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Evaluation of the Impact of Noise Metrics on Tiltrotor Aircraft Design

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Abstract

A subjective noise evaluation was conducted in which the test participants evaluated the annoyance of simulated sounds representative of future civil tiltrotor aircraft. The subjective responses were correlated with the noise metrics of A-weighted sound pressure level, overall sound pressure level, and perceived level. The results indicated that correlation between subjective response and A-weighted sound pressure level is considerably enhanced by combining it in a multiple regression with overall sound pressure level. As a single metric, perceived level correlated better than A-weighted sound pressure level due to greater emphasis on low frequency noise components. This latter finding was especially true for indoor noise where the mid and high frequency noise components are attenuated by typical building structure. Using the results of the subjective noise evaluation, the impact on tiltrotor aircraft design was also evaluated. While A-weighted sound pressure level can be reduced by reduction in tip speed, an increase in number of rotor blades is required to achieve significant reduction of low frequency noise as measured by overall sound pressure level. Additional research, however, is required to achieve comparable reductions in impulsive noise due to blade-vortex interaction, and also to achieve reduction in broad band noise.

Introduction

The metrics which are used to evaluate the impact of aircraft noise on communities in the vicinity of airports have been largely based on the unit of A−weighted sound pressure level and its derivative measures of sound exposure level and day−night level, all of which are defined in Reference 1. Since the major noise source at major airports are jet powered airplanes, whose noise signatures are dominated by broadband sources in the mid to high frequency range, the selection of A−weighted sound pressure level based measures is appropriate and have been supported by social surveys such as those reported by Schultz (Ref. 2) who showed a strong correlation between day−night level and the percentage of people who report being highly annoyed by the airport sounds.

With regard to helicopters, the general public exposure has been so minimal that significant surveys are virtually non−existent . It is recognized however that helicopter noise has been the target of considerable criticism by those exposed to it. The complaints, although usually anecdotal as opposed to being supported by hard data, often refer to feelings of discomfort and building vibration which appear to be in response to the discrete frequency rotor harmonics rather than the broadband noise. Figure 1 shows an un−weighted one−third octave band spectrum of a typical rotorcraft as compared with the same spectrum to which the A−weighting has been applied. The reduction in low frequency band levels due to the A−weighting raises a question as to whether A−weighted sound pressure level alone is an adequate descriptor for the community impact of rotorcraft noise.

The relative importance of rotorcraft noise assumes a greater significance when applied to the potential development of civil tiltrotor aircraft. Community noise may constitute a major potential barrier to the development of commercially viable tiltrotor aircraft. Since some of the design methods which are available for reducing higher frequency rotor noise components, and therefore the A−weighted sound pressure level, do not necessarily reduce, or may even increase, the low frequency noise components it is important to understand the interrelationship of these noise metrics in affecting, and predicting community response.

Another noise subjective effect may be due to the fundamental blade passage period which is a function of both the rotor rotational speed and the number of blades on the rotor. Since tiltrotor designs ranging from three blades, currently employed on the V−22, through five blades are under consideration in various design studies, the impact of this parameter should also be evaluated.

Since the noise characteristics of tiltrotor aircraft directly affect the design of the rotor systems it is timely to provide information relating the subjective evaluation of tiltrotor aircraft noise and its effect on those designs, at a time when the first generation civil tiltrotor aircraft are in the early design stages.

Noise Metrics, Symbols, and Abbreviations

Noise Metrics

L_A	A−weighted sound pressure level, dB
OASPL	overall sound pressure level, dB
PL	perceived level, dB
SPL	sound pressure level, dB

Symbols and Abbreviations

BPF	blade passage fundamental harmonic frequency, Hz
BVI	blade−vortex interaction
N	number of rotor blades
R^2	coefficient of multiple determination
SEE	standard error of estimate
SR	mean (across subjects) subjective rating
VTIP	rotor blade tip speed, ft/sec

Subjective Noise Test

Test Design

The general approach employed in this program was to present listeners with sounds which had the general characteristics of a hovering tiltrotor aircraft and ask them to rate the sounds with respect to annoyance. The sound samples differed from each other with respect to A−weighted sound pressure level, overall sound pressure level, and blade passage fundamental harmonic frequency. The sounds were presented as they might be heard out of doors and also inside a typical residential building. The subjective test responses were then correlated with objective noise measurements which were made adjacent to the listeners locations.

The test stimuli were prepared by the Contractor who also supplied all the sound reproduction equipment. The test was conducted , by the Contractor, in the Exterior Effects Room at the NASA Langley Research Center Acoustics Research Laboratory. Test participants were provided by NASA.

Preparation of Stimuli

The method for preparing the test stimuli was based on one which had been developed and demonstrated by the Boeing Defense and Space Group, Helicopters Division. Since analytical predictions of rotor noise signatures yield a single blade passage time history, the initial efforts to produce acoustic simulations by stringing together a series of identical cycles at the required blade passage period produced a series of unmodulated repetitive sounds. Although technically correct, the resulting simulation did not sound like existing tiltrotor aircraft such as the XV−15 and V−22. It was found that this was due to two elements; the signals were unrealistically steady, and broadband noise from the rotors and engines was missing. Based on these observations, a method was developed in which the acoustic signature of an actual tiltrotor aircraft (XV−15) was digitized and used as the basis for the new predicted sounds using the following procedures which are illustrated in Figure 2:

1− A sample of tape recorded data at least equal in time to the desired final sample is digitized.

2 – The data is transformed to the frequency domain in blocks of approximately 1/5 second intervals. Exact time may depend on specific equipment.

3 – The blocks of spectra are averaged to produce a single spectrum.

4 – The averaged spectrum of measured data is compared with the desired predicted spectrum in order to determine the adjustments which must be made to account for the following:
    a) Difference between desired and measured harmonic levels.
    b) Adjustments for equipment frequency response characteristics.
    c) Adjustments for specific room frequency response characteristics.

5 – Using digital computing techniques, the combined adjustments described in step 4 are applied at each harmonic frequency to each of the individual spectra from Step 2.

6 – The individual adjusted spectra are re-transformed into the time domain to provide a continuous record of the desired acoustic signal with temporal variation similar to that of the original data.

Employing the above methodology, samples were produced to develop the following test matrix:

L_A, dB	OASPL, dB						
72	78	81	84	87	90	93	96
75		81	84	87	90	93	96
78			84	87	90	93	96
81				87	90	93	96
84					90	93	96
87						93	96
90							96

The range of combinations of levels was selected so that the data would encompass those which could be expected from tiltrotor operation. In addition the A-weighted sound pressure level was kept at least 6dB below the Overall sound pressure level in order to minimize interaction between the two measures.

Each of the above 28 combinations was presented at fundamental blade passage frequencies of 15, 20, 25, 30 and 35 Hz to form 140 individual stimuli. As a check on consistency, five of the sounds were repeated for a total of 145 outdoor stimuli. The order of the stimuli was randomized with respect to all three variables and the final data was recorded in seven segments so that the order of presentation between groups of subjects could be varied.

A second set of stimuli representing indoor sounds was prepared by filtering the outdoor noise tapes . The filter shape selected, whose characteristics are shown in Figure 3 as "windows closed", is one which was used in previous NASA studies (Ref 3) and represents a typical residential structure.

The instrumentation system which was used to reproduce the stimuli is illustrated in Figure 4. In order to preserve the fidelity of the audio presentations it was essential to have low frequency reproduction equipment capable of delivering signals of the order of 96dB at 15Hz at the listeners locations which were approximately 15 feet away. This was made possible through the use of a loudspeaker which utilized servo motors rather than conventional voice coils as driving elements. As shown in Figure 4 this speaker was flat within 2 dB over the frequency range 15 Hz to 70 Hz and within 4 dB up to 125 Hz which is its upper frequency limit. A conventional speaker system, as illustrated was used to cover the remaining mid and high frequency range. Although two low frequency speakers were available, only one was used because evaluations indicated that a less uniform sound field resulted from the use of two speakers. The decreased uniformity with two speakers was probably due to phasing of the radiated sounds.

Since the sound actually experienced by the listeners is a function of the input signal, the reproduction system, and the acoustic characteristics of the room in which the listeners are located, it was necessary to adjust the input digital tapes to account for speaker and room acoustics. In order to accomplish this the audio system to be used was transported to the NASA facility and room acoustic calibrations were performed employing three types of sources: pure tones, pink noise, and typical test samples. Based on the results of this calibration the recordings were modified (Figure 2, step 4) so that the sound experienced by the listeners matched the desired stimulus. In addition to the frequency calibration of the entire room, measurements were made at many seat locations in order to aid in selecting locations for the test subjects. Seat selections were made to minimize differences in the sound levels experienced by the subjects. Based on criteria that L_A and OASPL at the listener locations should not differ from each other by more than ±1 dB, five seat locations , all in the 3rd row from the front, were selected. Since it was desired to test a total of 40 subjects, 8 sessions were required for each of the indoor and outdoor tests.

Test Program

Preliminary Test. The entire test program was prototyped in a 20x20x40ft acoustically treated chamber in the Boeing Helicopters Company Acoustical Laboratory using 5 participants prior to formal testing at the NASA Langley Research Center. The purpose of the preliminary testing was to confirm the test duration and to evaluate such factors as required intervals between stimuli, spacing and length of rest periods, and clarity of instructions and scoring sheets. In addition an evaluation of the results helped to confirm that the range of sounds would result in a satisfactory range of subjective responses. The data from this preliminary test was not included in the final results.

Based on the preliminary test, the duration of each stimulus was set at 5 seconds with a 1 second ramp at the beginning and a 1 second ramp at the end. An interval of 7 seconds was put between stimuli for the subjects to make and record their judgements of the sounds.

Test Subjects. Forty test subjects, from the local community, were provided by the NASA Langley Research Center. They included 19 males and 21 females. The ages of the group members ranged from 18 to 64. Screening audiograms were administered to all candidates prior to their participation. The subjects were also required to read and sign two voluntary consent forms which are reproduced in Appendix A.

Since the acoustic evaluation of the Exterior Effects Room indicated that there were five seats at which the sounds were matched within the desired tolerance limits of ±1dB, L_A and OASPL, the participants were divided into eight groups of five persons each. Each group reported for one half day and participated in evaluating both the outdoor sounds and the indoor sounds.

Test Procedures. The testing was conducted in the Exterior Effects Room of the NASA Langley Research Center Acoustics Research Laboratory. The loudspeakers were located in front of the room along with a projection screen. As cues to remind the subjects of the environment for the outdoor and indoor test samples, a projection of an artists rendering of a civil tiltrotor in flight was shown during the outdoor noise tests and a photograph of an interior scene depicting a home office was projected during the interior noise test.

Recordings were made of the sounds during each session using microphones located directly behind each subject. In addition, a complete set of recordings were made of all stimuli with the room empty.

The participants entered the room and were assigned seats which they used during the entire test. Instruction sheets, reproduced in Appendix B, were distributed and were read aloud. Any questions were answered and a practice session of three sounds was conducted in order to familiarize them with the sounds and the rating form. These forms were then scanned by the test administrator to ensure that the procedure was correctly understood. Any additional questions or problems were resolved. The test response forms were distributed and the test administrator left the room.

The 145 outdoor stimuli were evaluated first while the outdoor scene was projected onto the screen at the front of the room. The 145 indoor stimuli were evaluated next while the indoor scene was projected. Short breaks were given at the end of every 20 stimuli with a 15 minute break between the indoor and outdoor sessions.

Each test subject rated each stimulus on a unipolar, 11 point, numerical category scale ranging from 0 to 10. The end points of the scale were labeled "NOT ANNOYING" and "EXTREMELY ANNOYING." The term "ANNOYING" was not defined in the subject instructions.

Data Reduction

The subjective response ratings were read as the location on the 0–10 scale which was intercepted by the slash mark placed by the test subject. These ratings were transcribed directly from the paper forms by means of a digital optical encoder which was interfaced with a computer. The encoding pad used an optical target which was positioned by the analyst. Calibration was performed by taking readings at the 0 and 10 scale points and the data was read by moving the target from the 0 point on the scale to the point where the slash mark intercepted the rating line. The data was initially stored in ASCII format and then entered into a spreadsheet program for subsequent processing.

The microphone located behind the center seat in the row of occupied seats in the test facility was selected as representative of the acoustic data. Comparison of data with the room empty and with test subjects in place showed minimal effect of the occupants on the acoustic data and it was decided to use the room empty data rather than select data from any particular test session. The data for each stimulus, as recorded by the selected microphone, was analyzed using a real time frequency analyzer. The data was averaged over the length of the stimulus and the A–weighted and overall sound pressure levels were read. In addition the perceived level (Stevens Mark VII procedure, Reference 1) was calculated from one third octave band spectra. This measure was selected because it extends to a lower frequency range and is more sensitive to low frequency sound pressure levels than is A–weighted sound pressure level.

The mean value of the 40 individual subjective ratings for each noise stimulus was calculated to obtain the subjective response values for correlation with the noise measurements. A summary containing both the acoustic data and the mean subjective responses is presented in Appendix C of this report. The particular format shows the randomized order of the 145 stimuli, which was also broken into seven segments. The sequence of the seven segments was varied so that the order of presentation was changed for each group of subjects.

Evaluation of Subjective Results

In order to gain insight as to the general reasonableness of the test stimuli and the subjective responses to them, the mean values of the responses of the 40 participants to the 145 outdoor sounds and 145 indoor sounds were calculated separately. The results yielded a mean response across subjects of 5.58 to the outdoor sounds and 4.28 to the indoor sounds. Since these were reasonably close to the scale central value of 5 it can be concluded that the stimuli, as a group, were not biased toward either annoying or not annoying samples. Mean values of the response of each participant to all sounds was also calculated and compared with the mean of the entire group to determine if any subject(s) responses were so statistically variant from the group that the responses for that individual should be eliminated. No such findings resulted and all results were retained.

Regression equations and correlations relating the selected noise metrics and parameters with subjective response plus the statistical tests of validity were performed using a commercially available computer program. The regression analyses of both the outdoor and indoor data are contained in Appendix D.

The data on which the correlations and regressions were based are shown in Figures 5, 6, and 7. Examination of the L_A and OASPL values associated with each data point in Figures 5 and 6 indicate that a large part of the variation in subjective response at a given value of the independent variable (L_A or OASPL) is due to the variation in the other noise measurement. For example, in Figure 5 each data point corresponding to a specific L_A value has associated with it a different OASPL value. The subjective response tends to increase as the OASPL value increases. Similarly in Figure 6, the subjective response for a given OASPL increases as L_A increases. The relatively larger data spread in Figure 6 indicates that the subjective response is driven more by L_A than by OASPL. It is interesting to note that PL in Figure 7 displays the least scatter in subjective response. This is most likely due to PL's attempt to account for the entire frequency range. It appears to do a better job of accounting for the low frequency rotor noise than does L_A and a better job of accounting for the mid and high frequency range than does OASPL.

Also shown on Figures 5, 6, and 7 are the linear regressions which were calculated. Inspection of these figures indicates that a linear fit is justified and higher order regressions are not required. The linear regression equations are:

Outdoors

Single Variable Regressions

$SR = 0.29(L_A) - 16.24$ $R^2=0.85$ $SEE=0.63$ *(1)*

$SR = 0.25(OASPL) - 15.97$ $R^2=0.63$ $SEE=1.00$ *(2)*

$SR = 0.32(PL) - 19.36$ $R^2=0.87$ $SEE=0.59$ *(3)*

Multiple Variable Regressions

$SR = 0.29(L_A) + 0.02(BPF) - 16.83$ $R^2=0.86$ $SEE=0.62$ *(4)*

$SR = 0.26(OASPL) + 0.05(BPF) - 18.37$ $R^2=0.67$ $SEE=0.95$ *(5)*

$SR = 0.32(PL) + 0.3(BPF) - 20.64$ $R^2=0.89$ $SEE=0.54$ *(6)*

$SR = 0.22(L_A) + 0.9(OASPL) - 19.45$ $R^2=0.90$ $SEE=0.52$ *(7)*

$SR = 0.22(L_A) + 0.11(OASPL) + 0.03(BPF) - 21.03$ $R^2=0.92$ $SEE=0.47$ *(8)*

Indoors

Single Variable Regressions

$SR = 0.23(L_A) - 8.63$ $R^2=0.77$ $SEE=0.61$ *(9)*

$SR = 0.14(OASPL) - 5.43$ $R^2=0.39$ $SEE=1.06$ *(10)*

$SR = 0.32(PL) - 15.35$ $R^2=0.87$ $SEE=0.49$ *(11)*

Multiple Variable Regressions

$SR = 0.25(L_A) + 0.04(BPF) - 10.23$ $R^2=0.83$ $SEE=0.56$ *(12)*

$SR = 0.14(OASPL) + 0.02(BPF) - 6.46$ $R^2=0.41$ $SEE=1.05$ *(13)*

$SR = 0.33(PL) + 0.03(BPF) - 16.77$ $R^2=0.90$ $SEE=0.43$ *(14)*

$SR = 0.20(L_A) + 0.07(OASPL) - 11.65$ $R^2=0.85$ $SEE=0.49$ *(15)*

$SR = 0.20(L_A) + 0.07(OASPL) + 0.04(BPF) - 13.22$ $R^2=0.88$ $SEE=0.40$ *(16)*

The coefficient of multiple determination, R^2, is a measure of the variance in the data accounted for by the regression. An increase in R^2 indicates an improvement in prediction. The standard error of estimate, SEE, is an indicator of the difference between the predicted subjective response and the actual subjective response. A decrease in SEE indicates an improvement in prediction.

The coefficients of each independent variable in the above regressions were tested using a two–tailed Student's t–test at the 0.05 level to determine if they were significantly different from zero. With one exception, all the coefficients were significantly different from zero. This indicates that each corresponding independent variable (L_A, OASPL, PL, or BPF) makes a significant contribution to the prediction of subjective response. The one exception is the coefficient of BPF in equation 13 for the indoor data.

The sensitivity of the subjective responses to the individual noise metrics can be evaluated by inspection of the slopes shown in Figures 8 and 9. Figure 8 which is derived from the evaluations of outdoor noise indicates that the sensitivity to either A–weighted sound pressure level or perceived level are quite similar but, as expected, the sensitivity to OASPL is less. Figure 9, which is derived from the evaluations of indoor noise, however shows a stronger sensitivity to perceived level. This is probably because the indoor noise is more highly dominated by the low frequency harmonics than is the A–weighted sound pressure level. It is clear from the regression equations that PL is superior to L_A and OASPL as a response predictor when either metric is used alone. These results indicate that, if a single metric is desired to describe rotorcraft noise, perceived level would be a better predictor of subjective response than would A–weighted sound pressure level.

Figures 10 and 11 display the interrelationship between A–weighted sound pressure level and overall sound pressure level when considered as multiple variables. In order to show the effect in the simplest format, the plots shown are derived from the equations which do not include blade passage frequency. Examination of these figures clearly shows that A–weighted sound pressure level by itself can not define the subjective response. For example, as shown in in Figure 10, exposure to an L_A of 70dB can result in a subjective response rating of 3, 5, or 7 depending on OASPL. Including both L_A and OASPL in the same regression equation results in subjective response predictions that are better than those obtained when using either metric alone. Using both together also yields predictions that are comparable (indoors) or better (outdoors) than those obtained from PL used alone. Since L_A and OASPL are easier to calculate and more readily available to the aircraft designer and engineer, their combination is preferable to PL for predicting subjective response. In addition, the combination of L_A and OASPL has an advantage in that it imposes a balance between the OASPL, which results from the low frequency harmonic content, and the A–weighted sound pressure level, which results from the mid and high frequency content. A potential problem with PL is that its usage alone could result in a reduction of the subjective numerical value being achieved by reduction of high frequency noise, when the problem may actually be low frequency noise. Application of multiple metric criteria would help to focus attention on the critical problem area.

The addition of blade passage frequency to the regression models significantly improved subjective response prediction in every model except one. Even in that exception, OASPL alone for the indoor data (eq. 13), an increase in prediction ability was indicated, but it was not statistically significant. Comparison of the coefficients in the regression equations indicate that the contribution of BPF to subjective response is relatively small compared to the effect of L_A, OASPL, or PL.

IMPACT ON TILTROTOR AIRCRAFT DESIGN

Analytical Procedures

In order to evaluate the effects which designing to various noise criteria would have on the design of the rotor system the NASA Rotorcraft Noise Prediction Code ROTONET (Ref. 4) was used to predict the following noise components: Loading Noise, Thickness Noise, and Broadband Noise. These components are defined in Reference 4. Blade–Vortex Interaction Noise and Blade–Wake noise in hover were predicted using Boeing in–house methodology which is described in Reference 5. The prediction methodology was validated by comparing predicted ground level noise contours with XV–15 ground level noise contours which were developed from measured data. A comparison of acreage of the area within two A–weighted level contours follows:

	Ground Contour Area (acres)	
L_A, dB	Predicted	Measured
76	200	186
88	56	51

The predicted contours show excellent correlation with the measured data, both in the levels and shapes of the ground contours.

Noise Reduction

Given a specified aircraft weight the most powerful variable in determining rotor noise is tip speed, which affects all of the noise components. While the initial tiltrotor designs such as the XV–15 and V–22 employ relatively high tip speeds in the low speed and hover helicopter mode, it is clear that future tiltrotors designed for civil application will require significantly lower tip speeds. In order to maintain the rotor lift capability the reduction in tip speed must be countered by an increase in blade area which will vary inversely as tip speed squared. This increase in blade area can be achieved by: increasing the area of each blade, increasing the number of blades, or both.

It should be kept in mind, however, that these noise reduction techniques do not come without associated penalties. A lower speed rotor will result in higher torque requirements in the drive train and therefore increased weight of gearboxes and shafting. Increasing the number of blades obviously increases the complexity and weight of the rotor system.

The effects of tip speed and number of blades are shown by example in Figures 12, 13, 14, and 15 which compare a 3 blade design with a tip speed of 800 fps with two 700fps design rotors, one with 3 wide chord blades and the other with 5 narrower chord blades which have the same total blade area as the 3 blade configuration. The 3 blade, 800fps baseline is similar to the design of the V–22 military tiltrotor while the 700fps tip speed is considered reasonable for civil designs.

Figure 12 shows the design effects on A–weighted sound pressure level, and on the Overall sound pressure level during a descent condition on the centerline of the flight path at a point 2000ft ahead of the aircraft which is at an altitude of 1000ft. In descent the BVI component is strong and almost as dominant as the rotational noise when measured as OASPL and clearly the dominant source when measured as A–weighted sound pressure level. Slowing the three blade configuration to 700fps has a modest effect on the OASPL components resulting in about a 2dB reduction in OASPL. Despite a more significant reduction in the contributions of rotational and thickness noise to the A–weighted metric, the almost negligible effect on BVI noise yields only about a 1dB reduction in combined A–weighted sound pressure level. The five blade configuration, however, has a considerably greater effect on the low frequency rotational and thickness noise due to reductions in blade loading and blade cross section area resulting in a 9 dB reduction in OASPL. Reduction in vortex strength also provides about a 5 dB reduction in A–weighted sound pressure level as compared with a 1dB reduction due to tip speed alone. Figure 13 shows the effects on perceived level which tends to respond more like the A–weighted metric than like the OASPL.

Figures 14 and 15 present the results as applied to the hover condition at a distance of 500ft with the aircraft at an altitude of 100ft. Some of the fundamental differences between the hover and descent condition noise are: the observer is closer to being in the rotor plane thereby tending in increase the relative importance of thickness noise compared with rotational noise; blade vortex interaction noise is of lower intensity and somewhat erratic in temporal behavior; broadband noise tends to be more important due to the higher angle of attack of the rotor. As in the case with descent, the increased number of blades is required to give a significant reduction in OASPL. The A–weighted sound pressure level, however, is now strongly influenced not only by BVI but by broadband levels of nearly equal value.

Summarizing the above discussion it appears that significant reduction of OASPL requires an increase in number of blades and is not achievable by tip speed reduction alone. The ability to reduce A–weighted sound pressure level by tip speed and/or number of blades has a limited potential unless other methods of reducing BVI noise and broadband noise are developed.

Reduction of BVI noise has been, and continues to be, the subject of considerable research. Methods include: vortex alleviation, higher harmonic control, and individual blade control. Applications have yet to be developed to the point where they are incorporated on production aircraft and care must be taken to ensure that the method(s) selected do not cause increases in other noise components, airframe vibrations, or loads.

Broadband noise control has received much less attention than BVI noise but as BVI noise decreases the broadband noise will constitute the primary contributor to the A–weighted metric. Application of the ROTONET analysis indicates that the broadband noise due to the boundary layer exceeds that due to trailing edge turbulence and tip vortex shedding. This suggests that research into the effects of boundary layer control, such as employed on wings, might be a fruitful area of research.

CONCLUSIONS

A test program was conducted for the purpose of correlating subjective annoyance response with noise metrics that might be used to evaluate tiltrotor aircraft. The conclusions from this test program are:

1. A–weighted sound pressure level used by itself is not an adequate predictor of subjective response to tiltrotor noise because it fails to account for the effects of the low frequency rotor harmonics.
2. The use of both A–weighted sound pressure level and Overall sound pressure level results in a better assessment of subjective response than does the use of A–weighted sound pressure level alone.
3. The use of both A–weighted sound pressure level and Overall sound pressure level results in as good or better an assessment of subjective response than does the use of perceived level alone.
4. Perceived level calculated by the Stevens Mark VII method results in a better assessment of subjective response than does the use of A–weighted sound pressure level or Overall sound pressure level alone.
5. The use of blade passage frequency with noise metrics results in a better assessment of subjective response than does the use of the noise metrics alone.

An analytical evaluation was made of the impact of designing tiltrotor aircraft to an A–weighted sound pressure level criterion alone as compared with designing to both an A–weighted sound pressure level and an Overall sound pressure level criteria. The conclusions from the analytical evaluation are:

1. Moderate reductions in A–weighted sound pressure level can be achieved by reduction in tip speed while increasing blade area to maintain hover performance.
2. Increasing blade area by a larger number of thinner chord blades is required to reduce low frequency rotor harmonics and hence Overall sound pressure level.
3. Increasing the number of blades decreases the strength of shed tip vortices and provides a moderate reduction in A–weighted sound pressure level due to blade–vortex interaction.
4. Larger reductions in noise due to blade–vortex interaction will require additional treatments such as vortex alleviation devices or harmonic blade control. Additional research is required
5. Reducing tip speed, while maintaining lift, tends to increase broadband noise and sets the A–weighted sound pressure level when blade–vortex interaction does not occur. Additional research into methods for reducing broadband noise is required.

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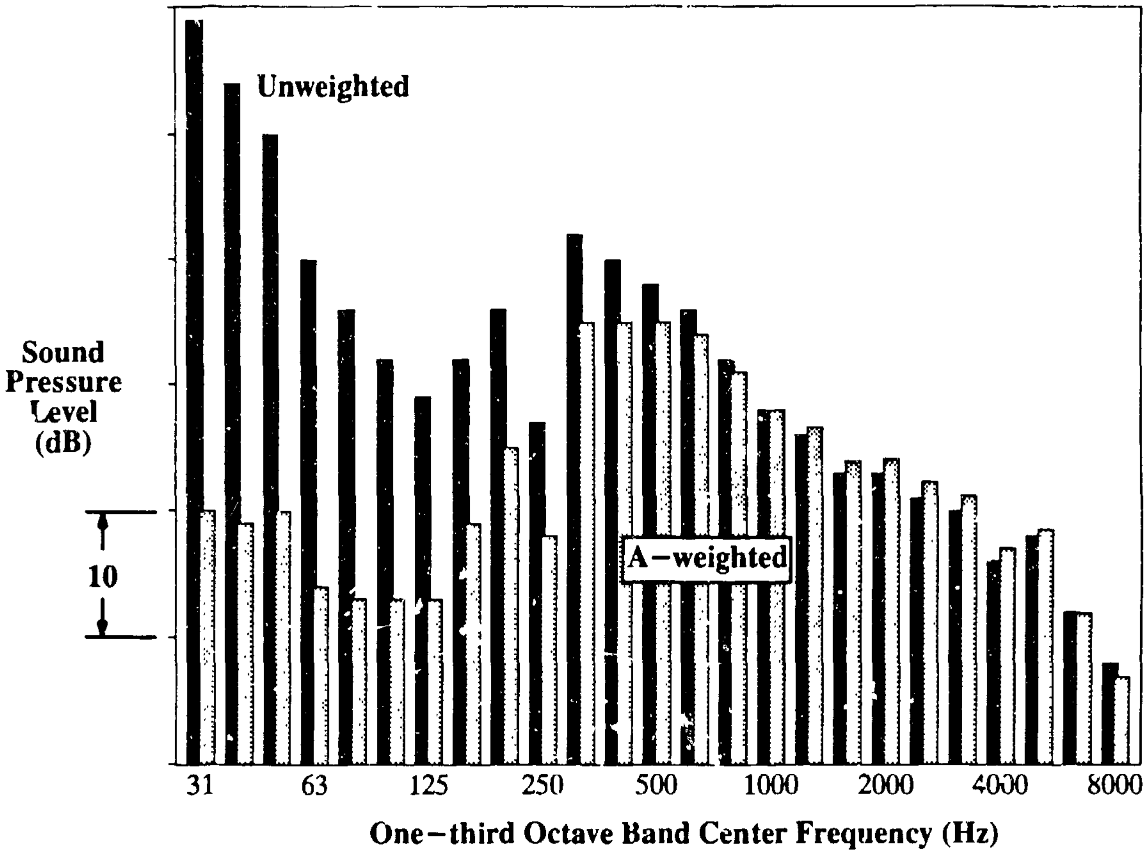


Figure 1. Effect of Frequency Weighting on Rotor Noise

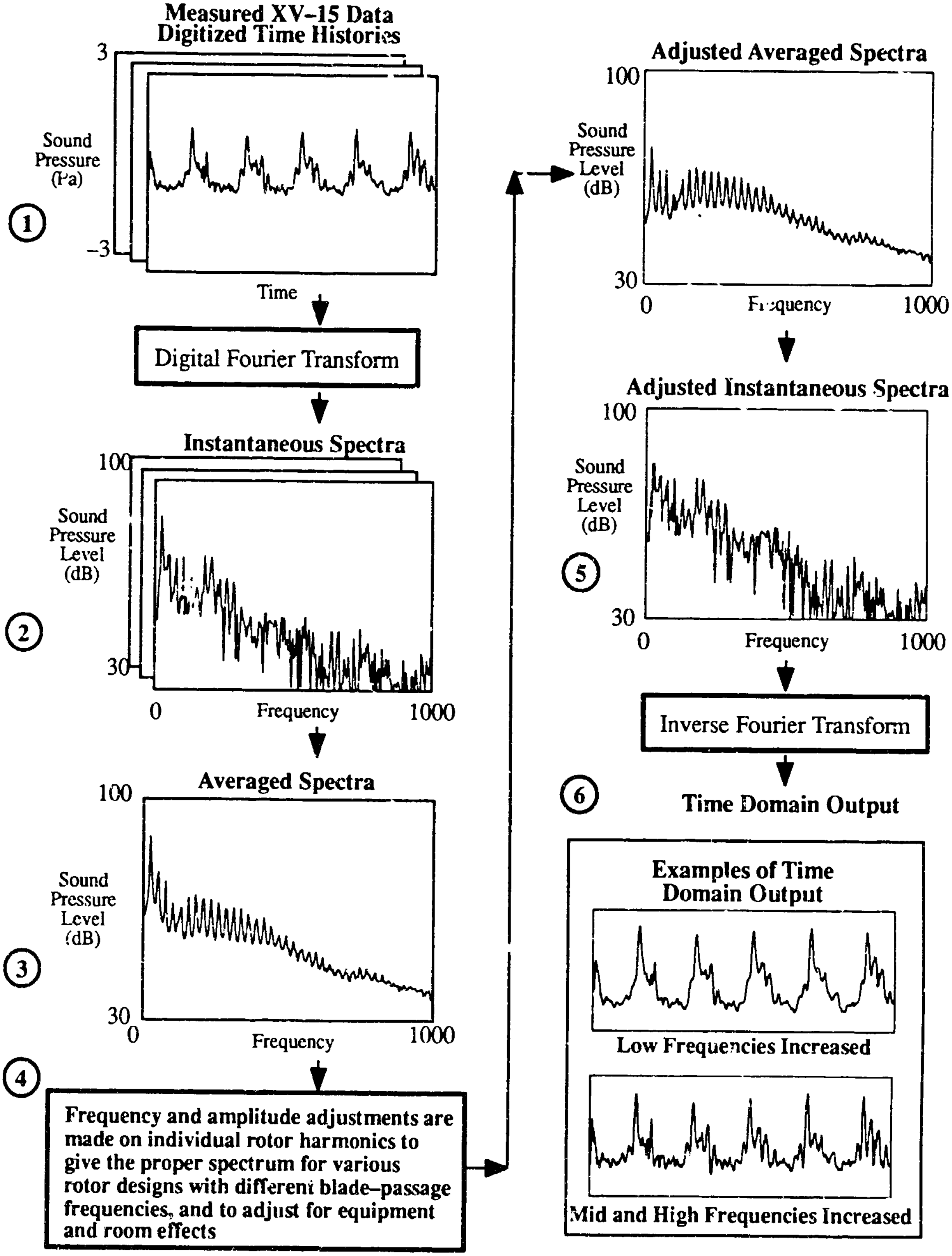


Figure 2. Method of Creating Stimulus Samples

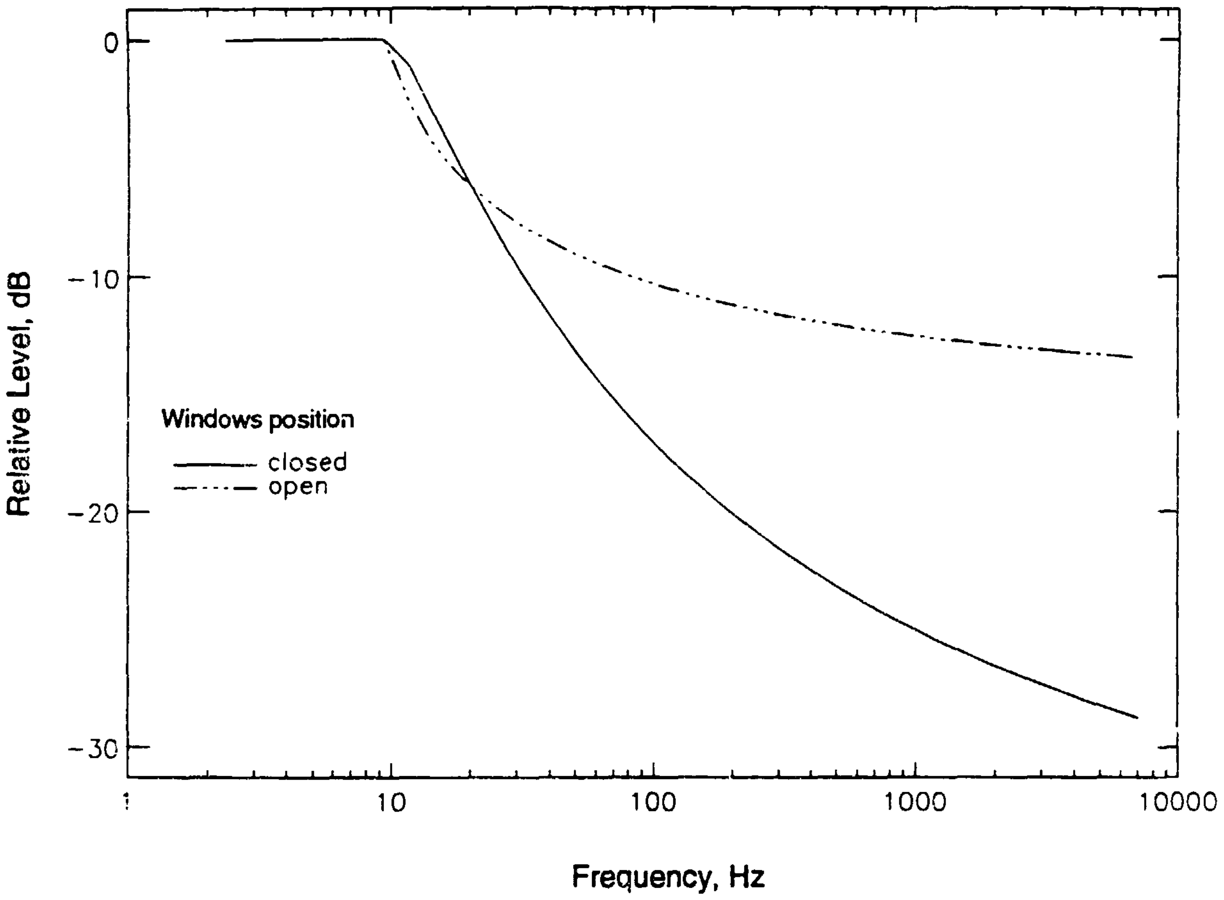


Figure 3. Windows open and windows closed house filters. (From Reference 4.)

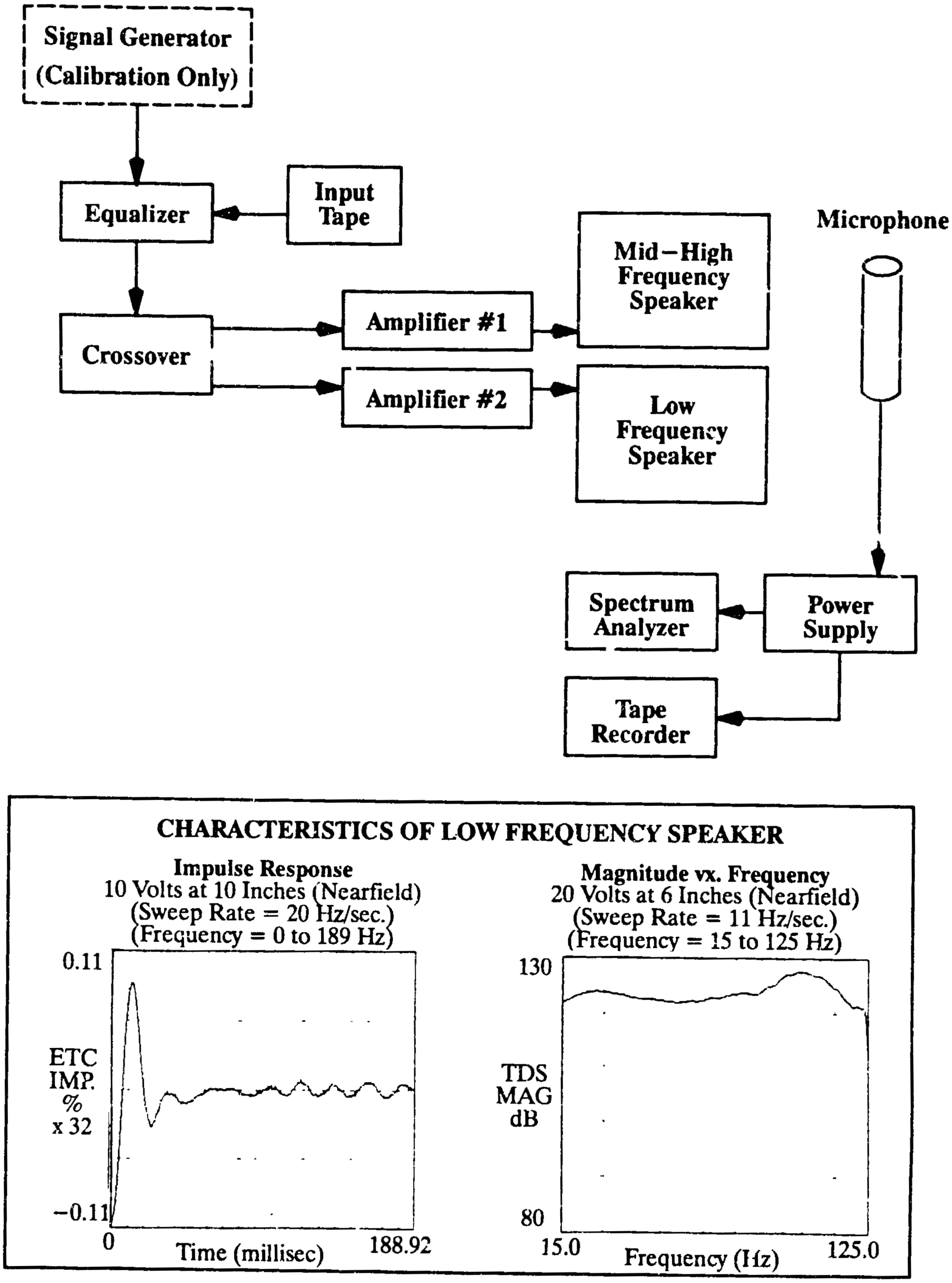
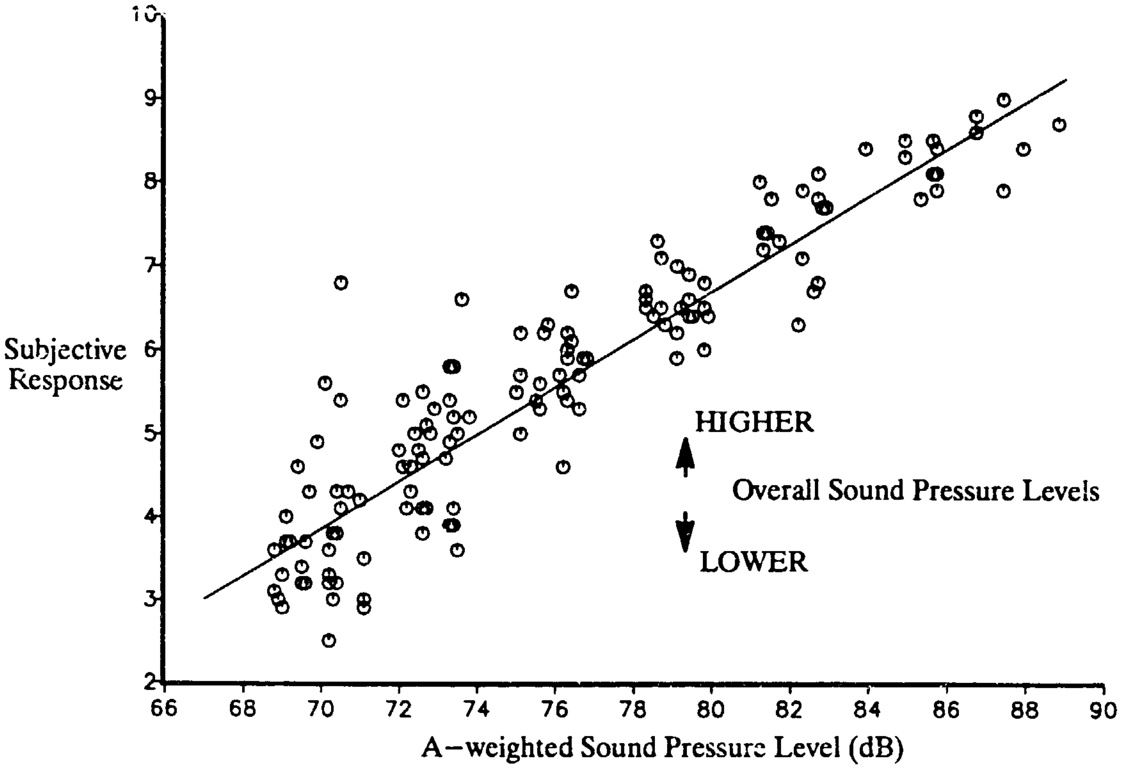
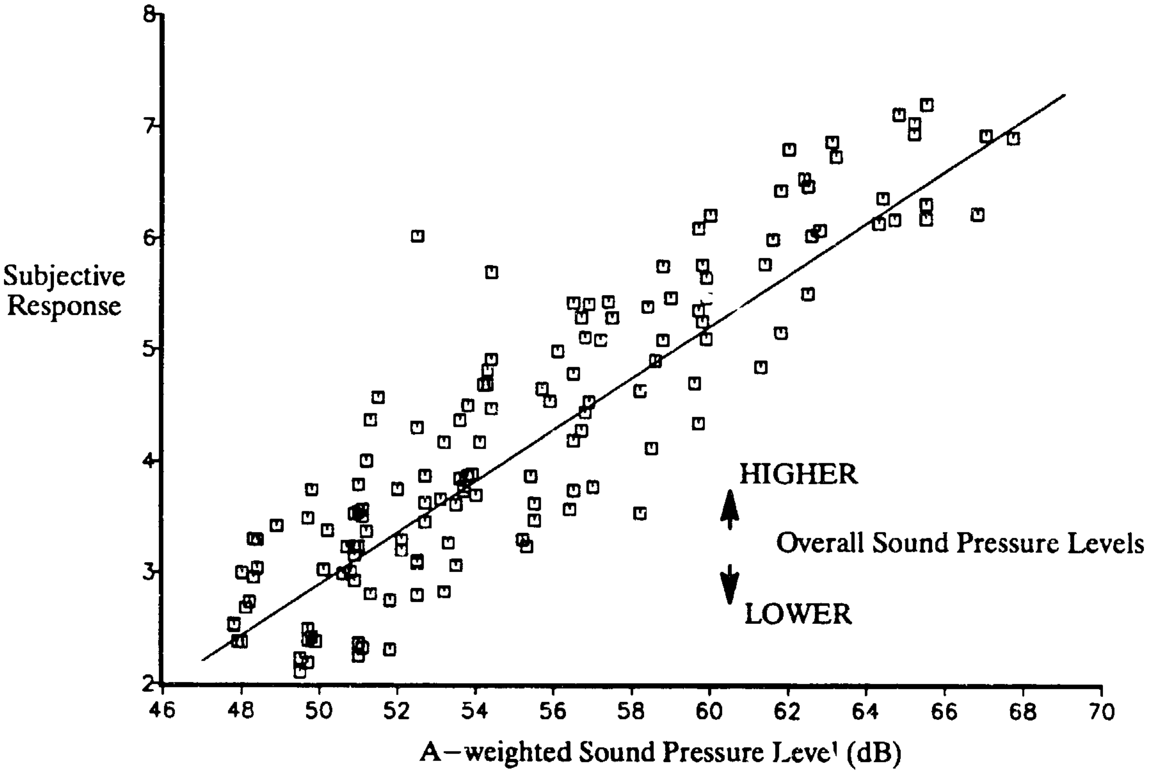


Figure 4. Instrumentation System

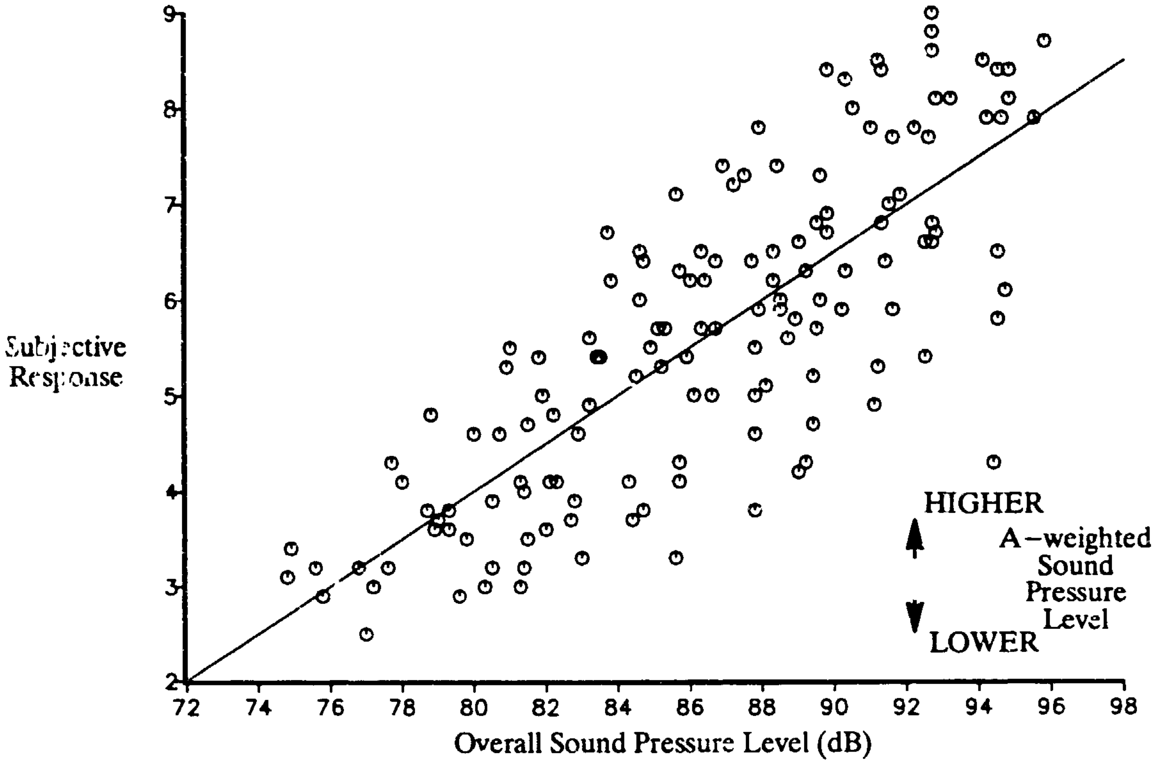


a) Outdoor Data

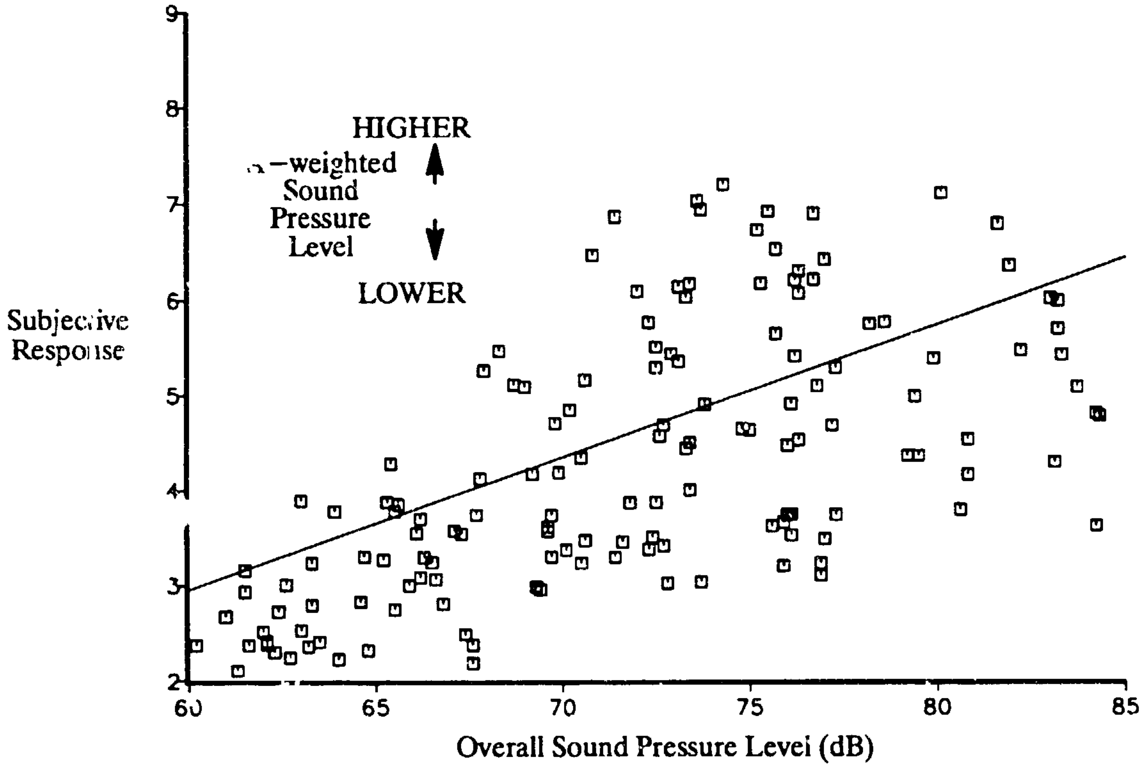


b) Indoor Data

Figure 5. Correlation of Subjective Response with A–weighted sound pressure level.

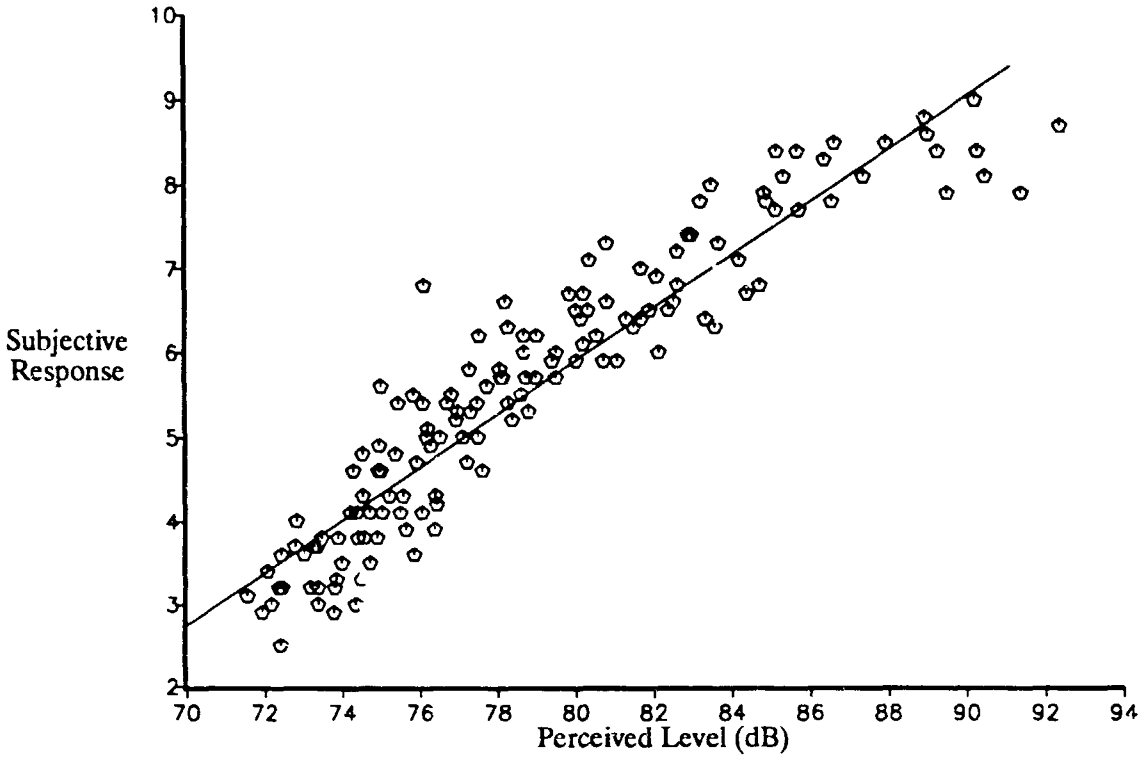


a) Outdoor Data

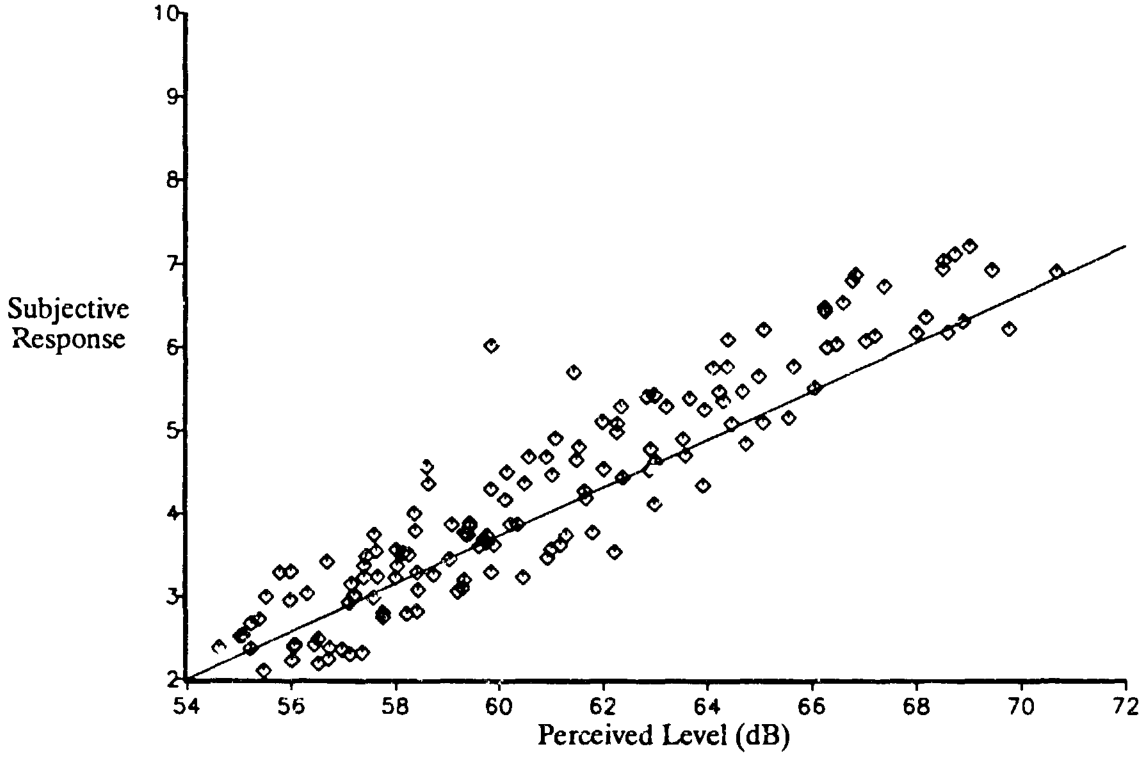


b) Indoor Data

Figure 6. Correlation of Subjective Response with Overall sound pressure level.



a) Outdoor Data



b) Indoor Data

Figure 7. Correlation of Subjective Response with Perceived Level.

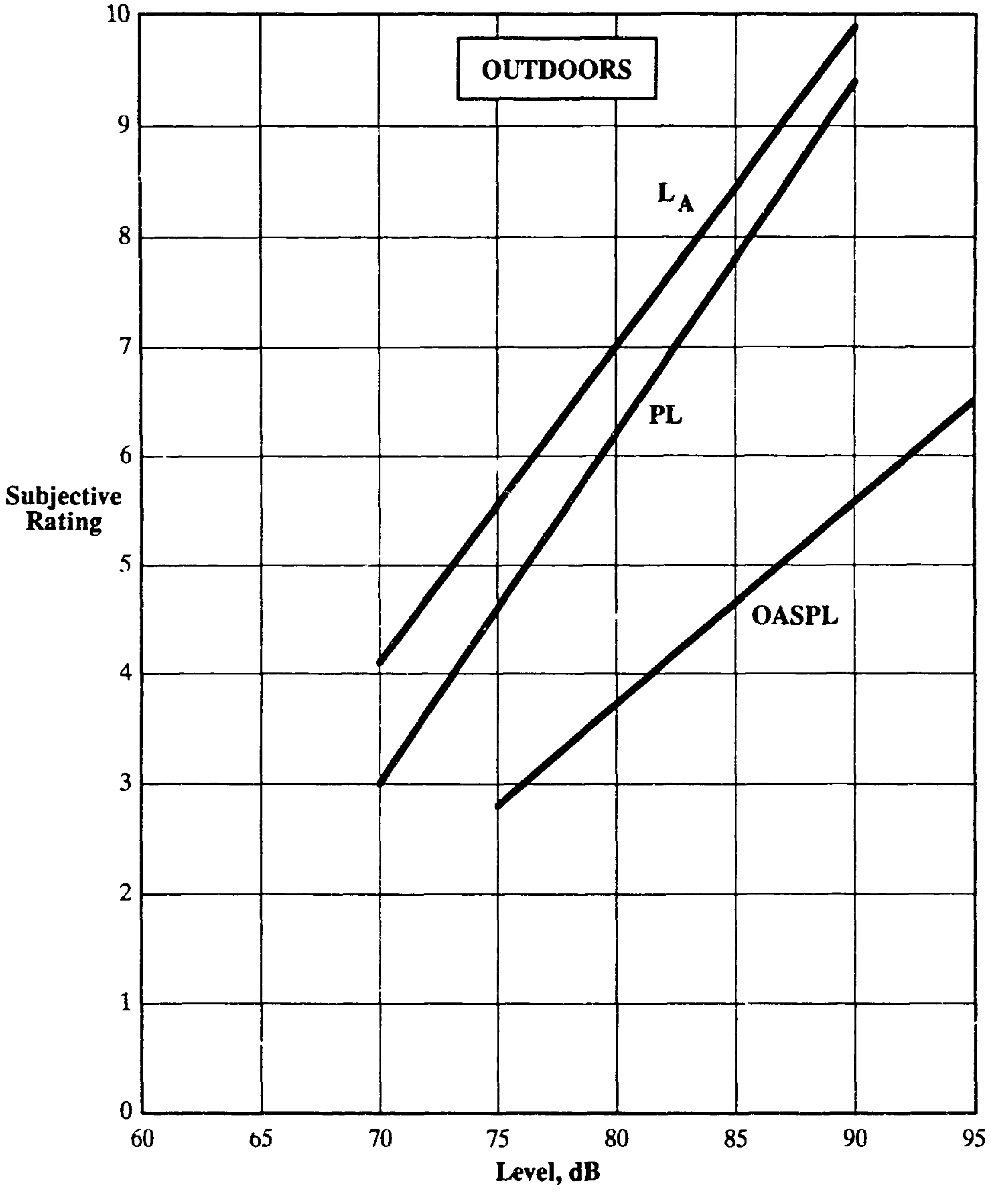


Figure 8. Sensitivity of Subjective Ratings to Single Noise Metrics for Outdoor Sounds

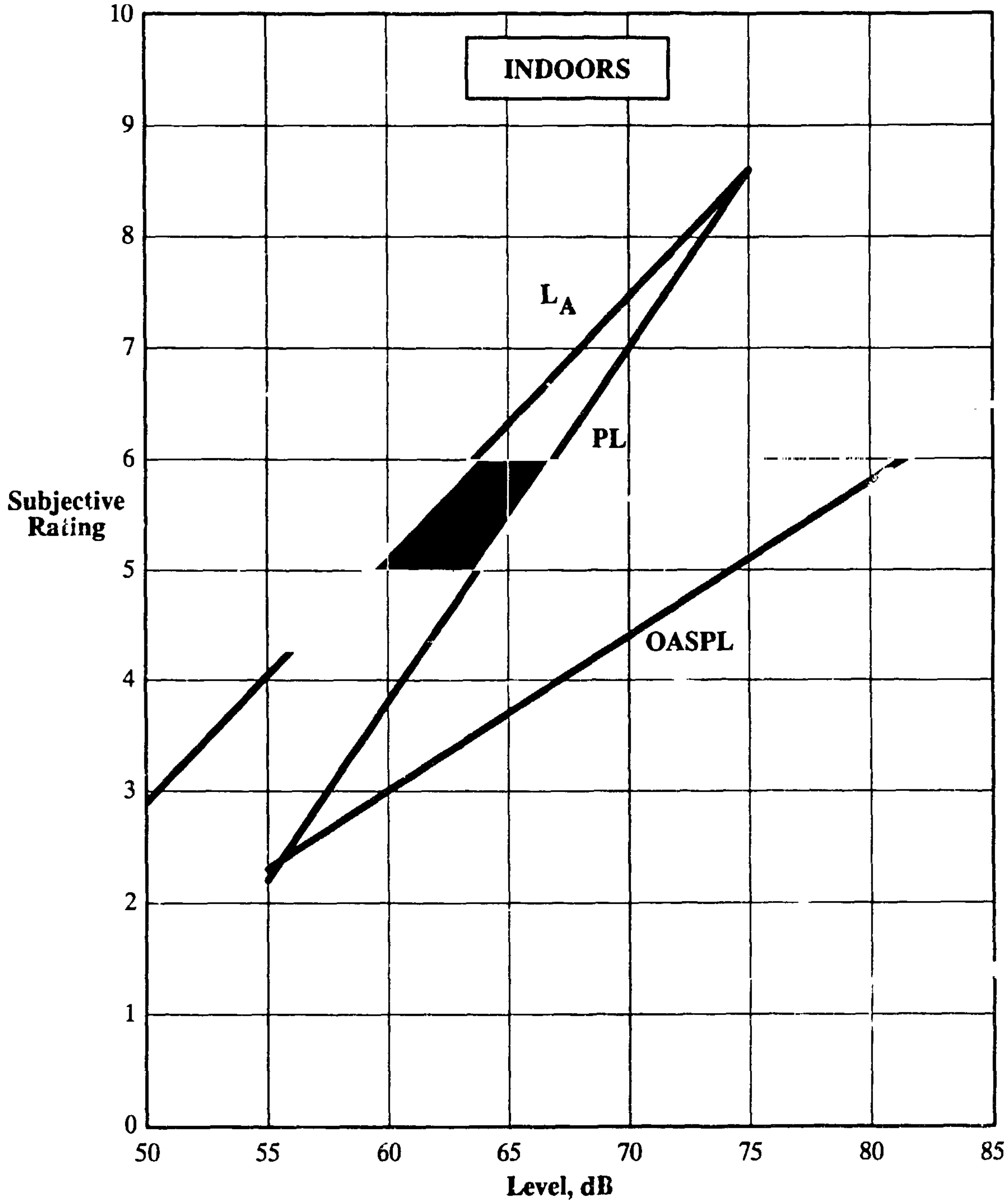


Figure 9. Sensitivity of Subjective Ratings to Single Noise Metrics for Indoor Sounds.

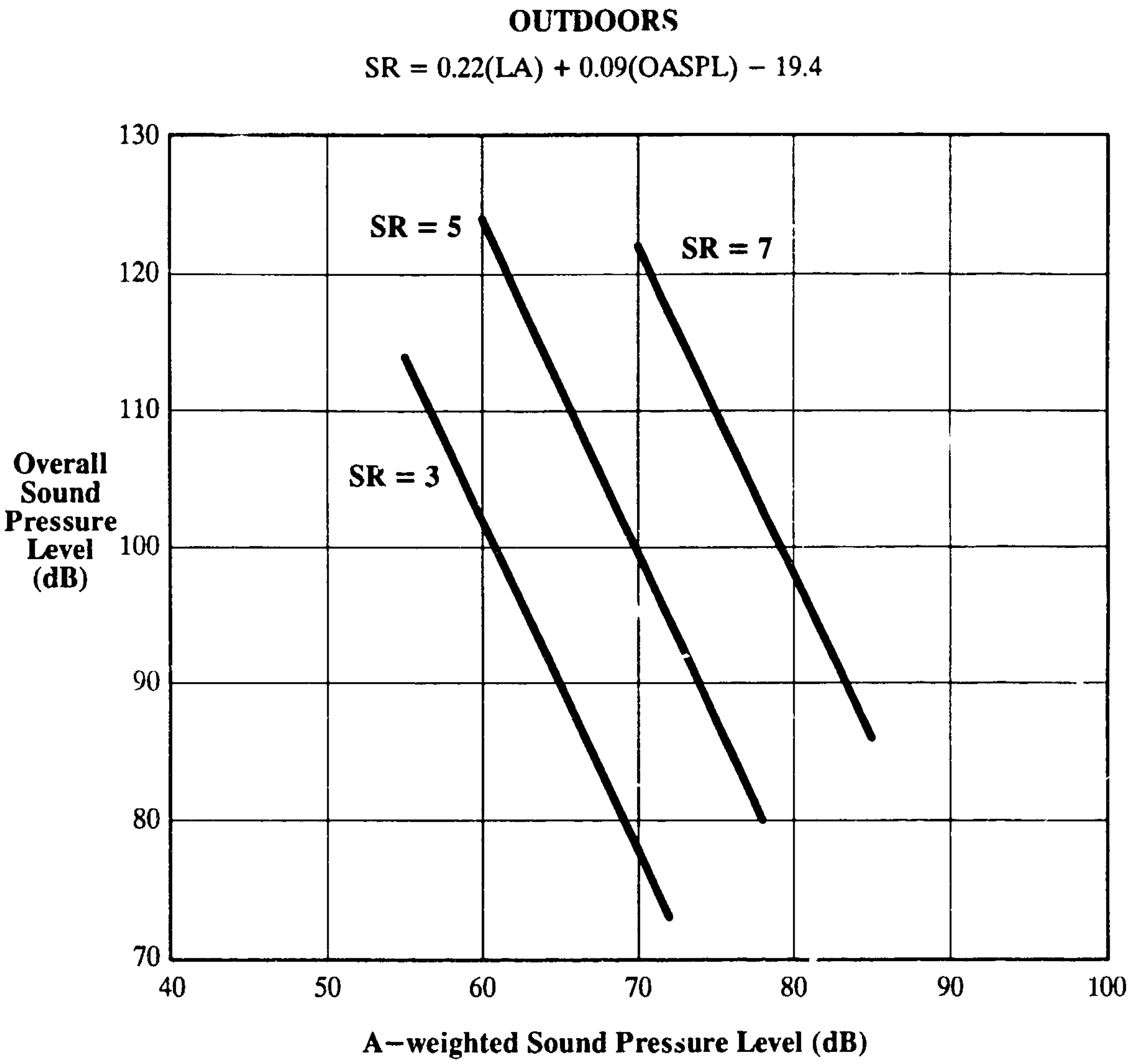
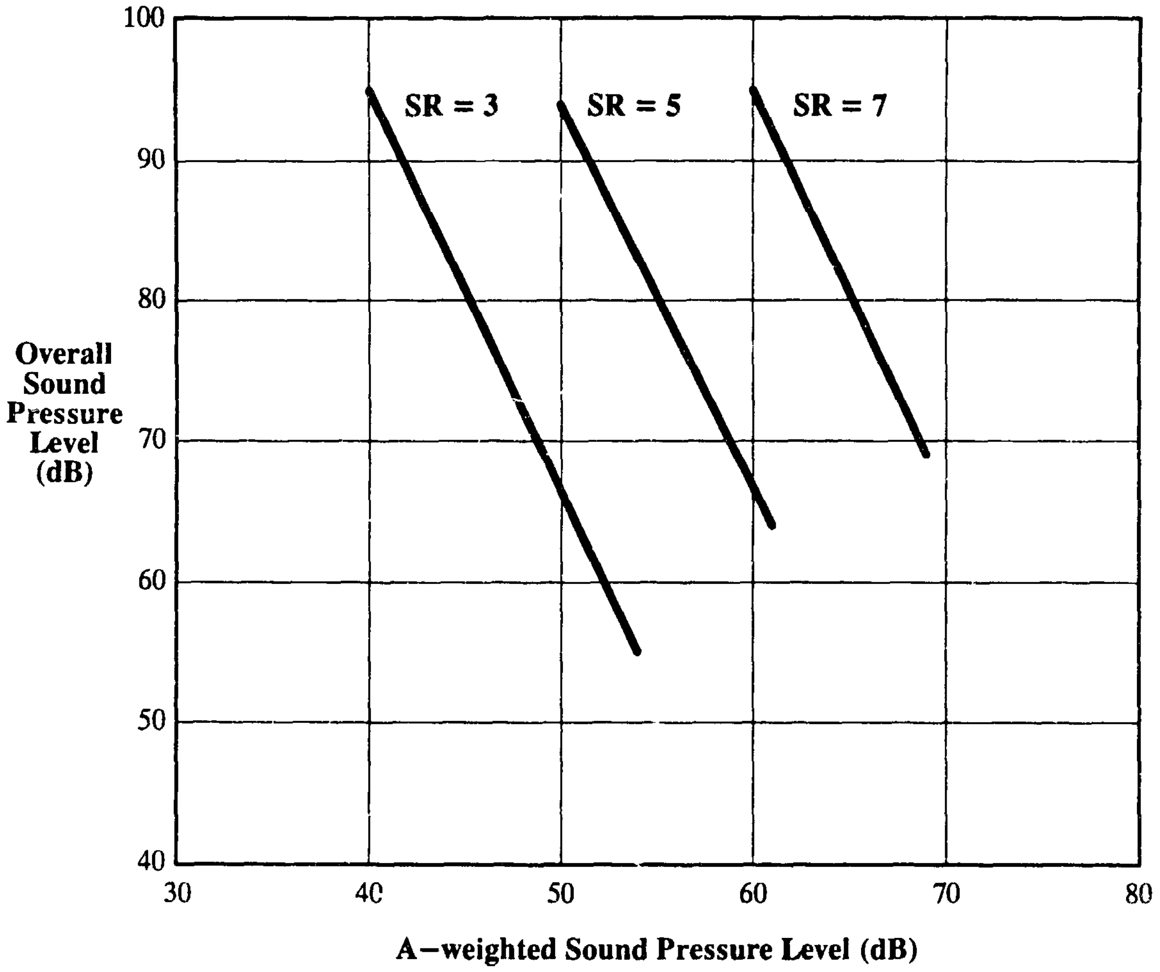


Figure 10. Subjective Ratings as a Function of A−weighted sound pressure level and Overall sound pressure level for Outdoor Sounds.



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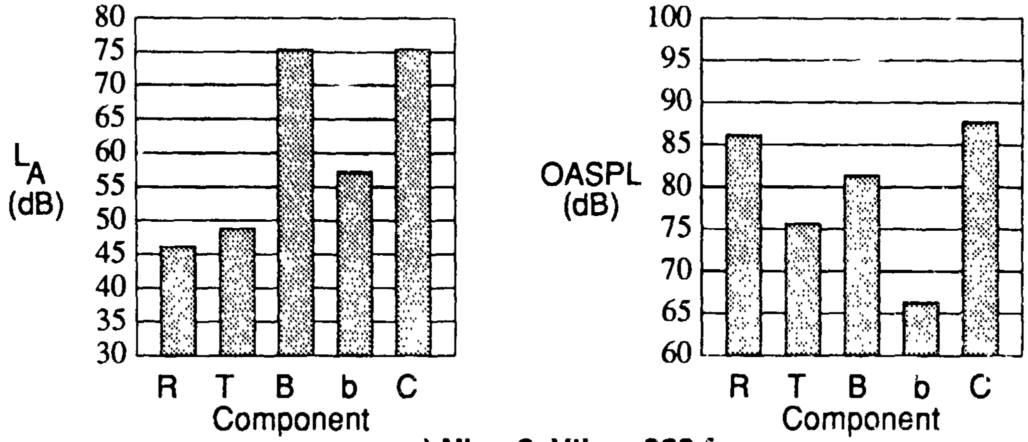
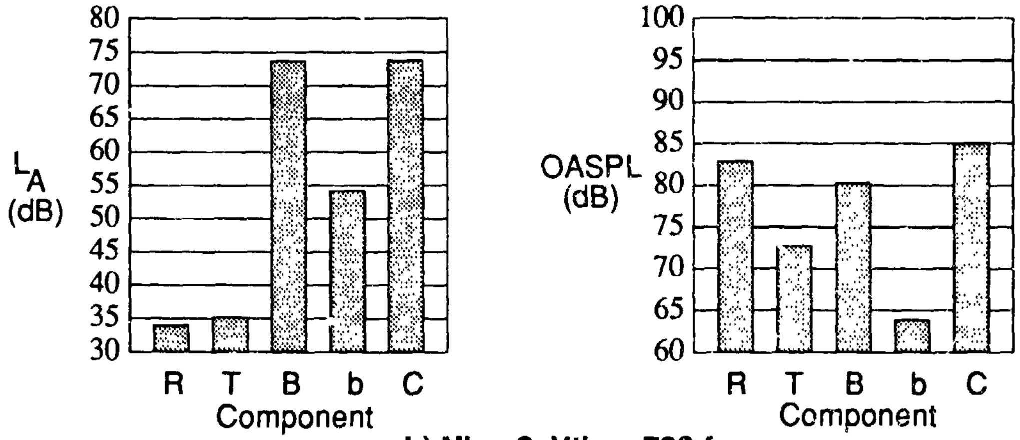
SR = 0.20(LA) + 0.70(OASPL) − 11.65

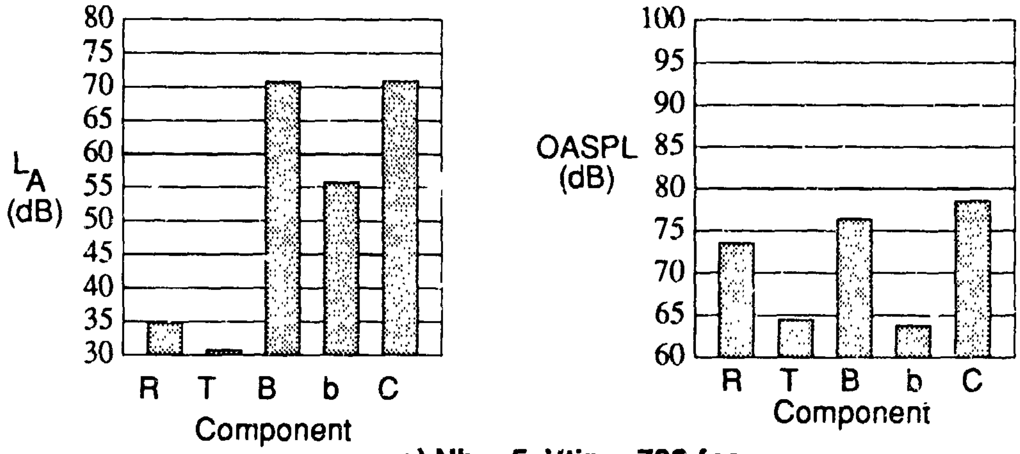
Figure 11. Subjective Ratings as a Function of A−weighted sound pressure level and Overall sond pressure level for Indoor Sounds.



a) Nb = 3, Vtip = 800 fps



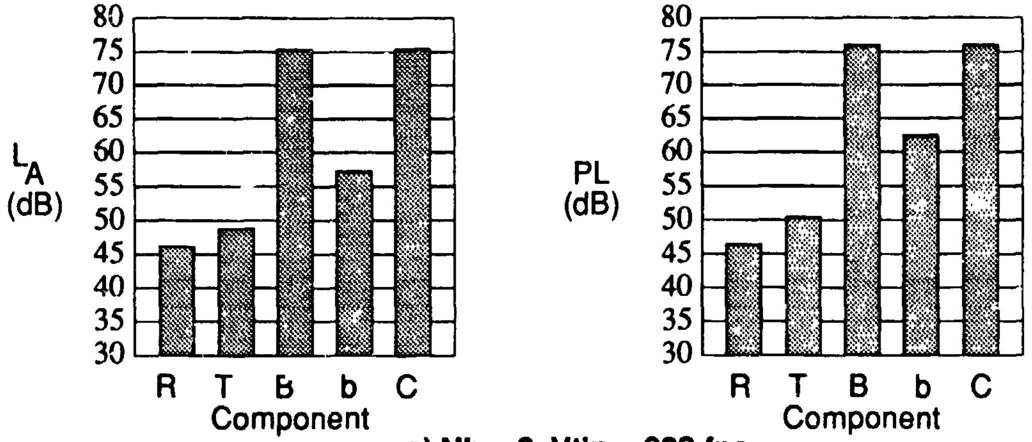
b) Nb = 3, Vtip = 700 fps



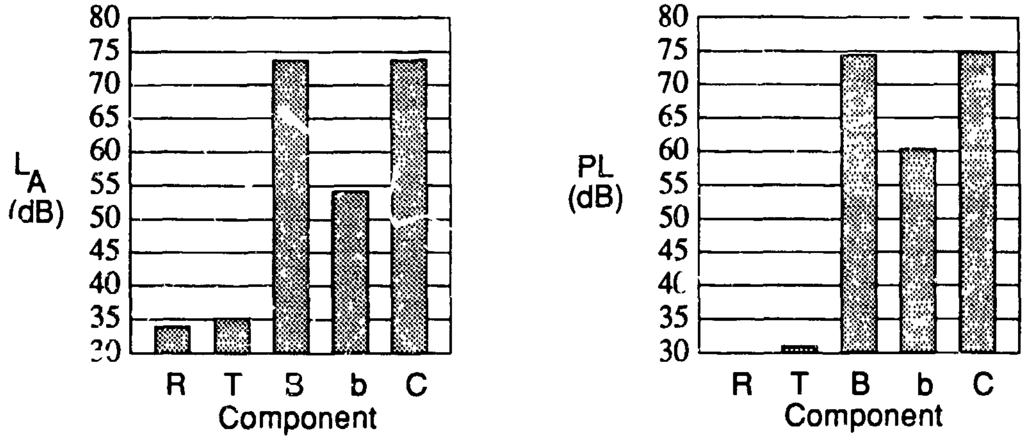
c) Nb = 5, Vtip = 700 fps

R – Rotational T – Thickness B – BVI b – Broadband C – Combined

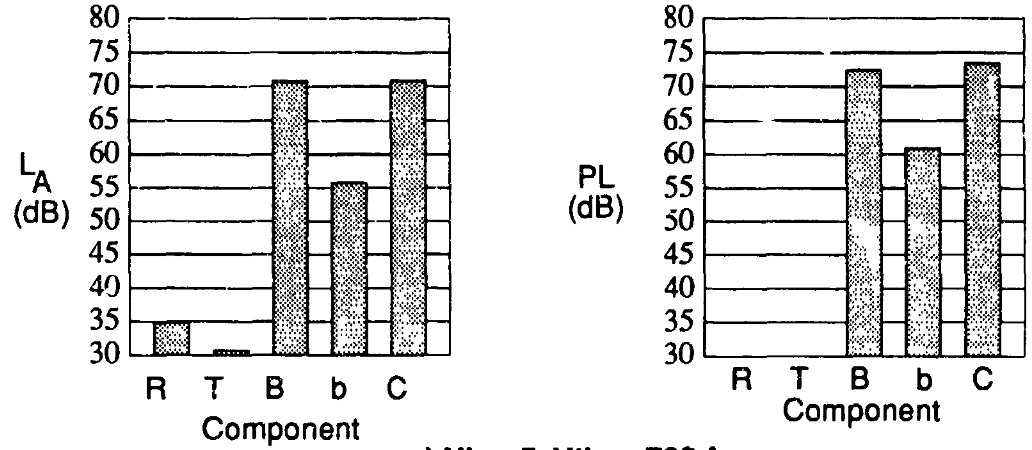
Figure 12. Effect of Tip Speed and Number of Blades on A–weighted and Overall sound pressure level for Descent.



a) Nb = 3, Vtip = 800 fps



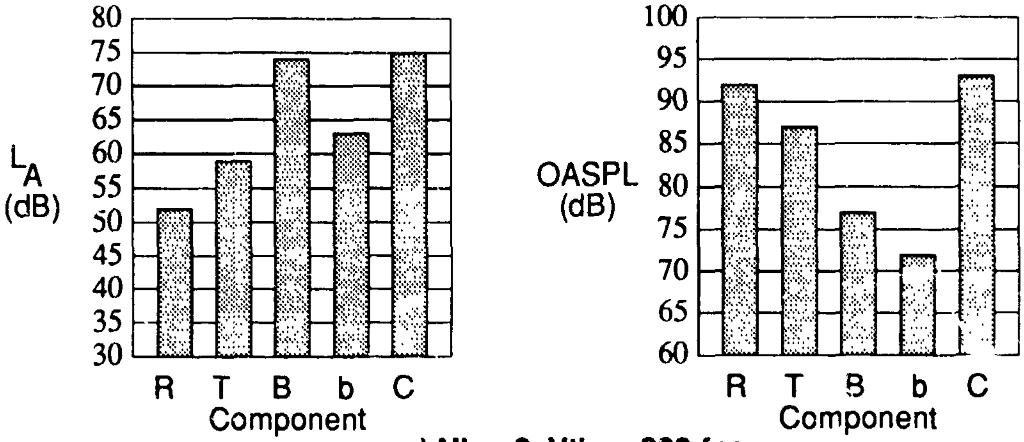
b) Nb = 3, Vtip = 700 fps



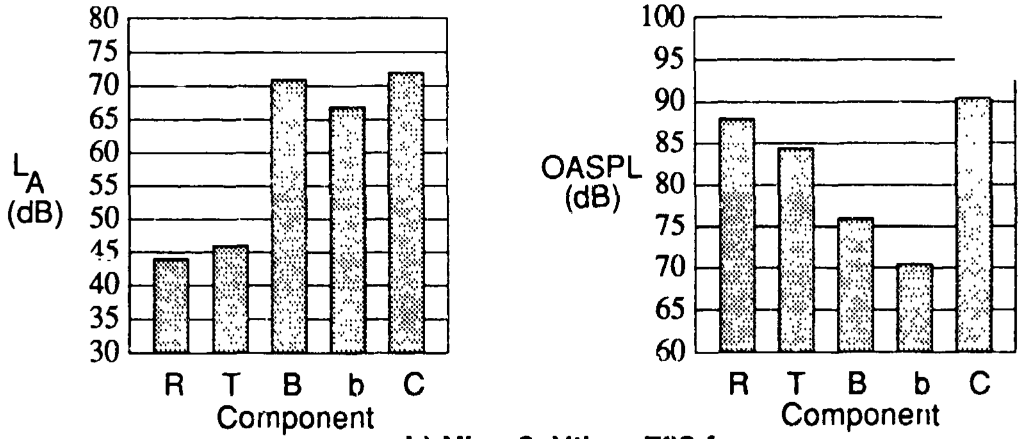
c) Nb = 5, Vtip = 700 fps

R – Rotational T – Thickness B – BVI b – Broadband C – Combined

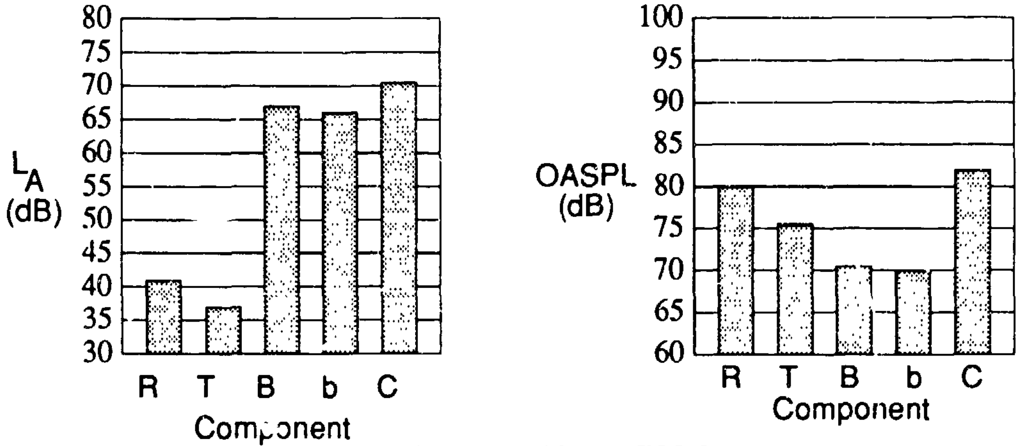
Figure 13. Effect of Tip Speed and Number of Blades on A–weighted sound pressure level and Perceived Level for Descent.



a) Nb = 3, Vtip = 800 fps



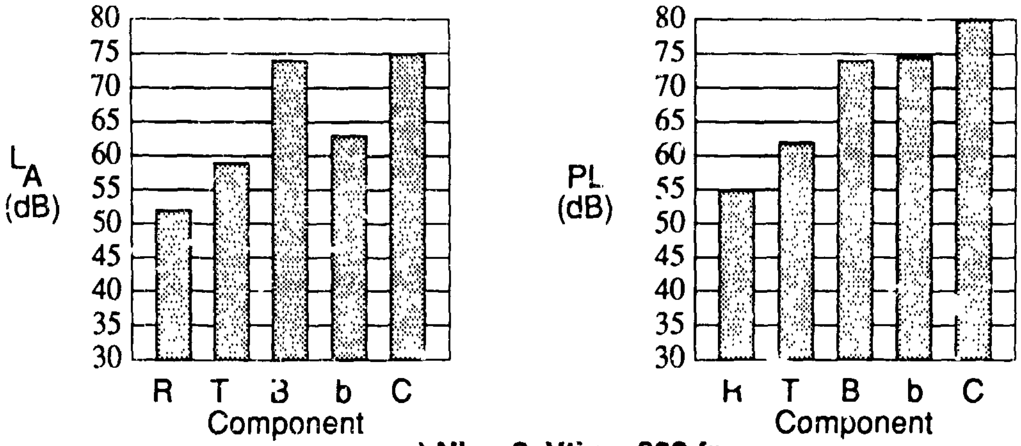
b) Nb = 3, Vtip = 700 fps



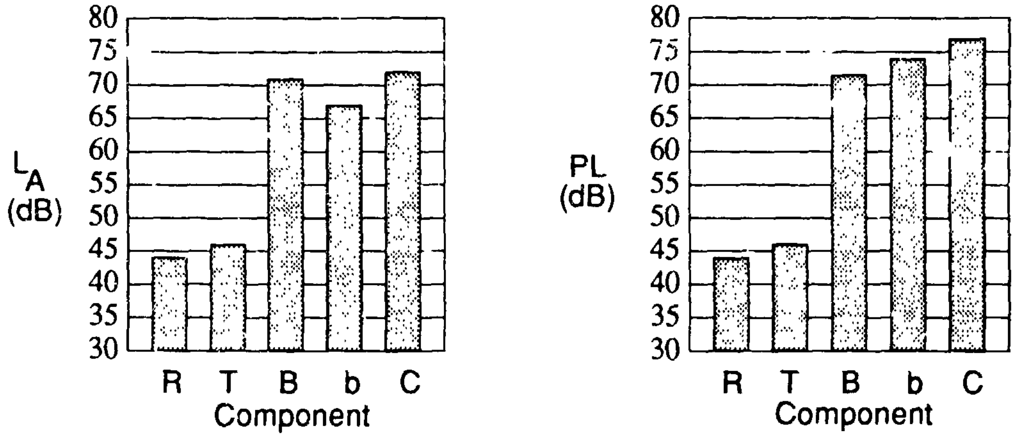
c) Nb = 5, Vtip = 700 fps

R – Rotational T – Thickness B – BVI b – Broadband C – Combined

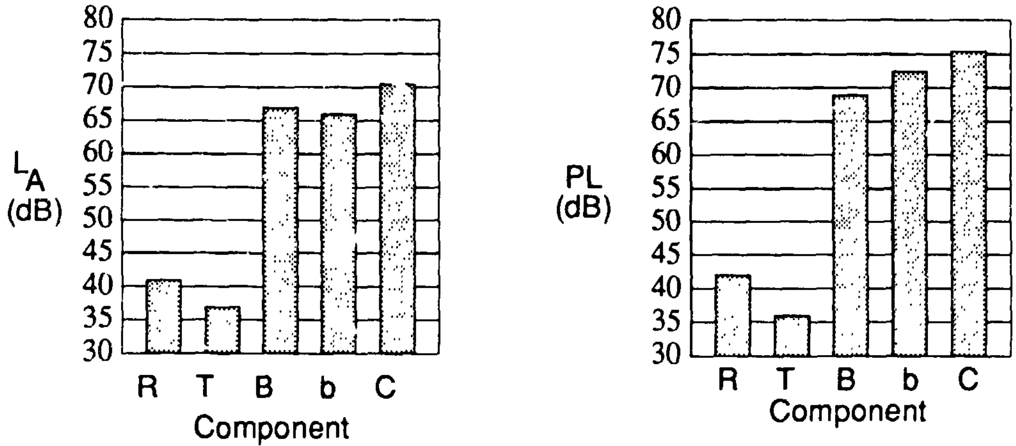
Figure 14. Effect of Tip Speed and Number of Blades on A–weighted and Overall sound pressure level for Hover.



a) Nb = 3, Vtip = 800 fps



b) Nb = 3, Vtip = 700 fps



c) Nb = 5, Vtip = 700 fps

R – Rotational T – Thickness B – BVI b – Broadband C – Combined

Figure 15. Effect of Tip Speed and Number of Blades on A–weighted sound pressure level and Perceived Level for Hover.

APPENDIX A

Consent Forms

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 by NASA Langley Research Center or

______________________.

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 participate again in the experimentation.

I undertake to obey the regulations for the facility and instructions 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.

____

Print Subject's Name

____

Signature of Subject or Legal Representative

VOLUNTARY CONSENT FORM FOR RECORDING OF SUBJECTS RESPONSE TO AIRCRAFT NOISE AND VIBRATION

I understand that AUDIO recordings are to be made of my response to the AIRCRAFT NOISE experiment to be conducted by NASA Langley Research Center on ____________, and that these recordings may be used in a technical report or presentation describing this research study.

I have been informed of the purpose of such recordings and do voluntarily consent to their use.

I further understand that I may withdraw my approval of such recordings at any time before or during the actual recording.

____

Print Subject's Name

____

Signature of Subject or Legal Representative

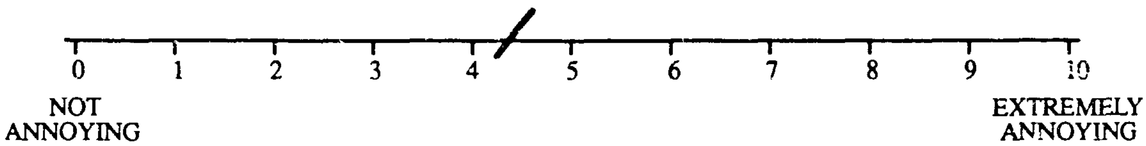
APPENDIX B

Instructions

Instructions for Rotorcraft Noise Subjective Experiment

The experiment in which you are participating will help us to understand the way people respond to various sounds produced by rotorcraft. We would like you to judge how annoying these sounds are.

This test will consist of a series of 6 minute test sessions over a period of approximately two and one half hours. During the first half of the test you will be listening to outdoor sounds, and for the second half you will hear sounds that are inside a residence or office. For each 6 minute session, 20 aircraft sounds will be presented for you to judge. You will be given scoring sheets containing rating scales like the one shown below.



After each sound there will be a few seconds of silence. During this interval please indicate how annoying you judge the sound to be by placing a ***slash*** mark along the scale, as shown in the example above. If you judge a sound to be slightly annoying, then place your slash close to the 'Not Annoying' end of the scale. Similarly, if you judge a sound to be very annoying, then place your slash near the 'Extremely Annoying' end of the scale. A moderately annoying judgement should be marked in the middle portion of the scale. You may place your mark anywhere along the continuous scale and may change your score for any sound, but 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.

Prior to the first session, you will listen to outdoors sounds that are similar to those you will be asked to rate. We will then give you a practice scoring session. Upon completion of the practice session we will collect the practice sheets and answer any questions you may have concerning the test. At this point the first test session will be conducted followed by a two minute break, a second test session and another two minute break, and so forth. There will be a total of seven (7) sessions of 20 sounds each during the first hour of testing. At that time, there will be a 10 minute break during which you may leave the room if you wish. Please do not discuss the test with other participants during any of the breaks. During each break you are encouraged to stand, stretch or move about.

The second hour will consist of indoor sounds where you are to assume you are inside a residence or office, but otherwise it will be conducted similar to the first series of tests.

APPENDIX C

Data Summary

OUTDOOR Raw Data Source (page 1 of 3)

OBS	RECNB	BPF	LA	OASPL	PL	SUBRESP
1	1	20	79.5	86.7	81.3	6.4
2	2	25	76.2	87.8	78.6	5.5
3	3	20	73.3	80.5	75.6	3.9
4	4	25	76.2	82.9	77.6	4.6
5	5	25	85.7	74.8	90.4	8.1
6	6	35	78.3	86.3	80.3	6.5
7	7	15	79.8	88.5	82.1	6.0
8	8	15	87.4	95.5	91.3	7.9
9	9	30	69.0	85.6	73.8	3.3
10	10	20	76.4	92.8	80.2	6.7
11	11	35	81.7	89.6	83.6	7.3
12	12	30	72.6	89.4	77.2	4.7
13	13	35	72.6	78.7	74.9	3.8
14	14	30	69.0	75.8	71.9	2.9
15	15	30	75.1	81.9	77.1	5.0
16	16	20	73.4	88.9	77.3	5.8
17	17	15	85.7	94.2	89.4	7.9
18	18	15	71.1	81.5	74.7	3.5
19	19	25	82.3	91.8	84.1	7.1
20	20	35	72.5	82.2	75.3	4.8
21	21	25	79.1	86.0	80.5	6.2
22	22	30	75.1	83.8	77.5	6.2
23	23	25	72.6	79.3	74.4	3.8
24	24	30	75.0	81.0	76.8	5.5
25	25	30	83.9	91.3	85.6	8.4
26	26	15	76.7	87.9	80.0	5.9
27	27	20	79.4	87.7	81.6	6.4
28	28	20	88.8	95.8	92.3	8.7
29	29	35	69.2	84.4	73.4	3.7
30	30	25	76.4	94.7	80.2	6.1
31	31	15	79.9	91.4	83.3	6.4
32	32	35	72.8	87.8	76.5	5.0
33	33	15	71.1	80.3	74.3	3.0
34	34	35	69.6	75.6	72.4	3.2
35	35	35	75.5	81.8	77.5	5.4
36	36	25	72.9	91.2	77.0	5.3
37	37	20	85.6	92.8	87.3	8.1
38	38	20	70.5	82.3	74.2	4.1
39	39	30	81.3	88.4	82.9	7.4
40	40	15	70.2	83.0	74.5	3.3
41	41	30	78.7	84.6	80.0	6.5
42	42	35	75.6	83.2	77.7	5.6
43	43	30	72.2	78.0	74.3	4.1
44	44	35	75.6	80.9	77.3	5.3
45	45	35	84.9	91.2	86.6	8.5
46	46	20	76.3	89.6	79.5	6.0
47	47	25	79.1	88.5	81.0	5.9
48	48	25	87.9	94.8	90.2	8.4
49	49	15	82.7	91.3	84.7	6.8
50	50	30	75.1	89.5	78.7	5.7
51	51	20	79.4	92.5	82.5	6.6
52	52	15	71.0	89.0	76.4	4.2

OUTDOOR Raw Data Source (page 2 of 3)

OBS	RECNB	BPF	LA	OASPL	PL	SUBRESP
53	53	20	70.4	80.5	73.8	3.2
54	54	15	71.1	79.6	73.8	2.9
55	55	15	73.4	82.8	76.4	3.9
56	56	30	72.4	86.1	76.1	5.0
57	57	25	85.3	92.2	86.5	7.8
58	58	25	70.3	84.7	73.9	3.8
59	59	35	81.5	87.9	83.2	7.8
60	60	20	70.5	85.7	74.7	4.1
61	61	35	78.3	83.7	79.8	6.7
62	62	15	73.4	84.5	76.9	5.2
63	63	35	72.3	77.7	74.5	4.3
64	64	15	73.4	82.1	76.6	4.1
65	65	15	82.9	92.6	85.7	7.7
66	66	25	76.3	91.6	79.4	5.9
67	67	30	78.7	85.6	80.3	7.1
68	68	30	86.7	92.7	88.9	8.8
69	69	20	82.6	89.8	84.3	8.7
70	70	35	75.7	88.3	78.6	6.2
71	71	25	79.2	94.5	82.3	6.5
72	72	20	70.5	92.5	76.1	5.4
73	73	25	70.2	81.4	73.4	3.2
74	74	20	70.4	77.6	73.2	3.2
75	75	20	73.3	83.2	76.2	4.9
76	76	35	72.6	84.9	75.8	5.5
77	77	30	83.9	89.8	85.1	8.4
78	78	30	68.8	79.3	72.4	3.6
79	79	15	79.8	89.5	82.6	6.8
80	80	25	70.4	87.8	74.5	3.8
81	81	15	76.6	85.3	78.9	5.7
82	82	20	73.3	85.9	76.7	5.4
83	83	15	71.1	79.8	74.0	3.5
84	84	20	73.2	81.5	75.9	4.7
85	85	20	82.7	93.2	85.3	8.1
86	86	30	75.1	86.7	78.1	5.7
87	87	35	78.5	84.7	80.1	6.4
88	88	35	87.4	92.7	90.1	9.0
89	89	25	82.2	89.2	83.5	6.3
90	90	15	73.8	89.4	78.4	5.2
91	91	30	78.8	90.3	81.5	6.3
92	92	25	70.7	94.4	76.4	4.3
93	93	30	68.9	77.2	72.2	3.0
94	94	25	70.2	77.0	72.4	2.5
95	95	25	72.7	84.3	75.5	4.1
96	96	15	70.4	85.7	75.2	4.3
97	97	35	84.9	90.3	86.3	8.3
98	98	35	69.6	79.0	72.8	3.7
99	99	20	79.4	89.8	82.0	6.9
100	100	30	69.1	82.7	73.3	3.7
101	101	20	76.3	84.6	78.7	6.0
102	102	25	72.7	88.1	76.2	5.1
103	103	20	70.4	78.7	73.5	3.8
104	104	25	72.6	81.3	75.0	4.1

OUTDOOR Raw Data Source (page 3 of 3)

OBS	RECNB	BPF	LA	OASPL	PL	SUBRESP
105	105	25	82.3	94.6	84.8	7.9
106	106	35	75.8	85.7	78.2	6.3
107	107	15	76.6	86.3	79.5	5.7
108	108	15	85.7	94.5	89.2	8.4
109	109	30	81.3	87.2	82.6	7.2
110	110	20	73.6	92.7	78.2	6.6
111	111	35	78.3	89.0	80.8	6.6
112	112	30	69.7	89.2	75.6	4.3
113	113	35	69.5	76.8	72.4	3.2
114	114	30	68.8	74.8	71.5	3.1
115	115	30	72.1	80.7	74.9	4.6
116	116	20	70.1	88.7	75.0	5.6
117	117	15	82.8	91.6	85.1	7.7
118	118	15	76.6	85.2	78.8	5.3
119	119	25	79.1	91.5	81.6	7.0
120	120	35	69.1	81.4	72.8	4.0
121	121	25	76.1	85.1	78.1	5.7
122	122	30	72.1	83.4	75.4	5.4
123	123	25	70.2	78.9	73.0	3.6
124	124	30	72.0	78.8	74.8	4.8
125	125	30	81.2	90.5	83.1	8.0
126	126	15	73.5	86.6	77.5	5.0
127	127	20	76.3	86.4	79.0	6.2
128	128	20	85.6	94.1	87.9	8.5
129	129	35	81.4	86.9	82.8	7.4
130	130	25	73.3	94.5	78.0	5.8
131	131	15	76.8	90.2	80.7	5.9
132	132	35	69.4	87.8	74.3	4.6
133	133	15	73.5	82.0	75.8	3.6
134	134	35	69.5	74.9	72.1	3.4
135	135	35	72.3	80.0	75.0	4.6
136	136	25	69.9	91.1	74.9	4.9
137	137	20	82.7	91.0	84.8	7.8
138	138	20	76.3	83.5	78.2	5.4
139	139	30	78.6	87.5	80.7	7.3
140	140	15	79.8	88.3	81.9	6.5
141	141	30	86.7	92.7	88.9	8.6
142	142	25	70.3	81.3	73.4	3.0
143	143	20	73.3	83.2	76.3	4.9
144	144	20	70.4	77.6	73.2	3.2
145	145	20	70.5	92.7	76.1	6.8

INDOOR Raw Data Source (page 1 of 3)

OBS	RECNB	BPF	LA	OASPL	PL	SUBRESP
1	1	20	58.5	67.8	63.0	4.1
2	2	25	55.5	75.6	61.2	3.6
3	3	20	52.5	63.3	58.2	2.8
4	4	25	55.2	64.7	59.9	3.3
5	5	25	64.4	81.9	68.2	6.4
6	6	35	56.7	72.5	62.3	5.3
7	7	15	59.7	70.5	63.9	4.3
8	8	15	66.8	76.7	69.8	0.2
9	9	30	48.4	73.7	56.3	3.0
10	10	20	56.5	83.3	63.0	5.4
11	11	35	59.9	75.7	65.0	5.7
12	12	30	52.0	77.3	59.4	3.7
13	13	35	50.8	62.6	57.3	3.0
14	14	30	47.8	62.0	55.0	2.5
15	15	30	53.6	65.6	59.4	3.8
16	16	20	53.6	79.5	60.5	4.4
17	17	15	65.5	75.3	68.6	6.2
18	18	15	51.3	66.8	57.8	2.8
19	19	25	61.4	78.6	65.7	5.8
20	20	35	51.1	69.6	58.0	3.6
21	21	25	58.2	67.3	62.2	3.5
22	22	30	53.7	69.7	59.8	3.7
23	23	25	51.8	62.3	57.1	2.3
24	24	30	53.7	63.9	59.3	3.8
25	25	30	62.4	75.7	66.6	6.5
26	26	15	56.8	73.3	62.4	4.4
27	27	20	58.6	73.8	63.5	4.9
28	28	20	67.7	76.7	70.7	6.9
29	29	35	48.9	72.7	56.7	3.4
30	30	25	56.5	84.3	62.9	4.8
31	31	15	59.9	76.8	65.1	5.1
32	32	35	52.0	76.1	59.4	3.8
33	33	15	51.1	64.8	57.4	2.3
34	34	35	48.0	61.6	55.2	2.4
35	35	35	54.0	66.2	59.7	3.7
36	36	25	53.2	80.8	60.1	4.2
37	37	20	64.7	73.4	68.0	6.2
38	38	20	50.2	72.3	57.4	3.4
39	39	30	59.8	72.3	64.4	5.8
40	40	15	50.6	69.3	57.6	3.0
41	41	30	57.0	65.5	61.8	3.8
42	42	35	54.1	69.2	60.1	4.2
43	43	30	50.9	61.5	57.1	2.9
44	44	35	53.9	63.0	59.4	3.9
45	45	35	63.2	75.2	67.4	6.7
46	46	20	56.1	79.4	62.3	5.0
47	47	25	58.2	75.0	63.0	4.6
48	48	25	67.0	75.5	69.5	6.9
49	49	15	62.5	72.5	66.1	5.5
50	50	30	54.2	77.2	60.9	4.7
51	51	20	59.0	82.2	64.7	5.5
52	52	15	52.1	75.9	59.3	3.2

INDOOR Raw Data Source (page 2 of 3)

OBS	RECNB	BPF	LA	OASPL	PL	SUBRESP
53	53	20	49.9	67.6	56.7	2.4
54	54	15	51.0	62.7	56.7	2.2
55	55	15	53.5	66.6	59.2	3.1
56	56	30	51.2	73.4	58.4	4.0
57	57	25	64.3	73.1	62.2	6.1
58	58	25	50.1	72.0	57.2	3.0
59	59	35	59.7	72.0	64.4	6 1
60	60	20	50.9	76.1	58.2	3.5
61	61	35	56.7	65.4	61.6	4.3
62	62	15	53.5	69.6	59.6	3.6
63	63	35	50.9	61.5	57.2	3.2
64	64	15	53.3	65.2	58.7	3.3
65	65	15	62.8	76.3	67.0	6.1
66	66	25	55.9	80.8	62.0	4.5
67	67	30	57.2	69.0	62.3	5.1
68	68	30	65.2	73.7	68.5	6.9
69	69	20	61.8	70.6	65.6	5.2
70	70	35	54.4	76.1	61.1	4.9
71	71	25	58.8	83.7	64.5	5.1
72	72	20	52.5	83.1	59.9	4.3
73	73	25	49.7	67.4	56.5	2.5
74	74	20	49.7	62.1	56.1	2.4
75	75	20	52.7	71.8	59.1	3.9
76	76	35	51.5	72.6	58.6	4.6
77	77	30	62.5	70.8	66.2	6.5
78	78	30	48.0	65.9	55.5	3.0
79	79	15	59.7	73.1	64 3	5.4
80	80	25	50.7	76.9	58.0	3.2
81	81	15	56.5	67.7	61.3	3.7
82	82	20	53.1	75.9	59.8	3.7
83	83	15	51.0	63.2	57.0	2.4
84	84	20	52.5	66.2	58.4	3.1
85	85	20	62.0	81.6	66.8	6.8
86	86	30	53.8	73.4	60.2	4.5
87	87	35	56.8	68.7	62.0	5.1
88	88	35	65.5	74.3	69.0	7.2
89	89	25	61.3	70.2	64.7	4.9
90	90	15	54.4	76.0	61.0	4.5
91	91	30	57.5	77.3	63.2	5.3
92	92	25	52.7	84.2	59.9	3.6
93	93	30	47.8	63.0	55.1	2.5
94	94	25	49.5	61.3	55.5	2.1
95	95	25	52.1	71.4	58.4	3.3
96	96	15	51.1	72.4	58.3	3.5
97	97	35	63.1	71.4	66.9	6.9
98	98	35	48.4	66.3	55.8	3.3
99	99	20	58.8	78.2	64.1	5.8
100	100	30	48.3	69.7	56.0	3.3
101	101	20	55.5	70.6	60.9	3.5
102	102	25	52.5	76.9	59.3	3.1
103	103	20	49.8	63.5	56.4	2.4
104	104	25	51.8	65.5	57.8	2.8

INDOOR Raw Data Source (page 3 of 3)

OBS	RECNB	BPF	LA	OASPL	PL	SUBRESP
105	105	25	61.6	83.2	66.3	6.0
106	106	35	54.3	72.7	60.6	4.7
107	107	15	56.5	69.9	61.7	4.2
108	108	15	65.5	76.3	68.9	6.3
109	109	30	59.8	67.9	64.0	5.3
110	110	20	54.4	83.2	61.4	5.7
111	111	35	56.9	76.2	62.8	5.4
112	112	30	49.7	77.0	57.4	3.5
113	113	35	48.2	62.4	55.4	2.7
114	114	30	47.9	60.2	54.6	2.4
115	115	30	51.0	66.5	57.7	3.2
116	116	20	51.3	79.2	58.6	4.4
117	117	15	62.6	73.3	66.5	6.0
118	118	15	56.4	67.1	61.0	3.6
119	119	25	58.4	79.9	63.7	5.4
120	120	35	48.3	69.4	56.0	3.0
121	121	25	55.3	70.5	60.5	3.2
122	122	30	51.2	70.1	58.0	3.4
123	123	25	49.5	64.0	56.0	2.2
124	124	30	50.9	63.3	57.4	3.2
125	125	30	60.0	76.2	65.1	6.2
126	126	15	53.8	72.5	60.2	3.9
127	127	20	55.7	74.8	61.5	4.7
128	128	20	64.8	80.1	68.7	7.1
129	129	35	59.9	68.3	64.2	5.5
130	130	25	54.3	84.2	61.5	4.8
131	131	15	56.9	76.3	62.9	4.5
132	132	35	49.8	76.0	57.6	3.7
133	133	15	53.2	64.6	58.4	2.8
134	134	35	48.1	61.0	55.2	2.7
135	135	35	51.0	66.1	57.6	3.5
136	136	25	51.0	80.6	58.4	3.8
137	137	20	61.8	77.0	66.3	6.4
138	138	20	55.4	65.3	60. 4	3.9
139	139	30	57.4	72.9	63.0	5.4
140	140	15	59.6	69.8	63.6	4.7
141	141	30	65.2	73.6	68.5	7.0
142	142	25	49.7	67.6	56.5	2.2
143	143	20	52.7	71.6	59.0	3.5
144	144	20	49.8	62.1	56.1	2.4
145	145	20	52.5	83.0	59.9	6.0

APPENDIX D

Statistical Analysis
Regression Equation Coefficients

OUTDOOR DATA

N = 145 Regression Models for Dependent Variable: SUBRESP

In	Rsq	MSE	SSE	Parameter Estimates Intercept	LA	OASPL	BPF	PL
1	0.8756	0.342	48.9	−19.3428	.	.	.	0.3163
1	0.8551	0.399	57.0	−16.2166	0.2872	.	.	.
1	0.6343	1.006	143.9	−15.9760	.	0.2499	.	.
1	0.0002	2.751	393.3	5.4963	.	.	0.00372	.
2	0.9020	0.272	38.6	−19.4429	0.2227	0.0941	.	.
2	0.8941	0.294	41.7	−20.6085	.	.	0.0322	0.3222
2	0.8841	0.321	45.6	−20.2445	.	0.0471	.	0.2761
2	0.8765	0.342	48.6	−18.9455	0.0475	.	.	0.2655
2	0.8616	0.383	54.4	−16.8259	0.2889	.	0.0191	.
2	0.6731	0.906	128.6	−18.3713	.	0.2639	0.0475	.
3	0.9207	0.221	31.2	−21.0092	0.2157	0.1088	0.0333	.
3	0.9088	0.254	35.9	−22.0538	.	0.0635	0.0381	0.2691
3	0.9053	0.264	37.2	−18.7898	0.3654	0.1309	.	−0.1860
3	0.8942	0.295	41.6	−20.8241	−0.0215	.	0.0331	0.3453
4	0.9216	0.220	30.8	−20.5922	0.2912	0.1275	0.0317	−0.0980

Statistical Analysis
Regression Equation Coefficients

INDOOR DATA

N = 145 Regression Models for Dependent Variable: SUBRESP

In	Rsq	MSE	SSE	Parameter Estimates Intercept	LA	OASPL	BPF	PL
1	0.8708	0.240	34.3	−15.3587	.	.	.	0.3218
1	0.8021	0.368	52.6	−8.9074	0.2386	.	.	.
1	0.3931	1.128	161.4	−5.5547	.	0.1370	.	.
1	0.0003	1.859	265.8	4.1937	.	.	0.00358	.
2	0.9143	0.160	22.8	−24.6195	−0.4031	.	.	0.8388
2	0.8997	0.188	26.7	−16.7677	.	.	0.0333	0.3313
2	0.8922	0.202	28.7	−16.1087	.	0.0379	.	0.2895
2	0.8732	0.237	33.7	−11.6684	0.2046	0.0646	.	.
2	0.833	0.312	44.3	−10.2336	0.2469	.	0.0348	.
2	0.4078	1.109	157.5	−6.4576	.	0.1413	0.0238	.
3	0.9359	0.121	17.0	−25.0978	−0.3705	.	0.0290	0.8052
3	0.9259	0.140	19.7	−17.7248	.	0.0422	0.0362	0.2961
3	0.9225	0.146	20.6	−31.5939	−0.7518	−0.0523	.	1.3305
3	0.9147	0.161	22.7	−13.4091	0.2117	0.0694	0.0402	.
4	0.9368	0.120	16.8	−27.5908	−0.5006	−0.0191	0.0262	0.9875

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13. ABSTRACT *(Maximum 200 words)*

A subjective noise evaluation was conducted in which the test participants evaluated the annoyance of simulated sounds representative of future civil tiltrotor aircraft. The subjective responses were correlated with the noise metrics of A-weighted sound pressure level, overall sound pressure level, and perceived level. The results indicated that correlation between subjective response and A-weighted sound pressure level is considerably enhanced by combining it in a multiple regression with overall sound pressure level. As a single metric, perceived level correlated better than A-weighted sound pressure level due to greater emphasis on low frequency noise components. This latter finding was especially true for indoor noise where the mid and high frequency noise components are attenuated by typical building structure. Using the results of the subjective noise evaluation, the impact on tiltrotor aircraft design was also evaluated. While A-weighted sound pressure level can be reduced by reduction in tip speed, an increase in number of rotor blades is required to achieve significant reduction of low frequency noise as measured by overall sound pressure level. Additional research, however, is required to achieve comparable reductions in impulsive noise due to blade-vortex interaction, and also to achieve reduction in broad band noise.

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