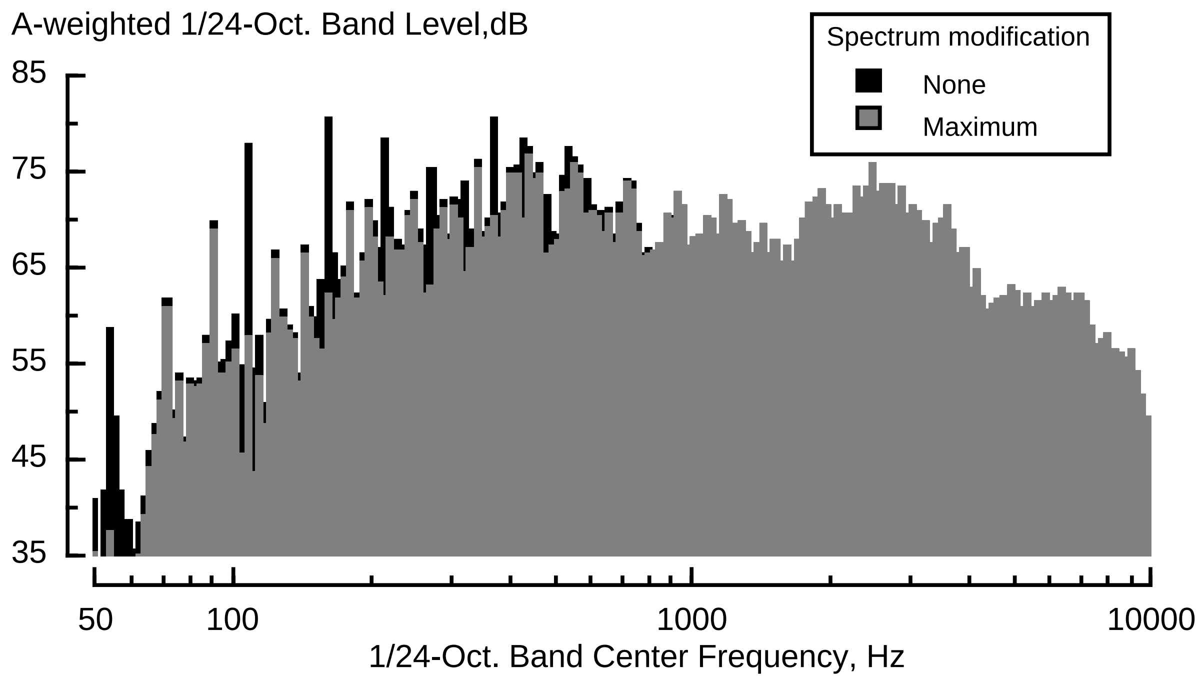


Figure A5. Spectra of noise stimuli for A/C 5, original spectrum and spectrum with the greatest reduction in tonal components illustrated.

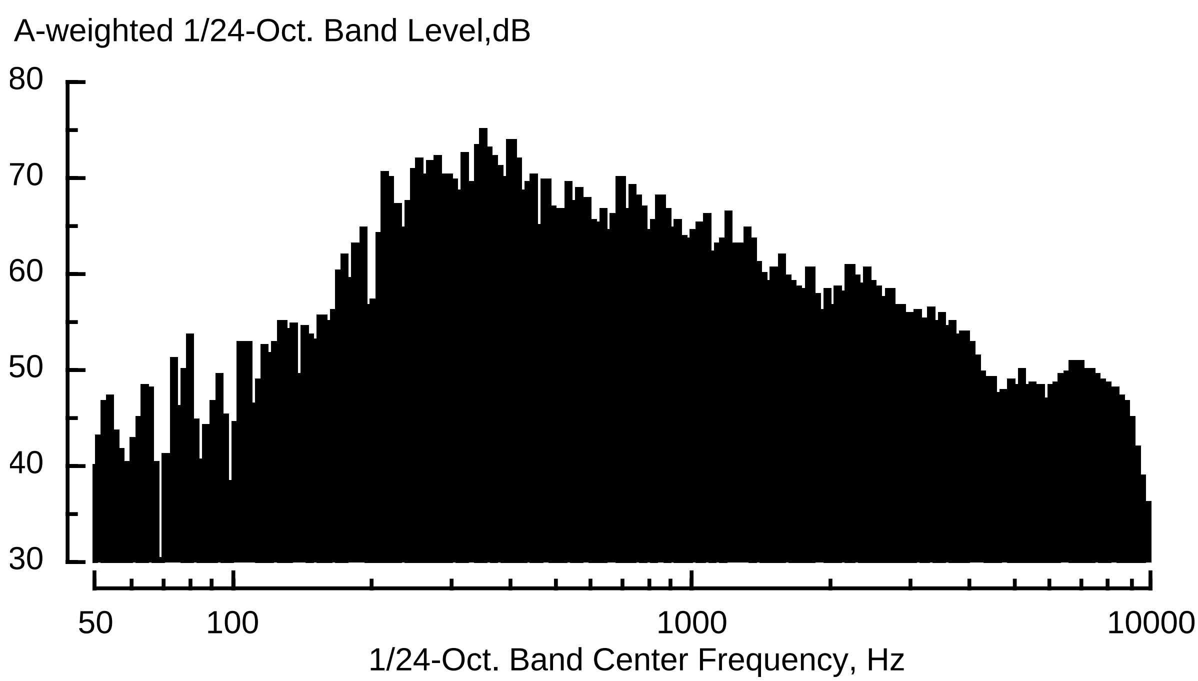


Figure A6. Spectrum of jet reference interior noise stimulus.

Appendix B

Table B1. Sound Levels of Noise Stimuli

Airplane	Number of harmonics reduced	Reduction in fundamental tone level, dB	SPL, dB		AL, dB		DL, dB	
			Left Ear	Right Ear	Left Ear	Right Ear	Left Ear	Right Ear
1	0	0	96.3	97.4	84.3	84.4	91.1	91.8
	3	7	93.1	93.7	83.8	83.5	89.8	90.1
	3	14	91.9	92.2	83.7	83.3	89.4	89.6
	3	21	91.4	91.7	83.6	83.3	89.3	89.5
	7	7	92.8	93.5	83.1	83.1	89.3	89.8
	7	14	91.2	91.7	82.7	82.6	88.6	89.0
	7	21	90.9	91.4	82.6	82.5	88.5	88.9
	15	7	92.8	93.6	82.9	83.0	89.2	89.8
	15	14	91.3	91.8	82.3	82.4	88.5	89.0
	15	21	91.0	91.5	82.1	82.4	88.4	89.0
2	0	0	96.9	95.2	81.6	77.2	90.2	87.4
	3	7	90.4	88.6	77.9	73.2	84.6	81.4
	3	14	85.3	82.8	76.5	71.5	81.2	77.3
	3	21	82.6	79.2	76.1	71.0	79.9	75.7
	7	7	90.4	88.5	76.8	71.8	84.2	81.0
	7	14	84.9	82.4	74.0	68.1	79.8	75.9
	7	21	81.5	78.2	72.8	66.6	77.6	73.2
	15	7	90.3	88.5	76.5	71.7	84.1	81.0
	15	14	84.7	82.4	73.0	68.1	79.5	75.9
	15	21	81.3	78.1	71.4	66.3	77.1	73.1
3	0	0	92.5	95.8	78.7	82.9	86.2	90.5
	3	7	90.7	92.5	77.3	80.0	84.2	87.2
	3	14	90.2	91.1	76.9	78.9	83.7	85.8
	3	21	89.9	90.7	76.7	78.5	83.4	85.4
	7	7	90.5	92.2	76.1	78.8	83.5	86.4
	7	14	89.9	90.7	74.8	76.4	82.4	84.3
	7	21	89.6	90.0	74.4	75.5	82.1	83.4
	15	7	90.6	92.2	75.9	78.7	83.5	86.4
	15	14	89.8	90.6	74.4	76.5	82.3	84.3
	15	21	89.6	90.1	73.8	75.5	81.9	83.4
4	0	0	100.4	98.4	80.4	77.8	90.9	88.8
	3	7	94.5	92.3	78.0	74.6	86.6	83.8
	3	14	90.8	88.1	77.2	73.5	84.7	81.4
	3	21	89.2	86.2	77.0	73.2	84.1	80.6
	7	7	94.5	92.3	77.3	74.3	86.3	83.7
	7	14	90.5	87.9	76.0	72.7	83.9	80.9
	7	21	88.7	85.9	75.5	72.3	82.9	80.0
	15	7	94.5	92.3	77.3	74.2	86.3	83.7
	15	14	90.5	88.0	76.0	72.7	83.9	81.0
	15	21	88.7	85.9	75.6	72.1	83.1	79.9
5	0	0	91.5	90.7	78.7	82.3	86.8	89.1
	3	7	87.5	88.6	77.7	82.0	84.9	88.5
	3	14	85.8	87.9	77.5	81.8	84.3	88.3
	3	21	85.4	87.7	77.5	81.8	84.2	88.3
	7	7	87.3	88.0	77.4	81.5	84.7	88.1
	7	14	85.4	86.9	76.9	81.2	83.9	87.8
	7	21	84.7	86.5	76.8	81.0	83.7	87.6
	15	7	87.3	87.9	77.0	81.2	84.5	88.0
	15	14	85.3	86.6	76.4	80.7	83.7	87.5
	15	21	84.5	86.2	76.1	80.5	83.5	87.4
Jet	-	-	89.2	88.3	82.6	81.1	87.7	86.5

Table B2. Loudness Levels of Noise Stimuli

Airplane	Number of harmonics reduced	Reduction in fundamental tone level, dB	LL_Z, phon			LL_{MG}, phon		
			Left Ear	Right Ear	Combined Sones	Left Ear	Right Ear	Combined Sones
1	0	0	101.9	102.4	112.2	102.0	102.6	110.2
	3	7	101.3	101.8	111.5	101.5	101.8	109.7
	3	14	101.0	101.4	111.2	101.2	101.6	109.5
	3	21	100.9	101.2	111.0	101.2	101.6	109.4
	7	7	101.2	101.7	111.4	101.3	101.5	109.5
	7	14	100.8	101.2	111.0	100.9	101.2	109.2
	7	21	100.6	101.0	110.8	100.8	101.1	109.1
	15	7	101.0	101.6	111.3	101.2	101.4	109.4
	15	14	100.5	101.1	110.8	100.8	101.1	109.1
	15	21	100.2	100.8	110.5	100.6	101.0	109.0
2	0	0	98.1	95.1	106.7	98.7	95.4	105.3
	3	7	95.2	91.5	103.5	96.4	93.0	103.2
	3	14	93.4	89.0	101.4	96.0	92.4	102.8
	3	21	92.5	87.8	100.3	95.8	92.3	102.7
	7	7	94.6	90.6	102.7	95.0	91.5	101.9
	7	14	92.2	87.3	99.9	94.3	90.4	101.0
	7	21	90.9	85.5	98.4	94.0	90.3	100.7
	15	7	94.3	90.6	102.6	94.4	90.8	101.2
	15	14	91.7	87.1	99.6	93.4	89.5	100.0
	15	21	90.1	85.2	97.9	93.0	89.4	99.8
3	0	0	95.4	97.9	106.7	97.1	99.3	106.4
	3	7	94.4	95.6	105.0	96.2	97.8	105.2
	3	14	94.1	95.0	104.5	95.8	97.3	104.8
	3	21	94.0	94.8	104.4	95.7	97.2	104.7
	7	7	93.7	95.2	104.5	95.9	97.2	104.8
	7	14	93.1	94.0	103.6	95.2	96.3	104.1
	7	21	92.8	93.6	103.2	95.0	96.2	104.0
	15	7	93.5	95.2	104.4	95.8	97.0	104.7
	15	14	92.6	93.9	103.3	95.0	95.9	103.9
	15	21	92.3	93.4	102.9	94.7	95.8	103.7
4	0	0	97.2	95.6	106.5	99.4	98.2	107.0
	3	7	94.7	92.8	103.8	96.9	95.9	104.7
	3	14	93.6	91.6	102.6	96.7	95.7	104.5
	3	21	93.1	91.1	102.2	96.7	95.7	104.5
	7	7	94.5	92.7	103.7	95.8	94.8	103.7
	7	14	93.2	91.4	102.4	95.4	94.6	103.5
	7	21	92.7	90.9	101.8	95.4	94.5	103.4
	15	7	94.5	92.7	103.6	95.3	94.4	103.3
	15	14	93.1	91.3	102.3	94.9	94.1	103.0
	15	21	92.6	90.8	101.7	94.9	94.0	102.9
5	0	0	97.7	100.0	108.9	98.4	100.5	107.7
	3	7	96.5	99.6	108.1	97.7	100.1	107.2
	3	14	96.1	99.4	107.8	97.5	99.8	107.0
	3	21	95.9	99.3	107.7	97.4	99.8	106.9
	7	7	96.3	99.3	107.9	97.4	99.9	107.0
	7	14	95.8	99.0	107.5	97.2	99.6	106.6
	7	21	95.6	98.8	107.3	97.0	99.4	106.5
	15	7	96.2	99.1	107.7	97.3	99.9	106.9
	15	14	95.5	98.7	107.2	97.0	99.5	106.5
	15	21	95.2	98.5	107.0	96.8	99.3	106.3
Jet	-	-	97.9	97.3	107.6	98.9	98.5	106.3

Table B3. Values of Sound Quality Measures of Noise Stimuli

Airplane	Number of harmonics reduced	Reduction in fundamental tone, dB	Fluctuation Strength, vacil		Roughness, asper		Sharpness, acum		Tonality	
			Left ear	Right ear	Left ear	Right ear	Left ear	Right ear	Left ear	Right ear
1	0	0	0.035	0.028	0.37	0.39	0.97	1.00	0.15	0.14
1	3	7	0.044	0.025	0.37	0.40	1.03	1.06	0.11	0.10
1	3	14	0.043	0.031	0.37	0.40	1.06	1.10	0.08	0.08
1	3	21	0.044	0.033	0.37	0.40	1.07	1.12	0.08	0.07
1	7	7	0.040	0.028	0.37	0.40	1.04	1.08	0.10	0.10
1	7	14	0.041	0.035	0.37	0.40	1.09	1.12	0.08	0.07
1	7	21	0.041	0.038	0.37	0.40	1.10	1.15	0.08	0.08
1	15	7	0.042	0.029	0.37	0.40	1.05	1.08	0.09	0.09
1	15	14	0.045	0.036	0.37	0.40	1.09	1.13	0.07	0.07
1	15	21	0.046	0.038	0.37	0.40	1.11	1.15	0.08	0.06
2	0	0	0.027	0.035	0.27	0.13	0.67	0.64	0.20	0.38
2	3	7	0.026	0.037	0.34	0.26	0.76	0.72	0.15	0.22
2	3	14	0.025	0.037	0.35	0.33	0.82	0.77	0.15	0.23
2	3	21	0.031	0.039	0.34	0.32	0.86	0.81	0.16	0.22
2	7	7	0.021	0.035	0.33	0.26	0.77	0.73	0.15	0.26
2	7	14	0.024	0.038	0.34	0.34	0.85	0.80	0.13	0.13
2	7	21	0.028	0.042	0.33	0.34	0.90	0.84	0.12	0.10
2	15	7	0.022	0.032	0.33	0.26	0.77	0.73	0.14	0.26
2	15	14	0.027	0.036	0.34	0.34	0.85	0.80	0.11	0.14
2	15	21	0.032	0.038	0.34	0.34	0.90	0.84	0.07	0.08
3	0	0	0.037	0.031	0.32	0.37	0.74	0.70	0.12	0.25
3	3	7	0.037	0.036	0.33	0.41	0.78	0.78	0.09	0.09
3	3	14	0.040	0.038	0.34	0.41	0.80	0.81	0.09	0.07
3	3	21	0.044	0.041	0.33	0.41	0.81	0.83	0.09	0.09
3	7	7	0.037	0.034	0.33	0.41	0.80	0.80	0.07	0.10
3	7	14	0.042	0.038	0.33	0.41	0.82	0.85	0.06	0.06
3	7	21	0.047	0.040	0.33	0.40	0.84	0.88	0.06	0.06
3	15	7	0.036	0.032	0.34	0.41	0.80	0.80	0.06	0.11
3	15	14	0.044	0.037	0.33	0.40	0.83	0.86	0.04	0.05
3	15	21	0.049	0.040	0.33	0.40	0.84	0.88	0.05	0.05
4	0	0	0.042	0.042	0.16	0.17	0.62	0.71	0.32	0.33
4	3	7	0.043	0.044	0.26	0.26	0.69	0.80	0.23	0.24
4	3	14	0.044	0.049	0.34	0.34	0.74	0.87	0.17	0.18
4	3	21	0.042	0.049	0.37	0.35	0.77	0.90	0.15	0.15
4	7	7	0.041	0.045	0.26	0.26	0.70	0.81	0.24	0.24
4	7	14	0.046	0.053	0.33	0.34	0.76	0.88	0.17	0.18
4	7	21	0.043	0.051	0.36	0.35	0.79	0.91	0.16	0.14
4	15	7	0.042	0.044	0.26	0.26	0.70	0.81	0.24	0.24
4	15	14	0.045	0.049	0.34	0.34	0.76	0.88	0.18	0.18
4	15	21	0.044	0.049	0.36	0.34	0.79	0.92	0.16	0.14
5	0	0	0.034	0.026	0.33	0.37	1.05	1.10	0.13	0.06
5	3	7	0.031	0.027	0.34	0.36	1.09	1.13	0.09	0.06
5	3	14	0.038	0.030	0.33	0.36	1.11	1.14	0.07	0.08
5	3	21	0.042	0.031	0.33	0.36	1.12	1.15	0.07	0.08
5	7	7	0.031	0.029	0.34	0.36	1.11	1.15	0.09	0.06
5	7	14	0.038	0.032	0.33	0.36	1.13	1.17	0.08	0.07
5	7	21	0.038	0.034	0.33	0.35	1.14	1.18	0.07	0.08
5	15	7	0.027	0.030	0.34	0.36	1.12	1.15	0.09	0.06
5	15	14	0.035	0.036	0.33	0.35	1.15	1.18	0.07	0.07
5	15	21	0.038	0.040	0.33	0.35	1.16	1.19	0.07	0.08
Jet	-	-	0.044	0.045	0.36	0.38	0.91	0.94	0.07	0.07

Appendix C
Instructions and Scoring Sheet for Preference Test

Test Instructions

We would like you to help us investigate peoples' reactions to aircraft interior sounds.

Today there will be 4 test sessions, each lasting 10 to 15 minutes. During each session, you will hear 50 pairs of aircraft interior sounds. Each sound in the pairs will last a few seconds. Your job will be to score each pair of sounds on a response sheet in the following manner:

After listening to each pair of sounds, you are to indicate which member of the pair you preferred on the response sheet. Each line has an A and B choice. If you prefer the first sound of the pair, you should circle the A for that sound pair. Likewise, if you prefer the second sound of the pair , you should circle the B. There are no right or wrong answers but you must choose either A or B for each sound pair. You will have a few seconds between pairs to make your choice. A voice message will be heard every 5 pairs to help you keep track of which pair is being presented. In case you lose track, please tell the test conductor at the end of the session and part of the session will be repeated.

Please listen carefully and make your choice at the end of each pair of sounds. Again, there are no right or wrong answers, we just want a measure of your own personal reaction to each pair of aircraft interior sounds. For this reason, we request that you do not talk during the tests nor make any sounds or express any emotion which might influence the response of the other people in the room.

Before we start the actual test we will play 5 sounds to give you the opportunity to hear the range of sounds and become comfortable with the headphones. We will then have a practice session with 6 pairs of sounds. This will let you become familiar with the scoring and give you the opportunity to ask us any questions about the test.

Thank you for helping us with this investigation.

Scoring Sheet

Subject Number:_ ___________ **Test Name: ______________**
Date: ___________ **Session name: ______________**

Circle **A** if you prefer the first sound you hear.
Circle **B** if you prefer the second sound you hear.

	First	Second
1.	A	B
2.	A	B
3.	A	B
4.	A	B
5.	A	B
6.	A	B
7.	A	B
8.	A	B
9.	A	B
10.	A	B
11.	A	B
12.	A	B
13.	A	B
14.	A	B
15.	A	B
16.	A	B
17.	A	B
18.	A	B
19.	A	B
20.	A	B
21.	A	B
22.	A	B
23.	A	B
24.	A	B
25.	A	B

	First	Second
26.	A	B
27.	A	B
28.	A	B
29.	A	B
30.	A	B
31.	A	B
32.	A	B
33.	A	B
34.	A	B
35.	A	B
36.	A	B
37.	A	B
38.	A	B
39.	A	B
40.	A	B
41.	A	B
42.	A	B
43.	A	B
44.	A	B
45.	A	B
46.	A	B
47.	A	B
48.	A	B
49.	A	B
50.	A	B

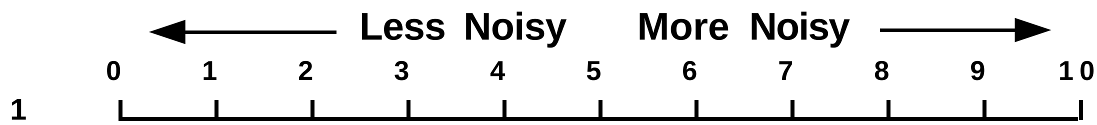
Appendix D

Instructions and Scoring Sheet for Noisiness Test

Test Instructions

We would like you to help us investigate peoples' reactions to aircraft interior sounds. We would like you to judge how **noisy** some of these sounds are. By noisy, we mean annoying, unwanted, objectionable, unacceptable, and so on.

Today there will be 4 test sessions, each lasting 10 to 15 minutes. During each session, you will hear 65 aircraft interior sounds. Each sound will last a few seconds. Before each session you will be given 5 scoring sheets, each containing 13 rating scales like the one shown below.



After each sound there will be a few seconds of silence. During this interval please indicate how **noisy** you judge the sound to be by placing a slash mark along the scale. If you judge a sound to be not very noisy, then place your slash mark close to the end of the scale marked 0, that is, near or between a low number near the left end of the scale. Similarly, if you judge a sound to be very noisy, then place your mark closer to the other end of the scale, that is, near or between a high number near the right end of the scale. A moderately noisy judgement should be marked in the middle portion of the scale. In any case, please make only one mark on each scale. There are no right or wrong answers; we are only interested in your opinion of the sound.

The scales on the first sheet are numbered 1 through 13, those on the second sheet are numbered 14 through 26. The third is 27 through 39, the fourth is 40 through 52 and the last is 53 through 65. A voice message will be heard every 5 sounds to help you keep track of which sound is being presented. In case you lose track, please tell the test conductor at the end of the session and part of the session will be repeated. Please listen carefully and make your rating at the end of each sound. Again, there are no right or wrong answers, we just want a measure of your own personal reaction to these aircraft interior sounds. For this reason, we ask that you do not talk during the tests nor make any sounds or express any emotion which might influence the response of the other people in the room. Before we start the actual test we will play 6 sounds to give you the opportunity to hear the range of sounds and become comfortable with the headphones. We will then have a practice session with 6 sounds. This will let you become familiar with the scoring and give you the opportunity to ask us any questions about the test.

Thank you for helping us with this investigation.

Scoring Sheet

Subject__________ Session ID_________ Date______

← Less Noisy More Noisy →

1 — 0 1 2 3 4 5 6 7 8 9 10

2 — 0 1 2 3 4 5 6 7 8 9 10

3 — 0 1 2 3 4 5 6 7 8 9 10

4 — 0 1 2 3 4 5 6 7 8 9 10

5 — 0 1 2 3 4 5 6 7 8 9 10

6 — 0 1 2 3 4 5 6 7 8 9 10

7 — 0 1 2 3 4 5 6 7 8 9 10

8 — 0 1 2 3 4 5 6 7 8 9 10

9 — 0 1 2 3 4 5 6 7 8 9 10

10 — 0 1 2 3 4 5 6 7 8 9 10

11 — 0 1 2 3 4 5 6 7 8 9 10

12 — 0 1 2 3 4 5 6 7 8 9 10

13 — 0 1 2 3 4 5 6 7 8 9 10

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Clemans A. Powell and Brenda M. Sullivan

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13. ABSTRACT *(Maximum 200 words)*
Active noise control technology offers the potential for weight-efficient aircraft interior noise reduction, particularly for propeller aircraft. However, there is little information on how passengers respond to this type of interior noise control. This paper presents results of two experiments that use sound quality engineering practices to determine the subjective effectiveness of hypothetical active noise control (ANC) systems in a range of propeller aircraft. The two experiments differed by the type of judgments made by the subjects: pair comparisons based on preference in the first and numerical category scaling of noisiness in the second. Although the results of the two experiments were in general agreement that the hypothetical active control measures improved the interior noise environments, the pair comparison method appears to be more sensitive to subtle changes in the characteristics of the sounds which are related to passenger preference. The reductions in subjective response due to the ANC conditions were predicted with reasonable accuracy by reductions in measured loudness level. Inclusion of corrections for the sound quality characteristics of tonality and fluctuation strength in multiple regression models improved the prediction of the ANC effects.

14. SUBJECT TERMS
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