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Single-Rotating Propeller Configuration

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David A. McCurdy

Langley Research Center
Hampton, Virginia

NASA

National Aeronautics
and Space Administration

Scientific and Technical
Information Division

Summary

Two laboratory experiments were conducted to quantify the annoyance response of people to synthesized advanced turboprop (propfan) aircraft flyover noise. The specific objectives were (1) to determine the effects on annoyance of fundamental frequency (blade passage frequency), frequency envelope shape (helical-tip Mach number), and tone-to-broadband noise ratio; (2) to compare the annoyance response to advanced turboprop aircraft with the annoyance responses to conventional turboprop and jet aircraft; and (3) to determine the ability of aircraft-noise measurement procedures and corrections to predict annoyance. Analyses of the data obtained from the two experiments are presented in this report.

In the first experiment a computer synthesis system was used to generate 45 realistic, time-varying simulations of propeller-aircraft takeoff noise in which the tonal content was systematically varied to represent the factorial combinations of 5 fundamental frequencies, 3 frequency envelope shapes, and 3 tone-to-broadband noise ratios. Sixty-four subjects judged the annoyance of recordings of the 45 synthesized takeoff noises presented at 3 sound pressure levels in a test facility that simulates the outdoor acoustic environment. In the second experiment, the computer synthesis system was used to generate 18 simulations of propeller-aircraft takeoff noise representing the factorial combinations of 6 fundamental frequencies and 3 tone-to-broadband noise ratios. These advanced turboprop simulations along with recordings of 5 conventional turboprop takeoffs and 5 conventional jet takeoffs were presented at 3 sound pressure levels to 32 subjects in an anechoic chamber.

Analyses of the judgments from the first experiment showed that frequency envelope did not significantly affect the annoyance response. The interaction of fundamental frequency with tone-to-broadband noise ratio did have a large and complex effect on annoyance. Duration-corrected, A-weighted sound pressure level with a modified tone correction predicted the annoyance of the first-experiment stimuli better than any other measurement procedure. Analyses of the judgments from the second experiment also indicated a significant interaction of fundamental frequency and tone-to-broadband noise ratio. The advanced turboprop stimuli were slightly less annoying than the conventional turboprop and jet stimuli. The use of a duration correction and a modified tone correction improved the annoyance prediction for the second-experiment stimuli.

Introduction

The return of the propeller to long-haul commercial service may be rapidly approaching in the form of the advanced turboprop, or "propfan," aircraft. The advanced turboprop aircraft, whose propeller is vastly different from conventional propellers in shape and number of blades, offers substantial savings in operating costs through improved energy efficiency. However, such an aircraft will come into general usage only if its noise, which has unique spectral characteristics, meets the standards of community acceptability currently applied to existing aircraft. Much research has been directed toward understanding and quantifying the annoyance caused by jet-aircraft flyover noise; but relatively little research has been conducted for conventional propeller noise, and almost none has been conducted for advanced turboprop noise. To address this need, two laboratory experiments were conducted to quantify the annoyance of people to advanced turboprop aircraft flyover noise.

The primary concern in quantifying advanced turboprop noise annoyance is the unique spectral characteristics of the noise. In general, propeller noise consists of a number of harmonically related pure tone components that are superimposed on broadband noise (fig. 1). The fundamental frequency of these tones, which can dominate the total noise produced by the aircraft, occurs at the propeller blade passage frequency and ranges from 50 Hz to about 150 Hz for conventional propeller aircraft. For advanced turboprop aircraft, the fundamental frequency is predicted to range from 150 Hz to as high as 300 Hz, hence the uniqueness of the noise. The annoyance caused by noise sources with strong tonal components has historically been more difficult to quantify than the annoyance caused by broadband noise. The uncertainty in accounting for tonal content is increased in this case because less basic psychoacoustic research has been conducted in the lower frequency ranges of tones from conventional and advanced turboprop propellers than in the higher frequency range of tones from jet aircraft.

The first laboratory experiment examined the effects of tonal characteristics on annoyance. The experiment had two specific objectives. The first objective was to determine the effects on annoyance of fundamental frequency, frequency envelope shape (i.e., the sound pressure levels of the harmonics relative to the fundamental), and tone-to-broadband noise ratio (fig. 1). The controlling mechanisms for these three tonal characteristics are, respectively, blade passage frequency, blade helical-tip Mach number, and engine core and airframe noise. The second objective was to determine the ability of aircraft-noise measurement procedures and corrections to predict annoyance to advanced turboprop aircraft.

The primary objective of the second laboratory experiment was to compare the annoyance response to advanced turboprop aircraft with the annoyance responses to conventional turboprop and jet aircraft. The effects on annoyance of fundamental frequency and tone-to-broadband noise ratio were also examined in the second experiment. The final objective of the second experiment was to determine the ability of aircraft-noise measurement procedures and corrections to predict annoyance to the combined set of aircraft types.

Noise Metrics, Symbols, and Abbreviations

Noise Metrics

EPNL	effective perceived noise level, dB
L_A	A-weighted sound pressure level, dB
L_D	D-weighted sound pressure level, dB
L_E	E-weighted sound pressure level, dB
L_1	weighted sound pressure level based on modified frequency weighting from reference 1 (see "Acoustic Data Analyses" section), dB
LL	loudness level (Stevens Mark VI procedure), dB
LL_Z	Zwicker's loudness level, dB
PL	perceived level (Stevens Mark VII procedure), dB
PNL	perceived noise level, dB
PNL_K, PNL_M, PNL_W	perceived noise level with critical-band corrections (see "Acoustic Data Analyses" section), dB

Detailed descriptions of the noise metrics used in this report can be found in references 1, 2, and 3.

Symbols and Abbreviations

ATP	advanced turboprop
FAR	Federal Aviation Regulation
F_o	fundamental frequency (blade passage frequency), Hz
L_S	subjective noise level, dB
M_{ht}	helical-tip Mach number
p	probability
T_1	EPNL tone-correction method (ref. 2)
T_2	tone-correction method identical to T_1 except that no corrections are applied for tones below the 500-Hz 1/3-octave band
T/N	tone-to-broadband noise ratio (defined as the difference between the level of the fundamental tone and the level of the highest 1/3-octave band of broadband noise), dB

Experimental Method

Test Facilities

First experiment. The Exterior Effects Room in the Langley Aircraft Noise Reduction Laboratory (fig. 2) was used as the test facility in the first experiment. This room, which has a volume of approximately 340 m^3 and a reverberation time of approximately 0.25 sec at 1000 Hz, simulates the outdoor acoustic environment. The subjects pictured in figure 2 occupy the seats used by each group of four subjects during testing. The monophonic recordings of the aircraft noise stimuli were played on a studio-quality tape recorder and presented to the subjects by means of six overhead loudspeakers. A commercially available noise reduction system that provided a nominal 30-dB increase in signal-to-noise ratio was used to reduce tape hiss to inaudible levels.

Second experiment. The Anechoic Listening Room in the Langley Aircraft Noise Reduction Laboratory (fig. 3) was used as the test facility in the second experiment. This room, which has a volume of 20 m^3 and an A-weighted ambient noise level of 15 dB, provides an essentially echo-free environment. This test facility was used instead of the facility used in the first experiment to eliminate any possibility of standing waves affecting the data. As in the first experiment, the aircraft-noise stimuli were played on a studio-quality tape recorder using a noise reduction system to reduce tape hiss. The stimuli were presented to the subjects using a special speaker system consisting of one high-frequency unit and one low-frequency unit. The high-frequency unit has a usable frequency range from 100 to 10 000 Hz, and the low-frequency subwoofer provides a flat response within ±1 dB in the frequency range from 30 to 100 Hz.

Test Subjects

Ninety-six subjects, 64 for the first experiment and 32 for the second 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 test subjects were given audiograms prior to the experiment to verify normal hearing. Table I gives the sex and age data for the subjects in each experiment.

Noise Stimuli

Advanced turboprop stimuli in first experiment. A recently developed Aircraft Noise Synthesis System was used to generate the advanced turboprop noise stimuli used in the first experiment (ref. 4). The computer-based system generates realistic, time-varying, audio simulations of aircraft flyover noise at a specified observer location on the ground. The synthesis takes into account the time-varying aircraft position relative to the observer; specified reference spectra consisting of broadband, narrowband, and pure tone components; directivity patterns; Doppler shift; atmospheric effects; and ground effects. These parameters can be specified and controlled in such a way as to generate stimuli in which certain noise characteristics such as fundamental frequency or duration are independently varied while the remaining characteristics such as broadband content are held constant. The synthesis system was used to generate 45 simulations of advanced turpoprop aircraft flyover noise in which the tonal content was systematically varied to represent the factorial combinations of 5 fundamental frequencies, 3 frequency envelope shapes, and 3 tone-to-broadband noise ratios.

The first step in generating the simulations was to define a synthesis-system input data set for each of the 45 flyovers. A literature review was conducted to determine the typical characteristics of advanced turboprop aircraft and the expected ranges of the tonal characteristics (refs. 5 to 19). Because of testing time constraints, the simulations were limited to one takeoff flight profile, one observer location, one broadband noise spectrum, and one broadband noise directivity pattern. Each of these parameters was the same for each simulation. The selected takeoff flight profile resulted in an altitude at closest approach to the observer of 380 m, about the altitude expected at the FAR 36 takeoff noise measurement location (ref. 2). The observer was located on the centerline of the ground track. Since predictions of advanced turboprop broadband noise were not available, the broadband spectral content was based on measurements of an existing, large, turboprop aircraft. The broadband 1/3-octave spectrum is given in figure 4. Aircraft speed was 70 m/sec (Mach number = 0.2). The propeller characteristics are given in table II. A wing-mounted, tractor, single-rotating propeller configuration was assumed for all the simulations. A model of this configuration is shown in figure 5. The numbers of blades correspond to a range of fundamental frequencies that covers both the conventional propeller aircraft (50 to 150 Hz) and the advanced turboprop aircraft (150 to 300 Hz). The blade diameters and aircraft speed resulted in helical-tip Mach numbers of 0.63, 0.73, and 0.78, which represent three frequency envelope shapes.

The propeller characteristics and descriptions of the SR-3 blade were used as data for a computer program that calculates the discrete frequency noise of propellers (ref. 20). This program determined the tonal components, frequency envelope shape (i.e., the sound pressure levels of the harmonics relative to the fundamental), and directivity patterns for each of the 15 combinations of number of blades and blade diameter. This information was then used in the synthesis-system input data sets. The numbers of blades yielded five fundamental frequencies: 67.5, 135, 180, 225, and 292.5 Hz. The three helical-tip Mach numbers, 0.63, 0.73, and 0.78, resulted in frequency envelope shapes with approximately linear roll-off rates of 11, 6.2, and 4.6 dB per 100 Hz, respectively.

The desired tone-to-broadband noise ratios of 0, 15, and 30 dB were obtained by specifying the relative levels of the tonal content and the broadband noise in the synthesis-system input data sets. (The tone-to-broadband noise ratio was defined to be the difference between the level of the fundamental tone and the level of the highest 1/3-octave band of broadband noise.)

For each of the 45 input data sets, the synthesis system generated an audio simulation that was recorded on tape. Each of these recordings was presented to the test subjects at D-weighted sound pressure levels of 70, 80, and 90 dB. The factorial combinations of 5 fundamental frequencies, 3 frequency envelope shapes, 3 tone-to-broadband noise ratios, and 3 sound levels resulted in 135 advanced turboprop aircraft flyover noise stimuli. The L_A time history and the 1/3-octave-band spectrum at peak L_A of the highest level presentation of each flyover noise with a helical-tip Mach number of 0.73 are given in figure 6. The time histories and 1/3-octave spectra of the noise stimuli with helical-tip Mach numbers of 0.63 and 0.78 are similar to the corresponding plots in figure 6 for a Mach number of 0.73. To illustrate the tonal content of the noise stimuli, figure 7 gives the narrowband spectrum of the 30-dB tone-to-broadband noise ratio condition for each combination of fundamental frequency (blade passage frequency) and frequency envelope shape (helical-tip Mach number).

Other stimuli in first experiment. A synthesized flyover recording containing only the broadband noise from the advanced turboprop simulations and a recording of a real Boeing 727-200 takeoff were also included in the first experiment. The broadband simulation was presented at six L_D levels ranging from 70 to 95 dB in 5-dB increments. The broadband simulation was included as a comparison and is not discussed in this paper. The Boeing 727-200 takeoff was presented at seven L_D levels ranging from 65 to 95 dB in 5-dB increments. The Boeing 727-200 stimuli were used in the analyses to convert subjective responses to subjective decibel levels. A total of 148 stimuli were presented to the test subjects in the first experiment.

Advanced turboprop stimuli in second experiment. Eighteen simulations of advanced turboprop aircraft takeoff noise were used in the second experiment. The tonal content of the 18 simulations was systematically varied to represent the factorial combinations of 6 fundamental frequencies and 3 tone-to-broadband noise ratios. The fundamental frequencies were 67.5, 135, 180, 225, 260, and 292.5 Hz. This range of fundamental frequencies covers frequencies typical of both the conventional propeller (50 to 150 Hz) and the advanced turboprop (150 to 300 Hz). The tone-to-broadband noise ratios were 0, 15, and 30 dB. A helical-tip Mach number of 0.73 was used for all 18 simulations, which resulted in a frequency envelope shape with an approximately linear roll-off rate of 6.2 dB per 100 Hz. Fifteen of these 18 simulations were used in the first experiment. The three simulations with a 260-Hz fundamental frequency were added for the second experiment. All 18 were generated in the manner previously described for the first experiment.

As in the first experiment, each simulation generated by the synthesis system was recorded on tape and presented to the test subjects at D-weighted sound pressure levels of 70, 80, and 90 dB. The factorial combinations of 6 fundamental frequencies, 3 tone-to-broadband noise ratios, and 3 sound levels resulted in 54 advanced turboprop aircraft takeoff noise stimuli. The L_A time history and the 1/3-octave-band spectrum at peak L_A of the highest level presentation of each flyover noise with a helical-tip Mach number of 0.73 are given in figure 6. The narrowband spectrum of the 30-dB tone-to-broadband noise ratio condition for each fundamental frequency at $M_{ht} = 0.73$ is given in figure 7.

Conventional turboprop and jet stimuli in second experiment. Recordings of five takeoffs of conventional turboprop aircraft and five takeoffs of conventional jet aircraft were included in the second experiment for comparison with the advanced turboprop noise stimuli. The types of aircraft used and some specifications of each are given in table III. The recordings of the jet aircraft were made on the extended runway centerline approximately 5000 m from the brake release point. All the conventional turboprop aircraft had maximum takeoff weights greater than 5700 kg. The turboprop aircraft recordings were made at several different airports and the distances from the brake release point varied. At each location, the turboprop aircraft recordings were made on or near the extended runway centerline. Because of the higher flight profiles and lower source noise levels of the turboprop aircraft, the recording sites for the turboprop aircraft were located closer to the brake release point than those for the jet aircraft. Each takeoff was presented to the test subjects at D-weighted sound pressure levels of 70, 80, and 90 dB for a total of 15 conventional turboprop noise stimuli and 15 conventional jet noise stimuli. The L_A time histories and the 1/3-octave-band spectra at peak L_A of the highest level presentations of the conventional turboprop and jet takeoffs are given in figure 8.

Other stimuli in second experiment. In addition to the three presentations made as part of the conventional jet stimuli, a Boeing 727-200 takeoff recording was also presented at L_D levels of 65, 75, 85, and 95 dB. This addition resulted in a total of seven Boeing 727-200 stimuli, ranging in L_D levels from 65 to 95 dB in 5-dB increments, being presented to the test subjects in the second experiment. As in the first experiment, these stimuli were used in the analyses to convert subjective responses to subjective decibel levels.

Four other aircraft flyover noises were included in the second experiment. Each was presented at three L_D levels. These stimuli were included as a pilot study for another experiment and are not discussed in this paper. A total of 100 stimuli were presented to the test subjects in the second experiment.

Experiment Design

Numerical category scaling was chosen as the psychophysical method for both experiments. The choice was made to maximize the number of stimuli that could be judged in the fixed amount of time available. The scale selected was a unipolar, 11-point scale from 0 to 10. The end points of the scale were labeled "EXTREMELY ANNOYING" and "NOT ANNOYING AT ALL." The term "ANNOYING" was defined in the subject instructions as "UNWANTED, OBJECTIONABLE, DISTURBING, OR UNPLEASANT."

For each experiment, the stimuli were divided into two sets of four groups (tapes). The first set of four tapes contained all the stimuli in the experiment. The second set contained the same stimuli as the first but in reverse order. There were 37 stimuli per tape in the first experiment and 25 per tape in the second experiment. The stimuli were divided between tapes so that each fundamental frequency, frequency envelope shape, tone-to-broadband noise ratio, sound level, and/or aircraft type were about equally represented on each tape. The order of the stimuli on the tape was then randomly selected. The orders for each tape are given in tables IV and V. A period of approximately 10 sec was provided after each stimulus for the subjects to make and record their judgments. Each tape served as one of four test sessions for the subjects and required approximately 35 min for playback in the first experiment and 25 min in the second experiment.

The 64 test subjects in the first experiment were divided into 16 groups of 4 subjects. The 32 test subjects in the second experiment were divided into 16 groups of 2 subjects. In each experiment the first four tapes were presented to eight groups of subjects and the second four tapes were presented to the other eight groups of subjects. To prevent subject fatigue and other temporal effects from unduly influencing the results, the order in which the tapes were presented was varied to provide a balanced presentation. Table VI gives the order of presentation used for the tapes in both experiments.

Procedure

Upon arrival at the laboratory, the subjects were seated in a conference room and each was given a set of instructions and a consent form. Copies of these items for the first experiment are given in the appendix. In the second experiment, these items were identical to those in the first experiment except that the length of the session was changed from 35 to 25 min and the number of aircraft sounds was changed from 37 to 25. After reading the instructions and completing the consent form, the subjects were given a brief verbal explanation of the cards used for recording judgments and were asked if they had any questions. The subjects were then taken into the test facility and randomly assigned to seat locations. Three practice stimuli were presented to the subjects while the test conductor remained in the test facility. In order for the subjects to gain experience in scoring the sounds, they were instructed to make and record judgments of the practice stimuli. After asking again for any questions about the test, the test conductor issued scoring cards for the first session and left the facility. Then, the first of four test sessions began. After the conclusion of each session, the test conductor reentered the test facility, collected the scoring cards, and issued new scoring cards for the next session. Between the second and third sessions, the subjects were given a 15-min rest period outside the test facility.

Results and Discussion

Acoustic Data Analyses

Each noise stimulus in each experiment was analyzed to provide 1/3-octave-band sound pressure levels from 20 Hz to 20 kHz for use in computing a selected group of noise metrics. The measurements were made with a 1.27-cm-diameter condenser microphone and a real-time, 1/3-octave analysis system that used digital filtering. In the first experiment the microphone was located at a subject's head position (the third subject from the left in fig. 2). In the second experiment the microphone was located at ear level at a point midway between the two seats. No subjects were present during the measurements. A total of 11 noise metrics were computed in the analyses. They included the simple weighting procedures L_A, L_D, L_E, and L_1 and the more complex calculation procedures LL, LL_Z, PL, and PNL. In addition, three types of critical-band corrections were applied to PNL.

The noise metric L_1 is based on a modified frequency weighting developed in a study of annoyance to simulated helicopter rotor noise (ref. 1). That study found that the annoyance prediction error was more correlated with the logarithm of the subjectively dominant frequency (approximated by the 1/3-octave-band center frequency with the greatest D-weighted energy) than with impulsiveness measures. Based on this result a modified frequency weighting was developed that provided improved annoyance prediction when implemented as the L_1 noise metric. For 1/3-octave bands with center frequencies less than or equal to 1000 Hz, the modified frequency weighting falls between the A- and D-weightings. D-weighting values are used for bands above 1000 Hz. The L_1 metric uses the same energy summation method used for L_A, L_D, and L_E.

The first critical-band correction procedure applied to PNL was suggested by Kryter (ref. 21). In this procedure, the increased bandwidths of critical bands below 400 Hz are approximated by three groups of 1/3-octave bands. The groups are the bands with the following center frequencies: 315 and 250 Hz; 200, 160, and 125 Hz; and 100, 80, 63, and 50 Hz. Within each group the band levels are summed on an energy basis, and the summed band levels are assigned to the band center frequency having the greatest intensity within the group. The PNL calculation procedure then uses these "critical bands" instead of the 1/3-octave bands below 400 Hz. The metric using this procedure is designated "PNL_K" in further discussions in this report.

The second critical-band correction procedure used the same groups for summing the 1/3-octave bands. The summed band levels, however, were assigned to the band center frequency responsible for the greatest "noy" value within the group before summing. The metric using this procedure is designated "PNL_M."

The third critical-band correction procedure also used the same groups of 1/3-octave bands. In this case, the noy values of the 1/3-octave-band levels were added on an energy basis within each group. The resultant noy values for all critical bands were then summed by using the PNL procedure. The metric using this procedure is designated "PNL_W."

Six different variations of each of the 11 previously described noise metrics were calculated. The first was the peak (maximum) level occurring during the flyover noise. Two other variations were calculated by applying two different tone corrections. Three more variations were attained by applying duration corrections to the non tone-corrected level and the two tone-corrected levels. The duration correction and the first tone correction T_1 are identical to those used in the effective perceived noise level procedure defined in the FAR 36 regulation of the Federal Aviation Administration (ref. 2). The second tone correction T_2 is identical to the first except that no corrections are applied for tones identified in bands with center frequencies less than 500 Hz.

Subjective Data Analyses

The means (across subjects) of the judgments were calculated for each stimulus in each experiment. In order to obtain a subjective scale with meaningful units of measure, these mean annoyance scores were converted to subjective noise levels L_S having decibel-like properties through the following process. Included in each experiment for the purpose of converting the mean annoyance scores to L_S values were seven presentations of a Boeing 727-200 takeoff recording ranging in values of L_D from 65 to 95 dB in 5-dB increments. Second-order polynomial regression analyses were performed separately for each experiment on data obtained for these seven stimuli. The dependent variable was the calculated PNL, and the independent variable was the mean annoyance score for each of the seven stimuli. Figure 9 presents the data for the first and second experiments and the resulting best fit regression curves. The regression equations were then used to predict the level of the Boeing 727-200 takeoff noise that would produce the same mean annoyance score as each of the other noise stimuli in the separate experiments. These levels were then considered as the subjective noise level for each stimulus. Comparisons in these studies and in previous studies indicate that analyses using subjective noise levels yield the same results as analyses using mean annoyance scores.

Comparison of Noise Metrics

In order to investigate the prediction ability of the aircraft-noise measurement procedures and corrections, the differences between the subjective noise level L_S and the calculated noise level for each of the six variations of the measurement procedures and corrections were determined for each stimulus in each experiment. These differences were considered to be the "prediction error" for each stimulus and noise metric variation. The standard deviation of the prediction errors for each noise metric variation is a measurement of how accurately the variation predicts annoyance. The smaller the standard deviation, the greater the prediction accuracy.

It should be noted that because of interrelationships between the data cases, statistical tests for significance of differences in the standard deviations of prediction error are not straightforward. The following results are based primarily on the consistent trends found in the data. Approximate statistical tests indicate that differences in standard deviations as small as 0.07 to 0.10 dB could be significant ($p \leq 0.05$).

First experiment. Table VII gives the standard deviations of prediction error for each noise metric variation examined for the 135 advanced turboprop stimuli in the first experiment. Comparisons of the standard deviations indicate that annoyance prediction ability was improved by the addition of duration corrections. The T_2 tone correction improved prediction ability, but the T_1 tone correction degraded prediction ability. The L_A with duration corrections and T_2 tone corrections had the smallest standard deviation of prediction error. Duration-corrected L_A and the modified-frequency weighting metric L_1 with duration corrections and T_2 tone corrections had the second and third smallest standard deviations of prediction error. The addition of critical-band corrections to PNL did not significantly improve its prediction ability.

Second experiment. Table VIII gives the standard deviations of prediction error for each noise metric variation examined for the combined set of 84 advanced turboprop, conventional turboprop, and conventional jet stimuli in the second experiment. Comparisons of the standard deviations indicate that annoyance prediction ability was improved by the addition of duration corrections. The T_2 tone correction improved prediction ability, but the T_1 tone correction degraded prediction ability. The LL_Z with duration corrections and T_2 tone corrections had the smallest standard deviation of prediction error. The PNL_M with duration corrections and T_2 tone corrections and the PL with duration corrections and T_2 tone corrections had the second and third smallest standard deviations of prediction error, respectively. Two of the critical-band corrections applied to PNL improved prediction ability. Both PNL_M and PNL_K had lower standard deviations of prediction error. In particular, PNL_M clearly showed a significant improvement in prediction ability.

Additional analyses of the advanced turboprop stimuli in both experiments will be presented in terms of duration-corrected L_A and duration-corrected PNL, since L_A and PNL are the most commonly used procedures. The results are similar for other noise measurement procedures and corrections.

Effects of Tone Characteristics

First experiment. Analyses of the annoyance prediction errors from the first experiment indicated two major results regarding the three tonal characteristics considered. First, frequency envelope shape (i.e., blade-tip Mach number) did not significantly affect annoyance. Figure 10 illustrates this result. Annoyance relative to the metric prediction is plotted against helical-tip Mach number. "Annoyance relative to metric prediction" is the prediction error (subjective noise level minus the calculated level of the metric) normalized by subtracting the average (across all stimuli) prediction error for the metric. When defined in this manner, a positive number represents annoyance greater than that predicted by the metric and results for different metrics can be directly compared. The helical-tip Mach numbers cover the entire range expected for takeoffs. Over this wide range the annoyance varied only about 1 dB. This indicates that the frequency envelope shape is not an important annoyance parameter, at least for the wing-mounted, tractor, single-rotating propeller configuration considered.

The second major result is that the interaction of fundamental frequency with tone-to-broadband noise ratio did have a large and complex effect on annoyance. Figures 11 and 12 illustrate this interaction for duration-corrected L_A and duration-corrected PNL, respectively. Annoyance relative to the metric is plotted versus fundamental frequency for each of the three tone-to-broadband noise ratios. For flyover noise with high tone-to-broadband noise ratios, annoyance varied extensively depending upon the fundamental frequency of the tonal content. The variations were most prominent above 150 Hz, the range expected for advanced turboprop noise. At 180 to 225 Hz, the annoyance for high tone-to-broadband noise flyovers was much less than that for other flyovers. At 292.5 Hz, the annoyance for high tone-to-broadband noise flyovers was higher. The maximum differences were almost 9 dB for duration-corrected L_A and 10 dB for duration-corrected PNL.

The tone-to-broadband noise ratios used in figures 11 and 12 are the ratios specified in the synthesis-system input data sets and are defined as the difference between the level of the fundamental tone and the level of the highest 1/3-octave band of broadband noise. In order to determine if the definition of tone-to-broadband noise ratio affected the interaction shown in figures 11 and 12, tone-to-broadband noise ratios based on several different definitions were determined from the acoustic measurements of the stimuli. The definitions used included the difference between the fundamental tone level and the level of the 1/3-octave band containing the tone; and the difference between the L_A or L_D level of the stimulus with tones and the L_A or L_D level of the stimulus with tones removed. Some of the definitions improved the correlation between tone-to-broadband noise ratio and annoyance prediction error, but none of them significantly altered the interaction between fundamental frequency and tone-to-broadband noise ratio illustrated in figures 11 and 12. This interaction indicates that fundamental frequency and tone-to-broadband noise ratio are potentially important annoyance parameters for advanced turboprop aircraft noise.

Second experiment. Analyses of the annoyance prediction errors from the second experiment also indicated that the interaction of fundamental frequency and tone-to-broadband noise ratio had a large effect on annoyance. Figures 13 and 14 illustrate this interaction as found in the second experiment for duration-corrected L_A and duration-corrected PNL, respectively. The annoyance to the flyovers having the highest tone-to-broadband noise ratio (30 dB) was less than the annoyance to the other flyovers and varied considerably depending on the fundamental frequency of the tonal content. Comparing the results for the two metrics shows that for duration-corrected PNL, the difference between the 30-dB tone-to-broadband noise ratio and the lower ratios was slightly less in the higher frequencies. In general, the better the annoyance prediction ability of the metrics (as indicated in table VIII), the smaller the difference in annoyance between the tone-to-broadband noise ratios at the higher frequencies. One calculation procedure, Zwicker's loudness level LL_Z, showed a slightly different interaction effect, as illustrated in figure 15 for duration-corrected LL_Z. In this case, at higher frequencies the annoyance to the flyovers with the 30-dB tone-to-broadband noise ratio is greater than the annoyance to the flyovers at other noise ratios. At the lower frequencies, the annoyance to the flyovers with the 30-dB tone-to-broadband noise ratio is only slightly less than the annoyance to the flyovers at other noise ratios as compared with the other metrics.

Comparisons of the results for the first experiment (figs. 11 and 12) with the results for the second experiment (figs. 13 and 14) show that both experiments indicate an interaction between fundamental frequency and tone-to-broadband noise ratio, but that the shapes of the indicated interactions are different. The interaction yielded by the first experiment has a somewhat greater effect on annoyance prediction than the interaction from the second experiment.

Comparison of Aircraft Types

Figure 16 compares the annoyance responses to advanced turboprop, conventional turboprop, and conventional jet aircraft flyover noises obtained in the second experiment. The figure plots subjective noise level versus duration-corrected L_A for each of the three categories of aircraft. Simple linear regression lines for each of the aircraft types are also shown. In general, the advanced turboprop noises are slightly less annoying. Although the differences in annoyance between aircraft types are small, indicator (dummy) variable analyses for the duration-corrected L_A metric show a significant difference in slope and intercept between the appropriate regressions for the advanced turboprop noises and the combined set of conventional turboprop and jet noises. Figure 17 compares the annoyance responses to advanced turboprop, conventional turboprop, and conventional jet aircraft flyover noises using EPNL. The results for EPNL are similar to those for duration-corrected L_A, except that the difference is less between the advanced turboprop and conventional turboprop noises. For EPNL, indicator variable analyses show a significant difference in intercept between the appropriate regressions for the advanced turboprop noises and the combined set of conventional turboprop and jet noises. For all the metrics considered, indicator variable analyses demonstrated a significant difference in appropriate regression slope and/or intercept between the advanced turboprop noises and the separate or combined conventional turboprop and jet noises.

Further examination of figures 16 and 17 reveals that several data points for the advanced turboprops lie well below the majority of the advanced turboprop data points and the corresponding regression line. These low-lying data points represent stimuli with 30-dB tone-to-broadband noise ratios. This finding agrees with the previous finding of an interaction between fundamental frequency and tone-to-broadband noise ratio, which indicates that annoyance to the high tone-to-broadband noise ratio stimuli is often less than annoyance to the other advanced turboprop stimuli. These stimuli with high tone-to-broadband noise ratios are responsible for the advanced turboprop noises being slightly less annoying than the conventional turboprop and jet noises in figures 16 and 17. The important result of these comparisons is that for a given level, the advanced turboprop aircraft flyover noise is not more annoying than the flyover noise of current aircraft.

Additional comparisons of aircraft types were made by dividing the advanced turboprop noises into two groups based on fundamental frequency. The first group consisted of the advanced turboprop stimuli with fundamental frequencies (67.5 and 125 Hz) in the range common to conventional turboprops. The second group consisted of the advanced turboprop stimuli with higher fundamental frequencies (180, 225, 260, and 292.5 Hz) in the range actually predicted for advanced turboprop aircraft. The two groups of advanced turboprop stimuli and the conventional turboprop and jet stimuli were compared by using indicator (dummy) variable analyses. The results were inconsistent across metrics, sometimes indicating small differences and sometimes indicating no differences. Where differences were indicated by the analyses, the low-frequency advanced turboprop stimuli were usually slightly less annoying than the high-frequency advanced turboprop stimuli. As in the three-way comparisons, the advance turboprop noises were not more annoying than those of the conventional turboprops and jets.

Conclusions

Two laboratory experiments were conducted to provide information on quantifying the annoyance response of people to synthesized advanced turboprop (propfan) aircraft flyover noise. In both experiments, a computer synthesis system was used to generate realistic simulations of advanced turboprop aircraft takeoff noise. The simulations were based on a wing-mounted, tractor, single-rotating propeller configuration of the advanced turboprop. The first experiment examined 45 advanced turboprop simulations representing the factorial combinations of 5 fundamental frequencies, 3 frequency envelope shapes, and 3 tone-to-broadband noise ratios. Sixty-four subjects judged the annoyance of recordings of the 45 synthesized takeoff noises presented at 3 sound pressure levels in a test facility that simulates the outdoor acoustic environment. The second experiment examined 18 advanced turboprop simulations representing the factorial combinations of 6 fundamental frequencies and 3 tone-to-broadband noise ratios. The advanced turboprop simulations along with recordings of 5 conventional turboprop takeoffs and 5 conventional jet takeoffs were presented at 3 sound pressure levels to 32 subjects in an anechoic chamber. Analyses of the annoyance responses were conducted in terms of several variations of seven conventional noise metrics (A-, D-, and E-weighted sound pressure levels, loudness level (Stevens Mark VI procedure), Zwicker's loudness level, perceived level (Stevens Mark VII procedure), and perceived noise level) and one other recently developed noise metric (L_1) based on a modified frequency weighting.

Based on the results presented in this paper, the following conclusions were noted:

1. In both experiments, the annoyance prediction ability of the noise metrics was improved by the addition of a duration correction.

2. In both experiments, the annoyance prediction ability of the noise metrics was improved by the addition of a tone correction similar to the one used in the effective perceived noise level (EPNL) but limited to tones in 1/3-octave bands with center frequencies greater than or equal to 500 Hz. Addition of the effective perceived noise level (EPNL) tone correction to the noise metrics degraded prediction ability in both experiments.

3. Critical-band corrections to the perceived noise level (PNL) did not significantly improve annoyance prediction for the advanced turboprop aircraft in the first experiment. However, for the combination of advanced turboprop, conventional turboprop, and conventional jet aircraft in the second experiment, two of the three critical-band correction methods did significantly improve annoyance prediction.

4. The frequency envelope shape of the tonal components (i.e., blade helical-tip Mach number) of the advanced turboprop noise did not significantly affect annoyance.

5. The interaction of fundamental frequency and tone-to-broadband noise ratio did have a large and complex effect on annoyance to the advanced turboprop aircraft noise. Although the indicated interaction varied somewhat between noise metrics and between the two experiments, in most cases the annoyance to the higher tone-to-broadband noise ratio flyovers was less than the annoyance to the other flyovers. The difference in annoyance between the higher tone-to-broadband noise ratio flyovers and the other flyovers varied with fundamental frequency.

6. For a given level, the flyover noise of advanced turboprop aircraft is not more annoying than the flyover noise of conventional turboprop and jet aircraft.

NASA Langley Research Center
Hampton, VA 23665-5225
December 4, 1987

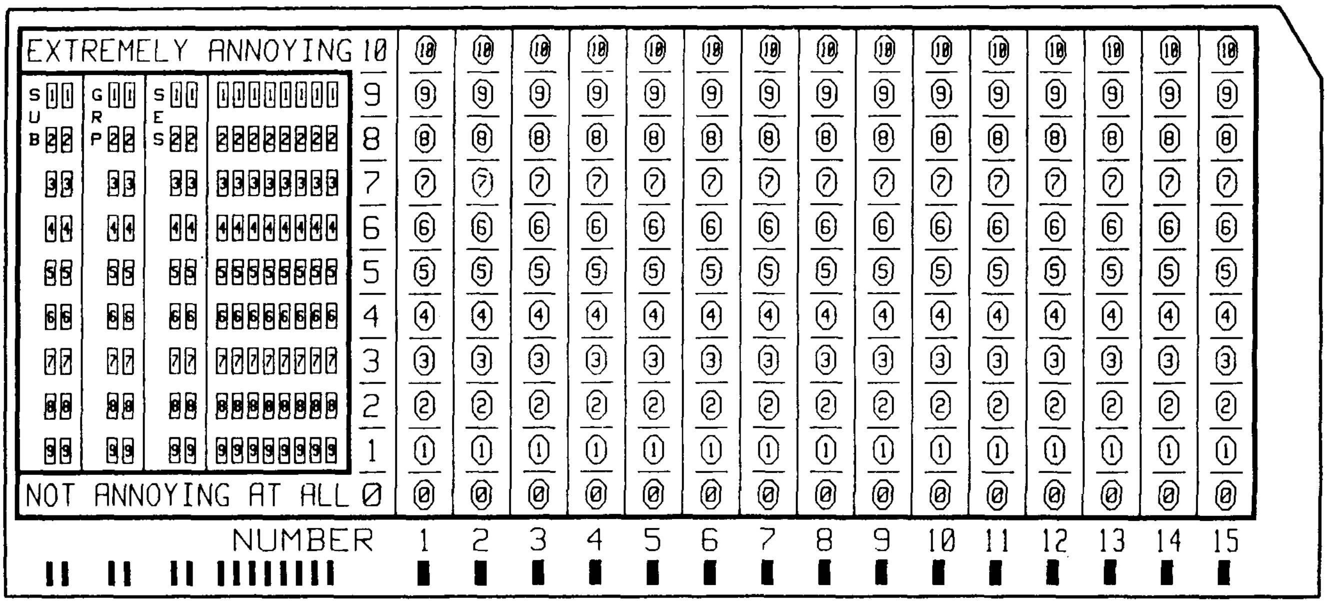
Appendix

Instructions and Consent Form

INSTRUCTIONS

The experiment in which you are participating will help us understand the characteristics of aircraft sounds which can cause annoyance in airport communities. We would like you to judge how ANNOYING some of these aircraft sounds are. By ANNOYING we mean - UNWANTED, OBJECTIONABLE, DISTURBING, OR UNPLEASANT.

The experiment consists of four 35 minute sessions. During each session 37 aircraft sounds will be presented for you to judge. You will record your judgments of the sounds on computer cards like the one 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 marking the appropriate numbered circle on the computer card. The number of each sound is indicated across the bottom of the card. If you judge a sound to be only slightly annoying, mark one of the numbered circles close to the NOT ANNOYING AT ALL end of the scale, that is a low numbered circle near the bottom of the card. Similarly, if you judge a sound to be very annoying, then mark one of the numbered circles close to the EXTREMELY ANNOYING end of the scale, that is a high numbered circle near the top of the card. A moderately annoying judgment should be marked in the middle portion of the scale. In any case, make your mark so that the circle that most closely indicates your annoyance to the sound is completely filled in. There are no right or wrong answers; we are only interested in your judgment of each sound.

Before the first session begins you will be given a practice computer card and three sounds will be presented to familiarize you with making and recording judgments. I will remain in the testing room with you during the practice time to answer any questions you may have.

Thank you for your help in conducting the experiment.

VOLUNTARY CONSENT FORM FOR SUBJECTS FOR HUMAN

RESPONSE TO AIRCRAFT NOISE AND VIBRATION

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

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

Date

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

I undertake to obey the regulations of the laboratory and 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.

____

Signature of Subject

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Table I. Data on Test Subjects

Experiment	Sex	Number of participants	Mean age	Median age	Age range
1	Male	22	29	24.5	20 to 65
	Female	42	39	35	23 to 62
	All subjects	64	35	27.5	20 to 65
2	Male	9	33	33	18 to 57
	Female	23	35	34	19 to 63
	All subjects	32	35	33.5	18 to 63

Table II. Characteristics of Advanced Turboprop Propeller

Parameter	Condition
Configuration	Wing-mounted, tractor, single-rotating propeller
Blade	SR-3
Rotational speed	1350 rpm
Disk loading	550 kW/m^2
Number of blades	3, 6, 8, 10, 13
Blade diameter	2.93, 3.42, 3.66 m

Table III. Conventional Turboprop and Jet Aircraft in Second Experiment

Aircraft	Number of engines	Engine type	Maximum takeoff weight, kg
de Havilland Canada DHC-7 Dash 7	4	Turboprop	20 000
Lockheed P-3	4	↓	61 200
NAMC YS-11	2	↓	24 500
Nord 262	2	↓	10 600
Shorts 330	2	↓	10 300
Airbus Industrie A-300	2	Turbofan	≥142 000
Boeing 707	4	↓	≥117 000
Boeing 727-200	3	↓	86 900
McDonnell Douglas DC-9	2	↓	≥41 100
McDonnell Douglas DC-10	3	↓	≥206 400

Table IV. Presentation Order of Stimuli on Tapes in First Experiment

Practice tape	Tape 1 ↓	Tape 2 ↓	Tape 3 ↓	Tape 4 ↓
322 80	222 80	431 80	522 90	113 70
131 70	323 80	322 90	421 80	521 90
433 90	513 70	123 70	133 70	212 80
	421 90	000 90	432 70	322 70
	213 70	312 80	212 90	121 70
	512 80	411 70	333 80	533 90
	000 95	233 80	131 90	431 90
	313 80	121 90	223 70	412 80
	112 80	132 70	000 70	532 70
	423 70	311 70	411 90	311 90
	511 90	231 90	213 80	523 70
	727 75	532 80	521 80	727 80
	132 80	727 85	313 70	111 90
	113 90	313 90	332 90	432 80
	522 70	212 70	727 90	323 90
	433 90	531 90	311 80	312 70
	321 70	211 80	433 80	233 90
	123 80	523 80	531 70	000 85
	431 70	221 90	423 90	122 80
	412 90	112 70	322 80	213 90
	231 80	332 80	412 70	421 70
	312 90	413 90	121 80	522 80
	211 90	000 75	331 70	333 70
	533 70	223 80	123 90	232 70
	221 70	422 70	222 90	223 90
	000 80	133 90	511 70	331 80
	333 90	222 70	413 80	133 80
	131 70	131 80	232 80	512 90
	422 80	521 70	727 65	413 70
	523 90	513 90	112 90	422 90
	531 80	323 70	533 80	321 80
	111 70	432 90	111 80	211 70
	332 70	423 80	231 70	727 95
	232 90	727 70	532 90	221 80
	411 80	512 70	321 90	132 90
	122 90	113 80	513 80	433 70
	233 70	331 90	122 70	511 80
	Tape 5 ↑	Tape 6 ↑	Tape 7 ↑	Tape 8 ↑

<table>
<tr><th colspan="4">Stimuli key</th></tr>
<tr><th colspan="3">Noise characteristics</th><th>Nominal L_D</th></tr>
<tr><td colspan="3">727 = Boeing 727-200 recording

000 = Broadband noise only, no tones</td><td rowspan="4">65 = 65 dB
70 = 70 dB
75 = 75 dB
80 = 80 dB
85 = 85 dB
90 = 90 dB
95 = 95 dB</td></tr>
<tr><th>A</th><th>B</th><th>C</th></tr>
<tr><td>Blade-
passage
frequency</td><td>Helical-
tip
Mach number</td><td>Tone-to-
broadband
noise ratio</td></tr>
<tr><td>1 = 67.5 Hz
2 = 135 Hz
3 = 180 Hz
4 = 225 Hz
5 = 292.5 Hz</td><td>1 = 0.63
2 = 0.73
3 = 0.78</td><td>1 = 0 dB
2 = 15 dB
3 = 30 dB</td></tr>
</table>

Table V. Presentation Order of Stimuli on Tapes in Second Experiment

Practice tape	Tape 1 ↓	Tape 2 ↓	Tape 3 ↓	Tape 4 ↓
DC9 T 80	260 1 90	135 3 80	LP3 T 90	292 2 80
180 3 70	DC9 T 80	727 T 90	067 2 70	YYY T 90
LP3 T 90	292 3 90	180 Z 80	YYY T 70	225 2 70
	LP3 T 70	225 1 70	707 T 80	YS1 T 80
	135 3 70	DD7 T 90	180 2 90	135 3 90
	YYY T 80	180 1 70	260 3 90	260 1 80
	727 T 85	262 T 80	300 T 80	292 1 70
	067 3 90	300 T 90	135 1 70	XXX F 80
	292 2 70	YYY F 90	292 1 90	300 T 70
	XXX T 70	135 2 70	330 T 80	260 2 90
	180 3 80	292 3 70	135 2 90	180 3 90
	DD7 T 80	067 1 80	067 3 80	LP3 T 80
	262 T 90	D10 T 80	260 1 70	180 2 70
	260 2 70	135 1 90	727 T 75	727 T 95
	225 1 80	XXX F 70	292 3 80	262 T 70
	067 2 80	260 2 80	D10 T 90	067 1 90
	YS1 T 70	727 T 65	XXX T 90	T35 2 80
	707 T 90	067 2 90	DD7 T 70	330 T 90
	260 3 80	292 1 80	180 3 70	D10 T 70
	XXX F 90	225 3 90	225 2 80	225 1 90
	135 1 80	330 T 70	180 1 80	727 T 80
	225 2 90	XXX T 80	YS1 T 90	YYY F 70
	727 T 70	260 3 70	DC9 T 70	225 3 80
	067 1 70	292 2 90	YYY F 80	DC9 T 90
	180 1 90	707 T 70	225 3 70	067 3 70
	Tape 5 ↑	Tape 6 ↑	Tape 7 ↑	Tape 8 ↑

Stimuli key					
Aircraft type and/or blade-passage frequency				Operation type or tone-to-broadband noise ratio	Nominal L_D
Advanced turboprop	Conventional turboprop	Conventional jet	Pilot study	T = Takeoff	65 = 65 dB
				F = Flyover	70 = 70 dB
					75 = 75 dB
067 = 67.5 Hz	DD7 = Dash 7	300 = Airbus A-300	XXX = Aircraft 1	1 = 0 dB	80 = 80 dB
135 = 135 Hz	LP3 = P-3	707 = Boeing 707	YYY = Aircraft 2	2 = 15 dB	85 = 85 dB
180 = 180 Hz	YS1 = YS-11	727 = Boeing 727-200		3 = 30 dB	90 = 90 dB
225 = 225 Hz	262 = Nord 262	DC9 = DC-9			95 = 95 dB
260 = 260 Hz	330 = Shorts 330	D10 = DC-10			
292 = 292.5 Hz					

Table VI. Order of Tapes Presented to Test Subjects in Both Experiments

Test subject group	Tapes presented during session—			
	1	2	3	4
1	1	2	3	4
2	2	1	4	3
3	3	4	1	2
4	4	3	2	1
5	5	6	7	8
6	6	5	8	7
7	7	8	5	6
8	8	7	6	5
9	1	3	4	2
10	2	4	3	1
11	3	1	2	4
12	4	2	1	3
13	5	7	8	6
14	6	8	7	5
15	7	5	6	8
16	8	6	5	7

Table VII. Standard Deviations of Prediction Error for Advanced Turboprop Stimuli in First Experiment

Metric	Standard deviation, dB, for—					
	No duration correction			Duration corrected		
	No tone correction	T_1	T_2	No tone correction	T_1	T_2
L_A	3.89	4.16	3.69	3.18	3.29	3.08
L_D	4.85	5.19	4.66	3.95	4.16	3.82
L_E	4.71	5.05	4.52	3.78	3.99	3.66
L_1	4.08	4.36	3.89	3.37	3.50	3.26
LL	4.19	4.38	4.04	3.71	3.82	3.61
$\mathrm{LL_Z}$	3.70	3.81	3.46	3.44	3.46	3.37
PL	3.83	4.06	3.70	3.43	3.52	3.35
PNL	4.01	4.29	3.81	3.46	3.59	3.34
$\mathrm{PNL_K}$	4.04	4.34	3.88	3.40	3.54	3.29
$\mathrm{PNL_M}$	4.04	4.31	3.89	3.41	3.54	3.29
$\mathrm{PNL_W}$	4.14	4.44	3.99	3.59	3.73	3.47

Table VIII. Standard Deviations of Prediction Error for Advanced Turboprop, Conventional Turboprop, and Conventional Jet Stimuli in Second Experiment

Metric	Standard deviation, dB, for—					
	No duration correction			Duration corrected		
	No tone correction	T_1	T_2	No tone correction	T_1	T_2
L_A	3.18	3.52	3.09	2.53	2.88	2.51
L_D	3.84	4.28	3.76	3.16	3.64	3.12
L_E	3.83	4.27	3.77	3.08	3.57	3.07
L_1	3.09	3.57	3.11	2.57	2.99	2.54
LL	3.37	3.72	3.21	2.79	3.11	2.69
$\mathrm{LL_Z}$	2.78	3.00	2.60	2.33	2.45	2.21
PL	2.85	3.19	2.71	2.36	2.63	2.26
PNL	3.01	3.48	2.93	2.51	2.90	2.42
$\mathrm{PNL_K}$	2.95	3.39	2.85	2.41	2.80	2.33
$\mathrm{PNL_M}$	2.90	3.26	2.75	2.35	2.68	2.25
$\mathrm{PNL_W}$	3.11	3.55	3.01	2.55	2.97	2.48

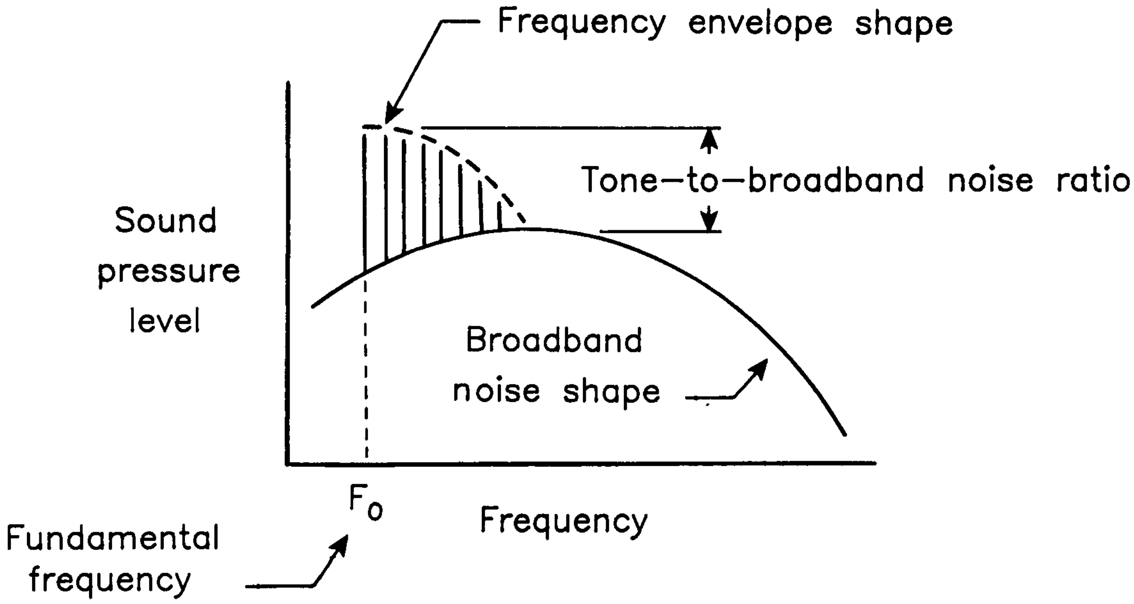

Figure 1. Noise characteristics of propeller aircraft.

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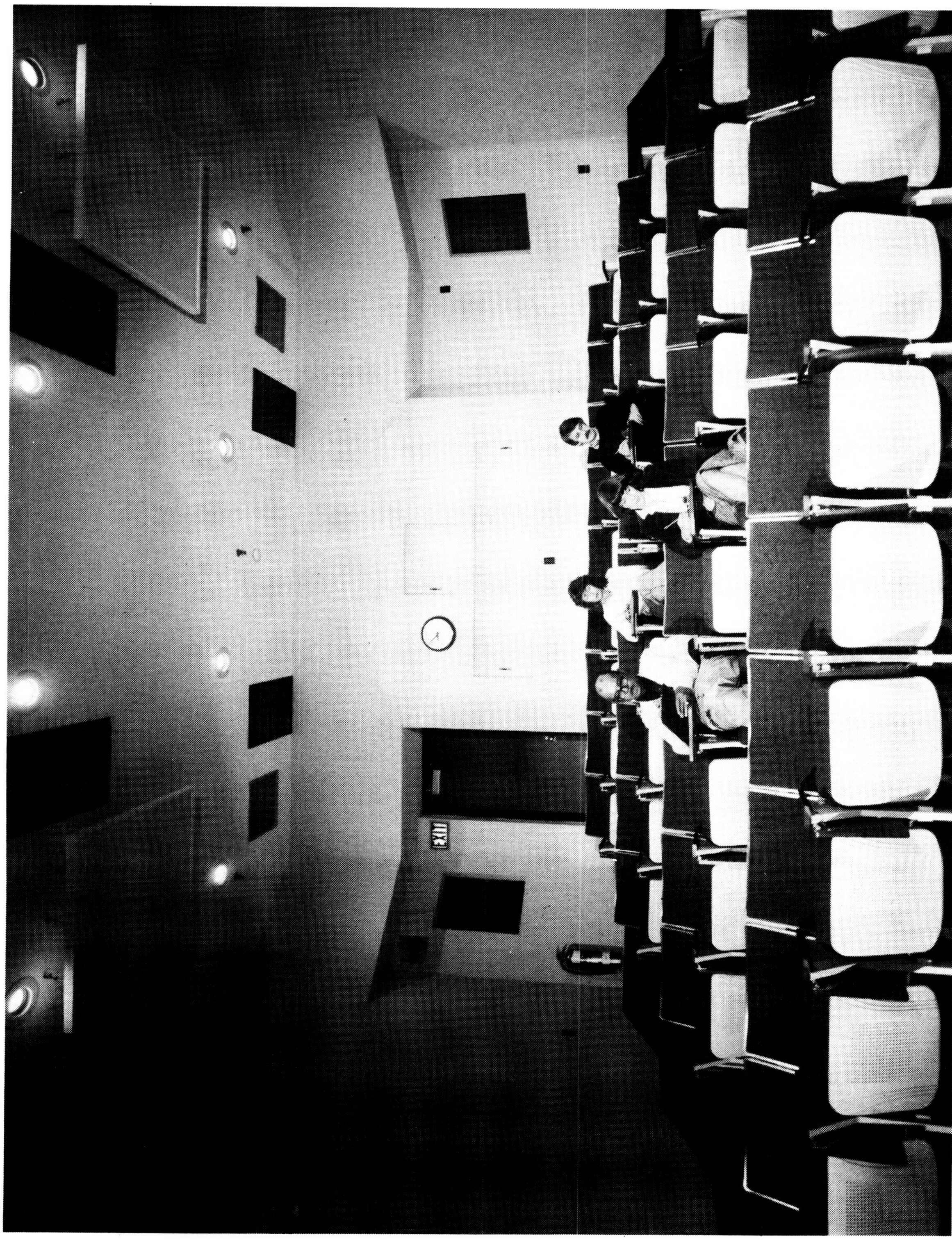

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Figure 2. Subjects in Exterior Effects Room in the Langley Aircraft Noise Reduction Laboratory.

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Figure 3. Subjects in Anechoic Listening Room in the Langley Aircraft Noise Reduction Laboratory.

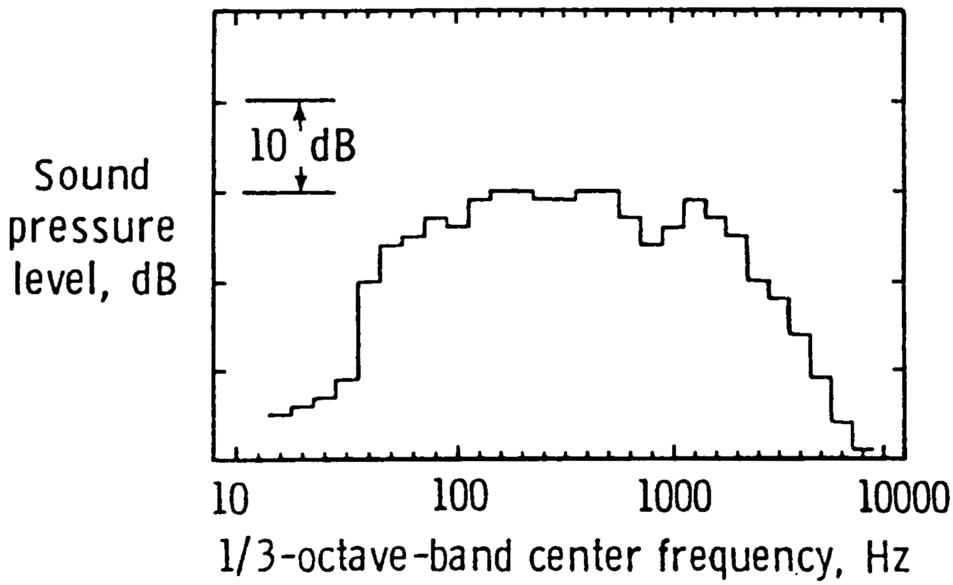

Figure 4. Broadband 1/3-octave spectrum used in synthesis of advanced turboprop aircraft noise.

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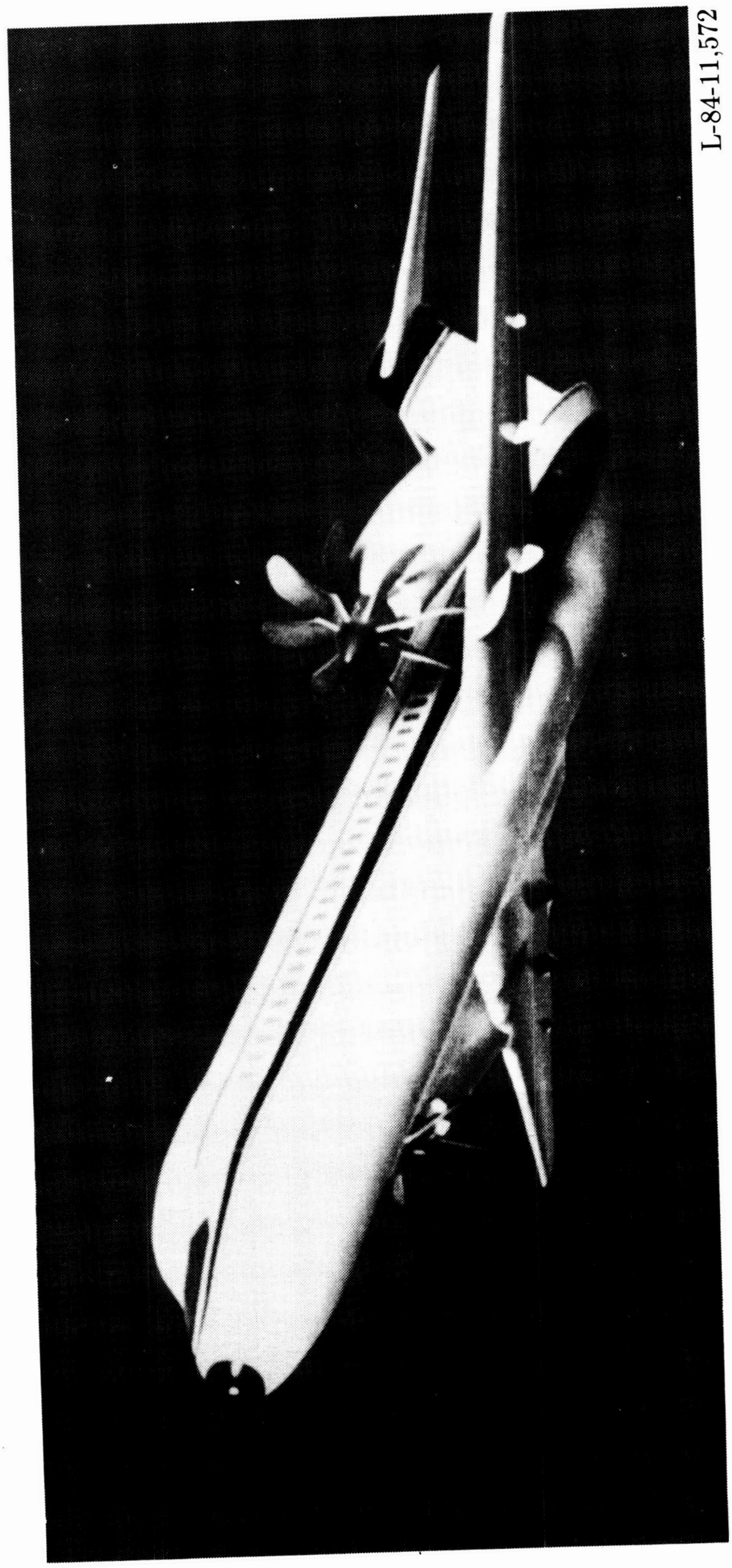

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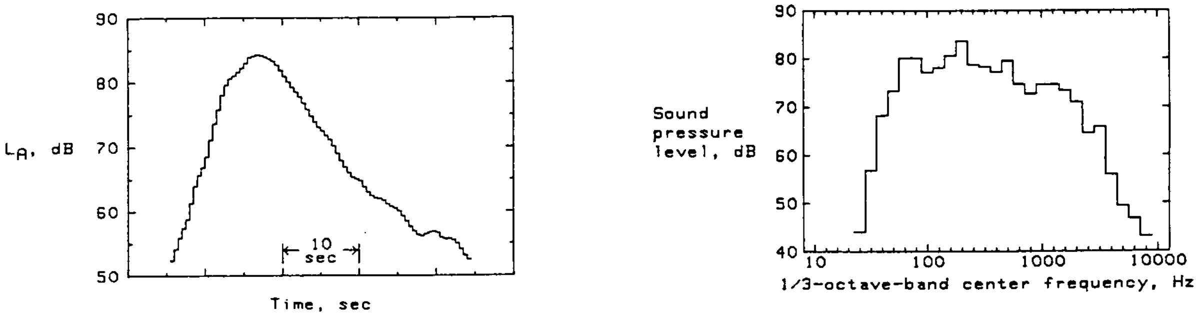
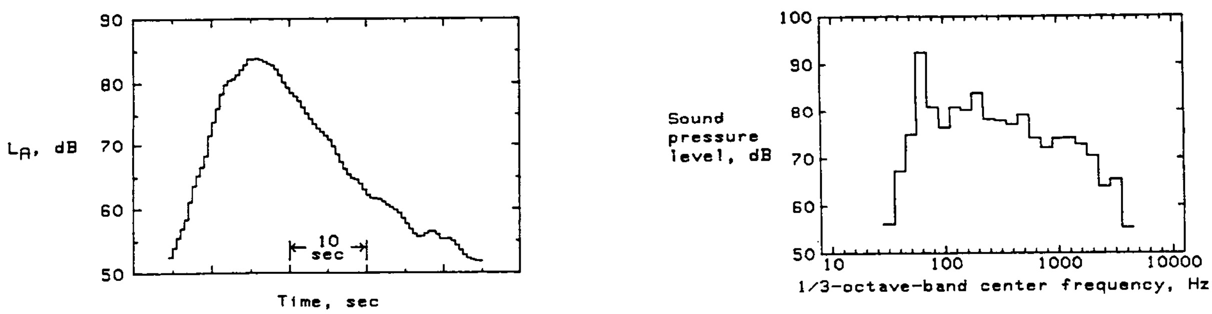
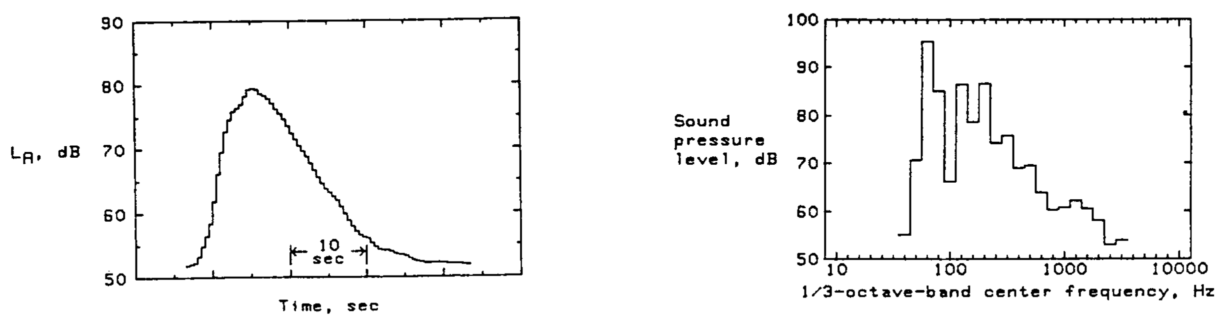
Figure 5. A wing-mounted, tractor, single-rotating propeller configuration of an advanced turboprop aircraft.



(a) $F_o = 67.5$ Hz; $T/N = 0$ dB.

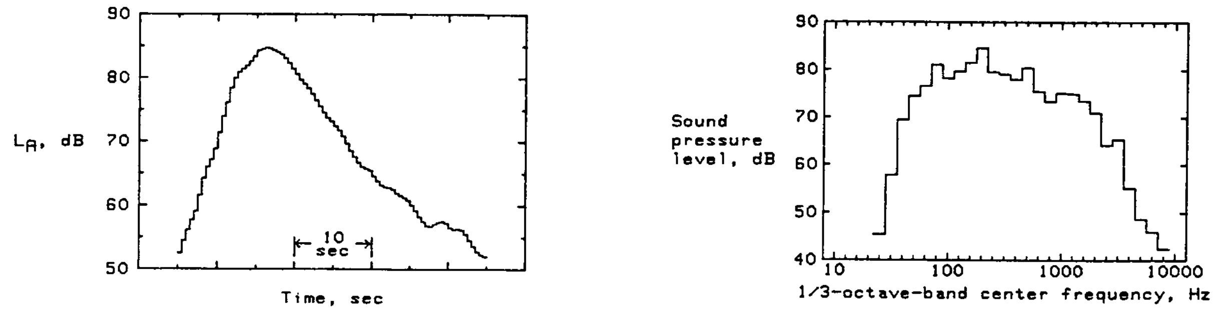


(b) $F_o = 67.5$ Hz; $T/N = 15$ dB.

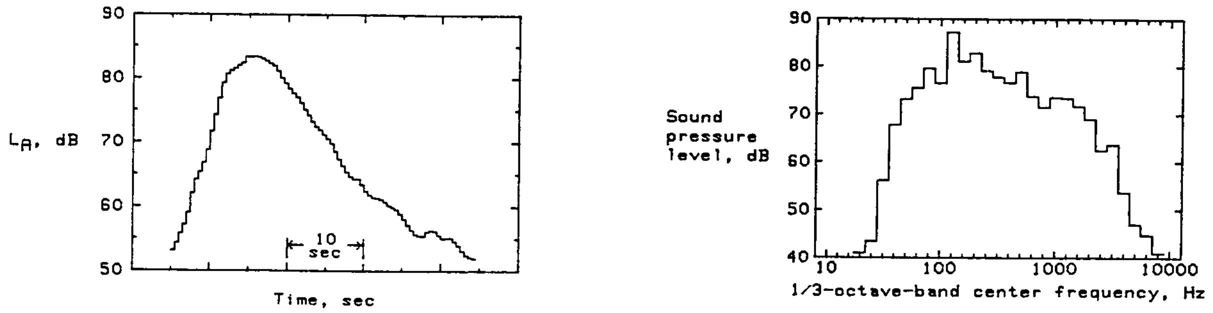


(c) $F_o = 67.5$ Hz; $T/N = 30$ dB.

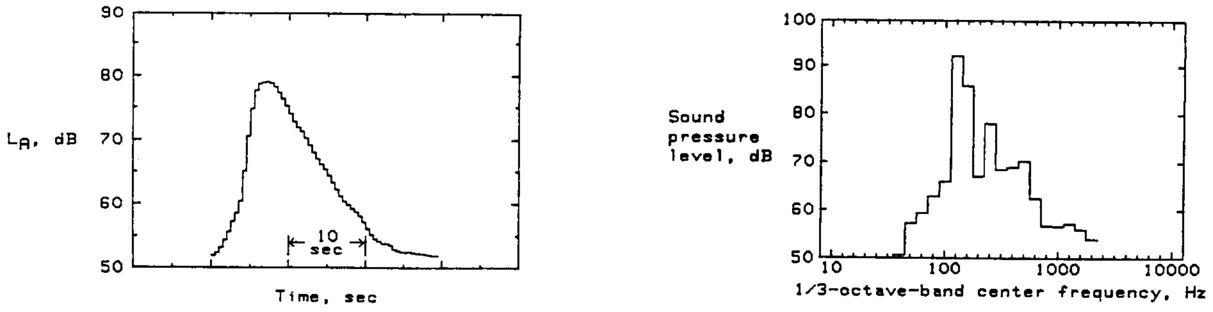
Figure 6. L_A time history and 1/3-octave-band spectrum at peak L_A of highest level presentation of each advanced turboprop flyover noise with $M_{ht} = 0.73$.



(d) $F_o = 135$ Hz; $T/N = 0$ dB.

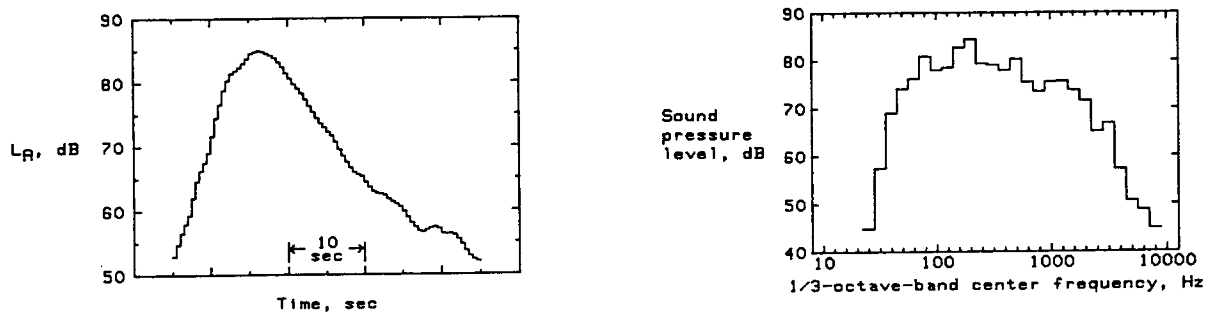


(e) $F_o = 135$ Hz; $T/N = 15$ dB.

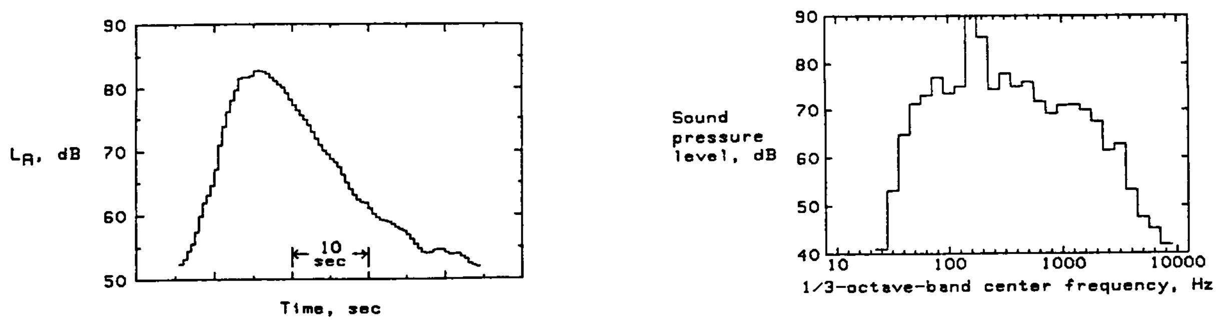


(f) $F_o = 135$ Hz; $T/N = 30$ dB.

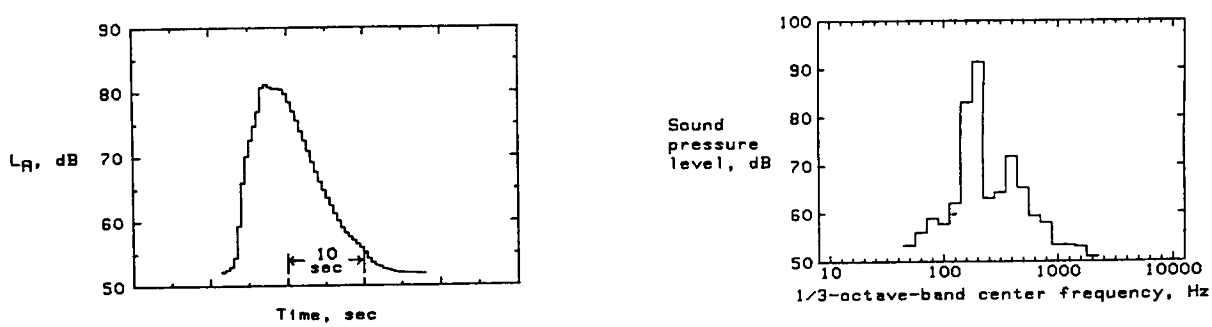
Figure 6. Continued.



(g) $F_o = 180$ Hz; $T/N = 0$ dB.



(h) $F_o = 180$ Hz; $T/N = 15$ dB.



(i) $F_o = 180$ Hz; $T/N = 30$ dB.

Figure 6. Continued.

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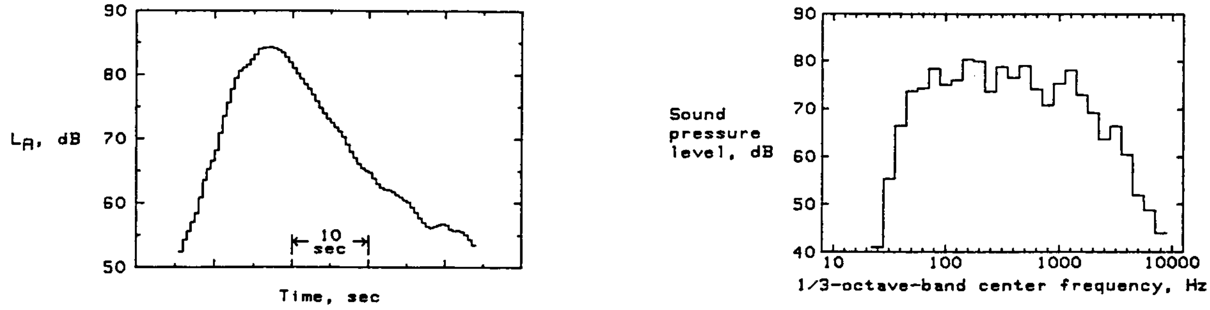
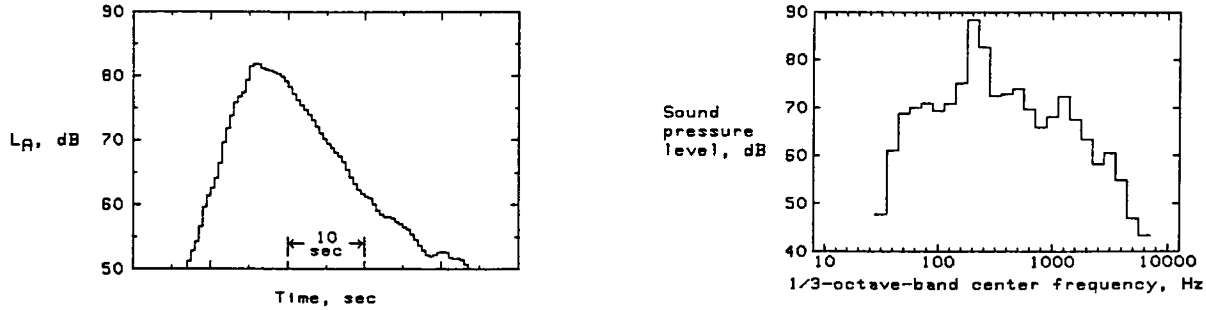
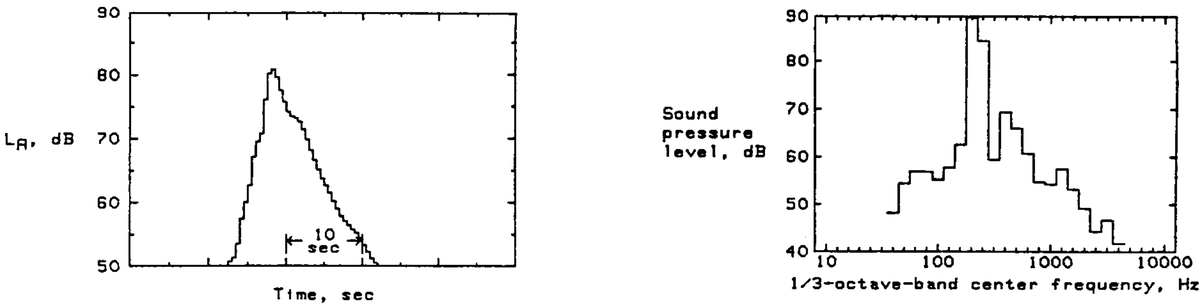


(j) $F_o = 225$ Hz; $T/N = 0$ dB.

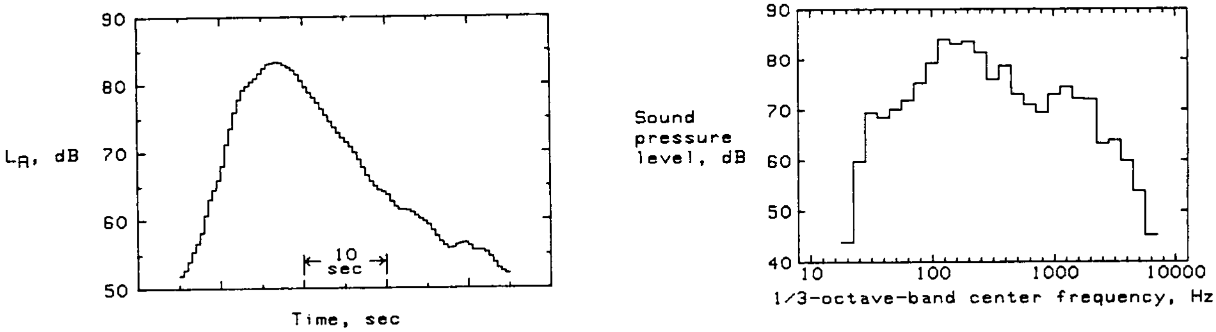


(k) $F_o = 225$ Hz; $T/N = 15$ dB.

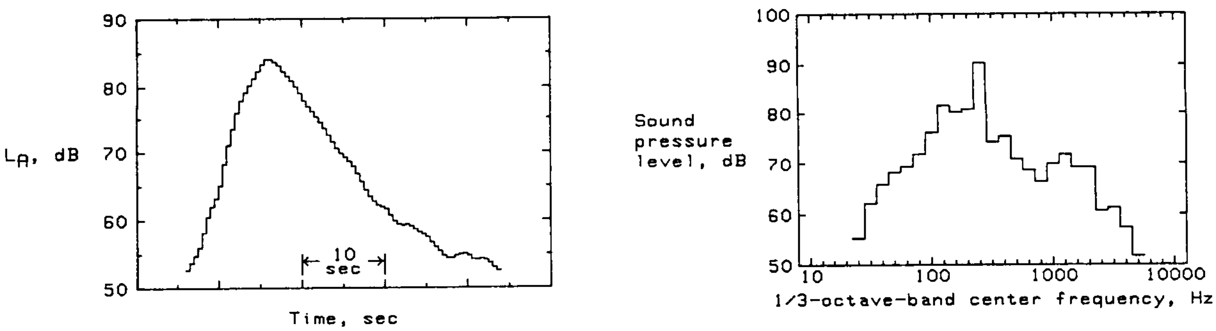


(l) $F_o = 225$ Hz; $T/N = 30$ dB.

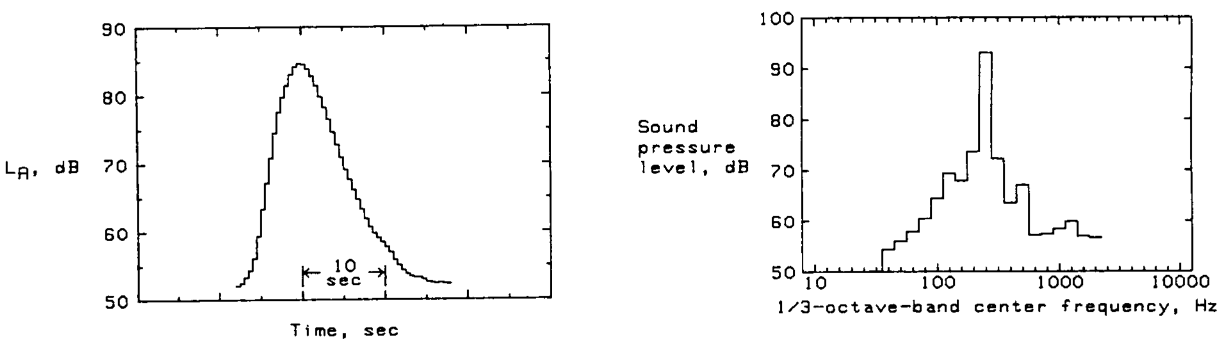
Figure 6. Continued.



(m) $F_o = 260$ Hz; $T/N = 0$ dB.

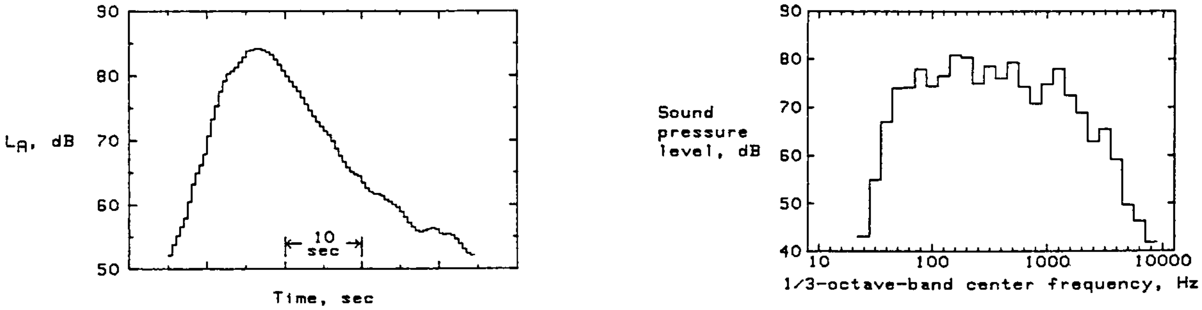


(n) $F_o = 260$ Hz; $T/N = 15$ dB.

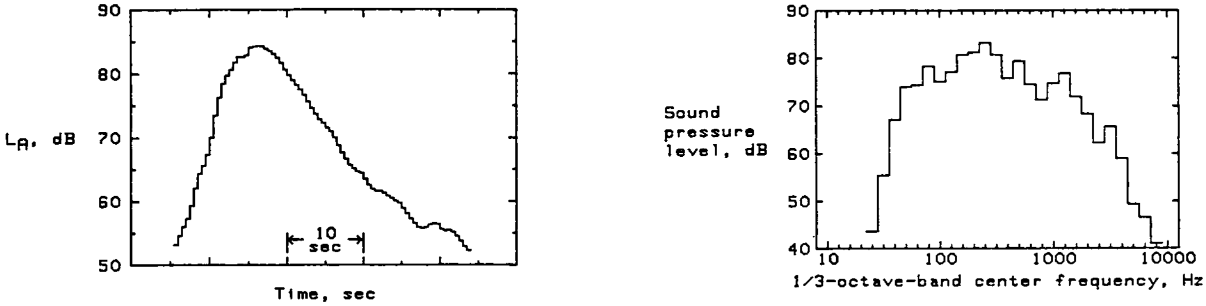


(o) $F_o = 260$ Hz; $T/N = 30$ dB.

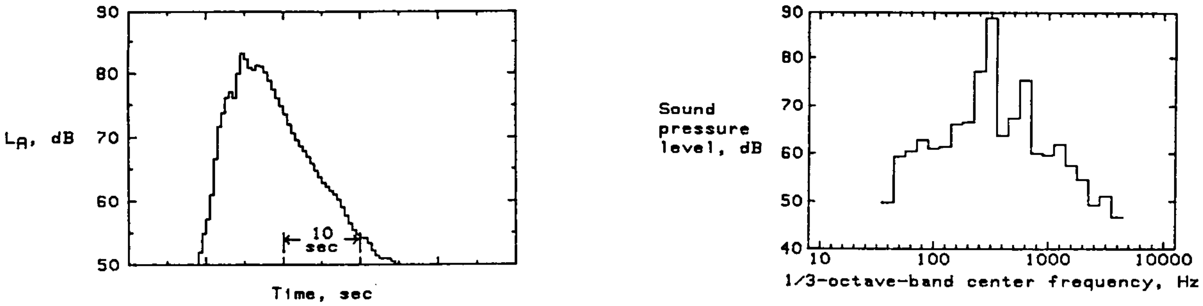
Figure 6. Continued.



(p) $F_o = 292.5$ Hz; $T/N = 0$ dB.

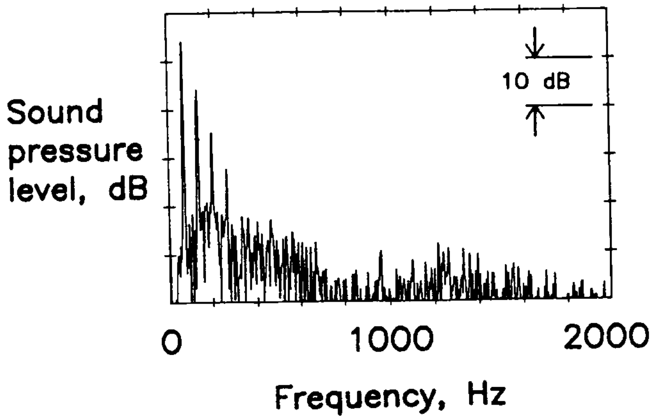


(q) $F_o = 292.5$ Hz; $T/N = 15$ dB.

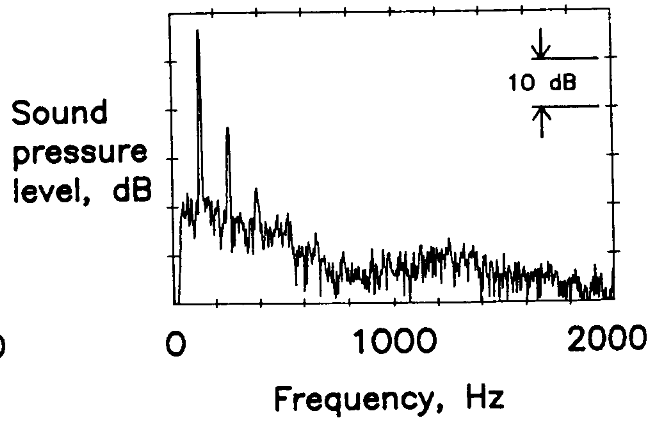


(r) $F_o = 292.5$ Hz; $T/N = 30$ dB.

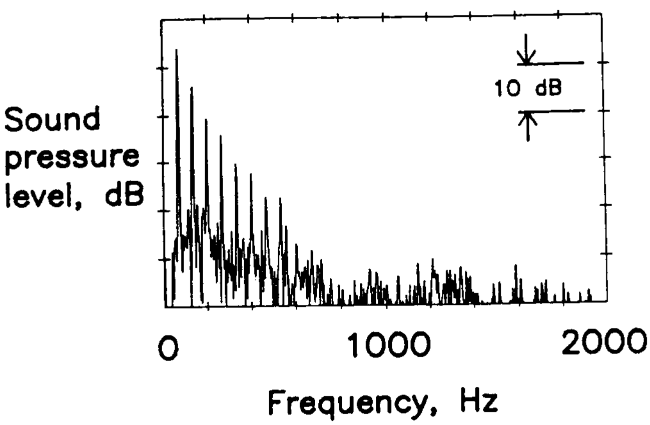
Figure 6. Concluded.



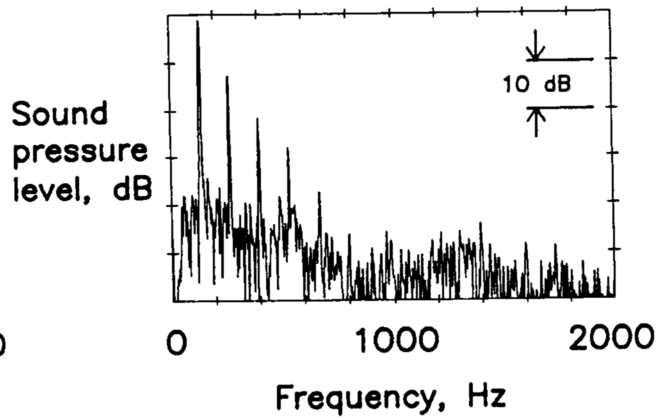
(a) $F_o = 67.5$ Hz; $M_{ht} = 0.63$.



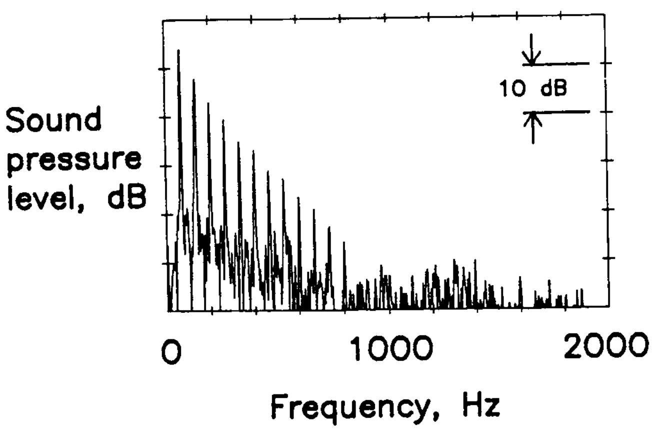
(d) $F_o = 135$ Hz; $M_{ht} = 0.63$.



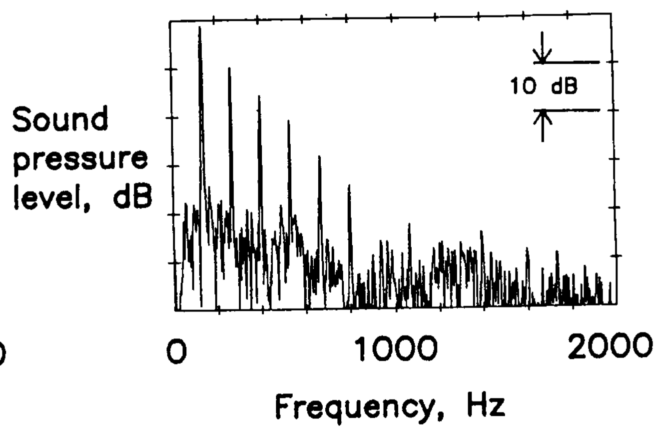
(b) $F_o = 67.5$ Hz; $M_{ht} = 0.73$.



(e) $F_o = 135$ Hz; $M_{ht} = 0.73$.

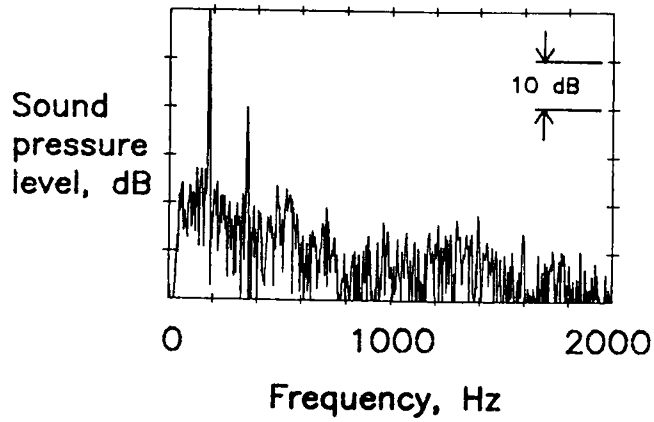


(c) $F_o = 67.5$ Hz; $M_{ht} = 0.78$.

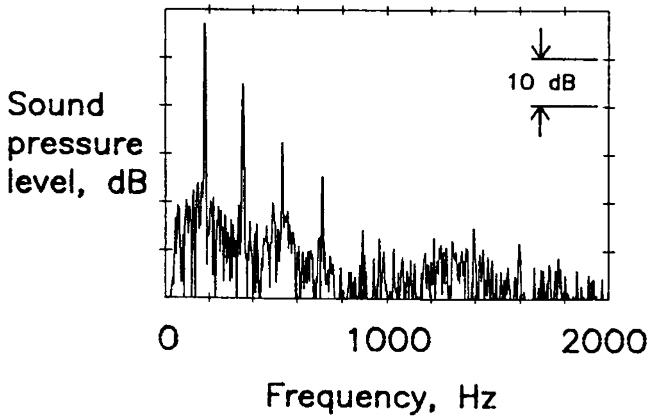


(f) $F_o = 135$ Hz; $M_{ht} = 0.78$.

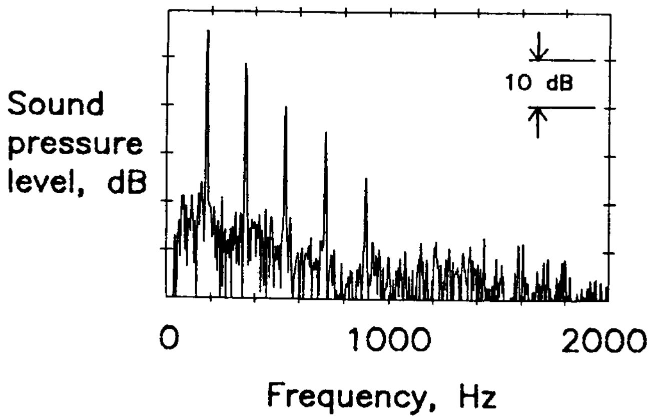
Figure 7. Narrowband spectrum of each advanced turboprop flyover noise with 30-dB tone-to-broadband nois ratio.



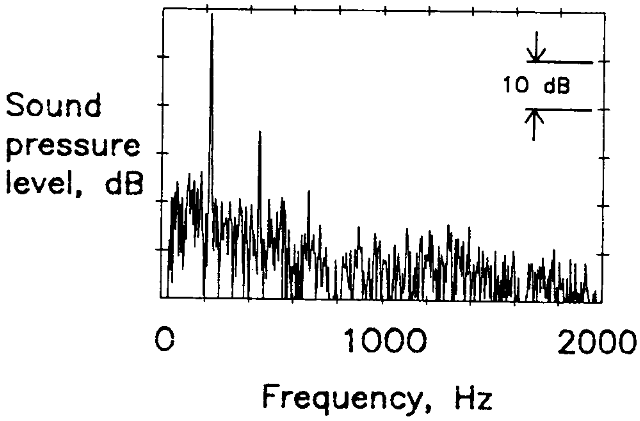
(g) $F_o = 180$ Hz; $M_{ht} = 0.63$.



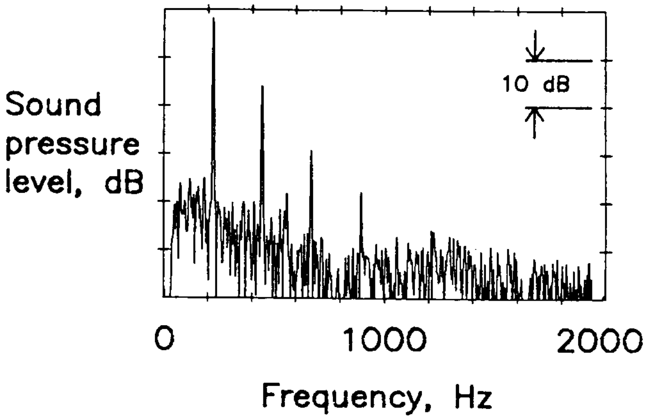
(h) $F_o = 180$ Hz; $M_{ht} = 0.73$.



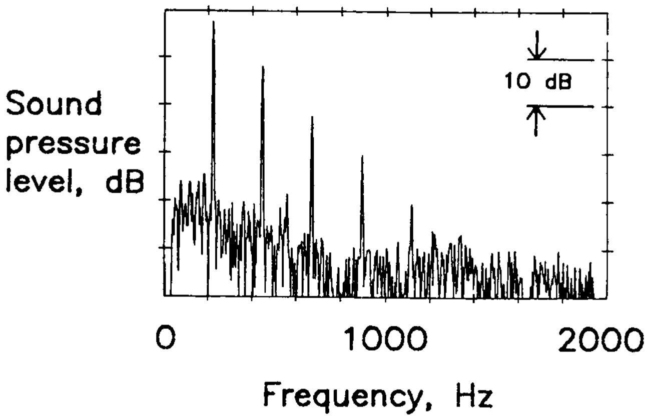
(i) $F_o = 180$ Hz; $M_{ht} = 0.78$.



(j) $F_o = 225$ Hz; $M_{ht} = 0.63$.

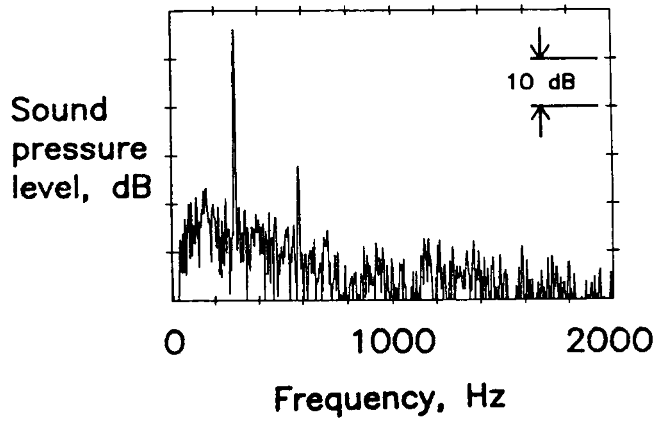


(k) $F_o = 225$ Hz; $M_{ht} = 0.73$.

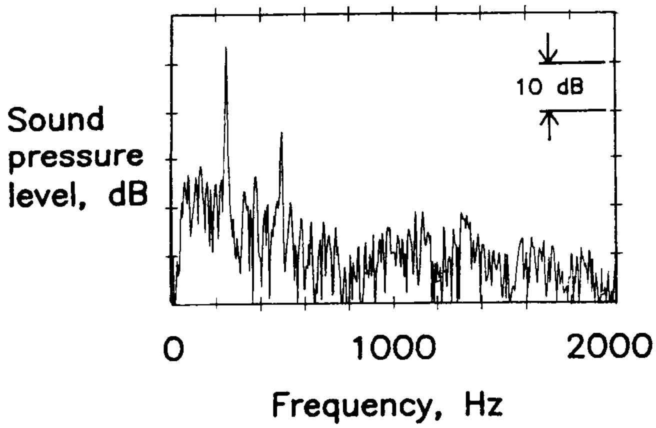


(l) $F_o = 225$ Hz; $M_{ht} = 0.78$.

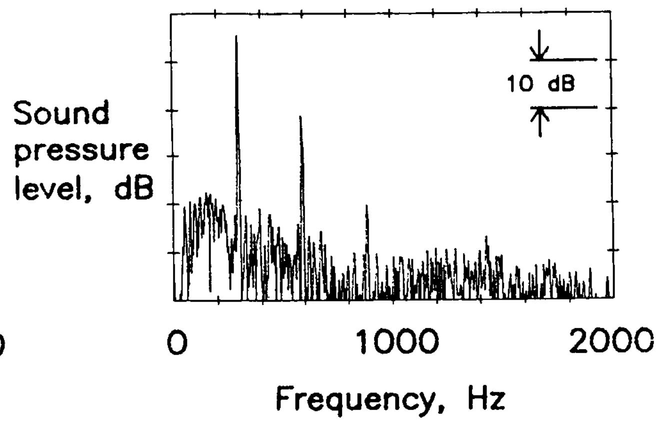
Figure 7. Continued.



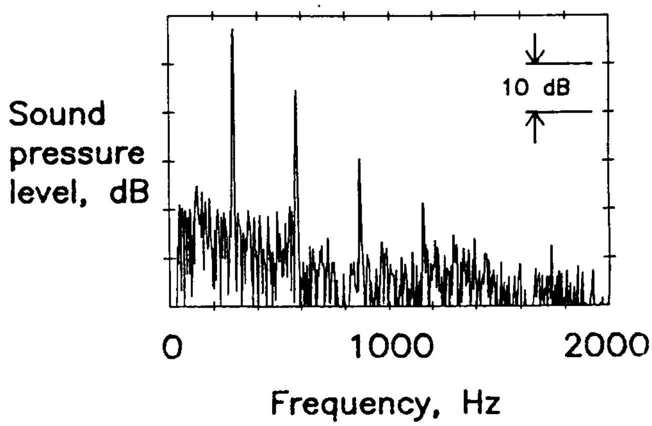
(n) $F_o = 292.5$ Hz; $M_{ht} = 0.63$.



(m) $F_o = 260$ Hz; $M_{ht} = 0.73$.

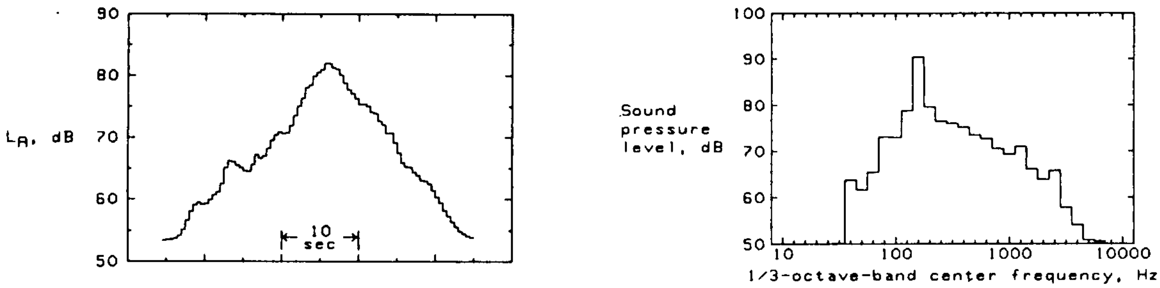


(o) $F_o = 292.5$ Hz; $M_{ht} = 0.73$.

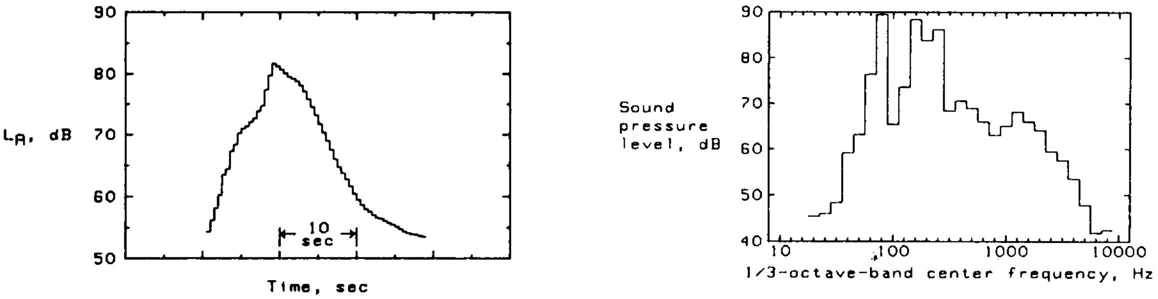


(p) $F_o = 292.5$ Hz; $M_{ht} = 0.78$.

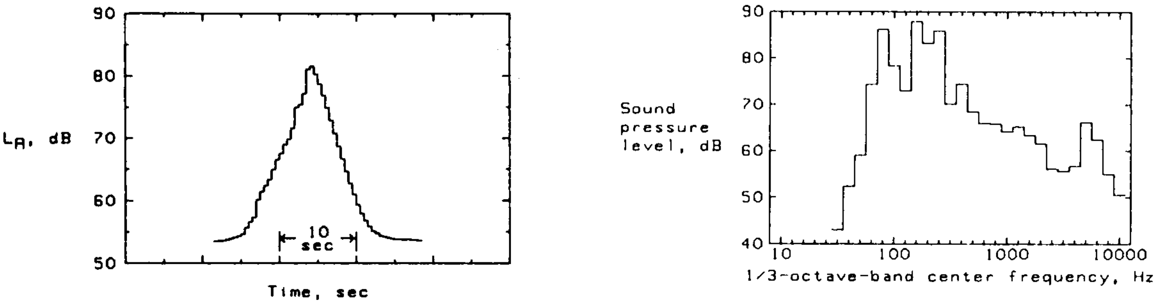
Figure 7. Concluded.



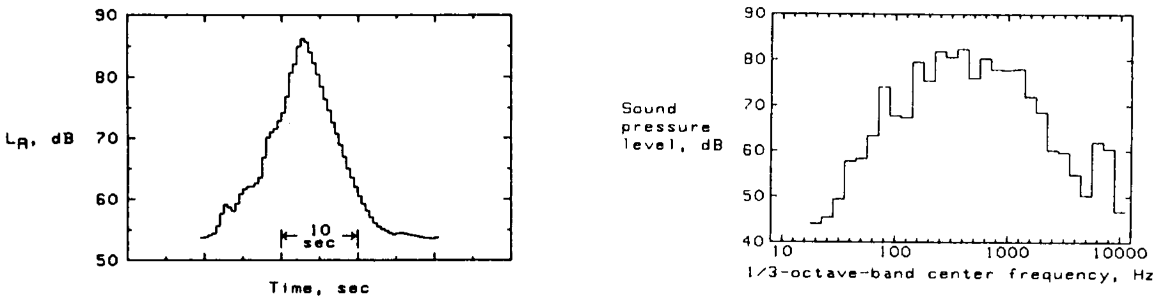
(a) de Havilland Canada DHC-7 Dash 7 takeoff.



(b) Lockheed P-3 takeoff.

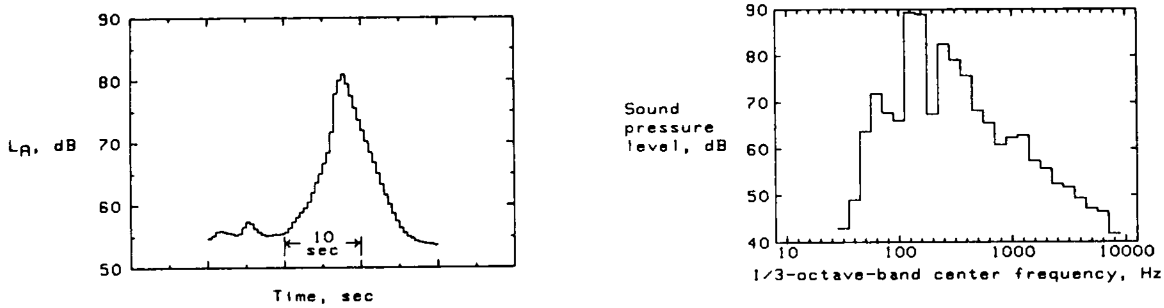


(c) NAMC YS-11 takeoff.

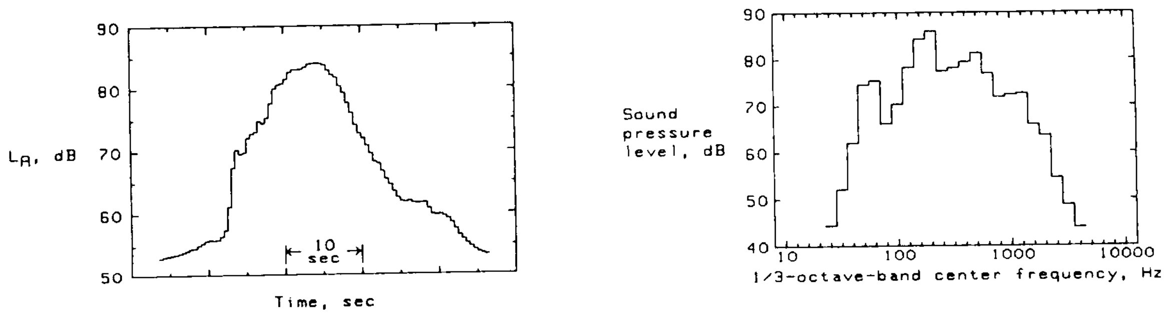


(d) Nord 262 takeoff.

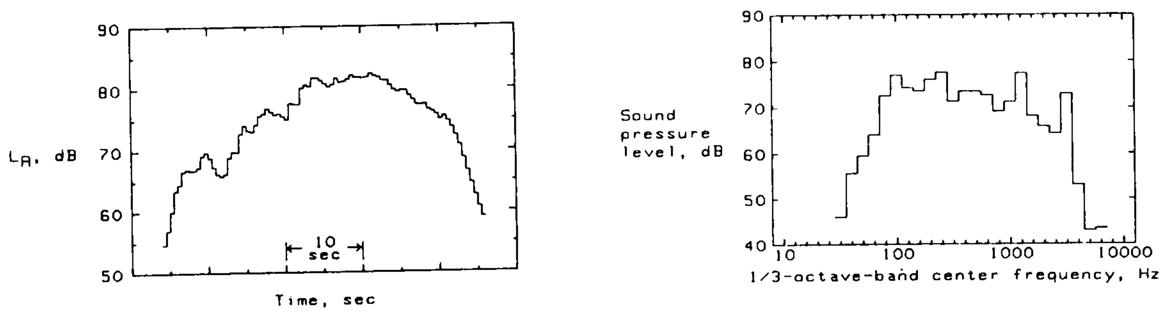
Figure 8. L_A time histories and 1/3-octave-band spectra at peak L_A of highest level presentations of takeoffs of conventional turboprop and jet aircraft.



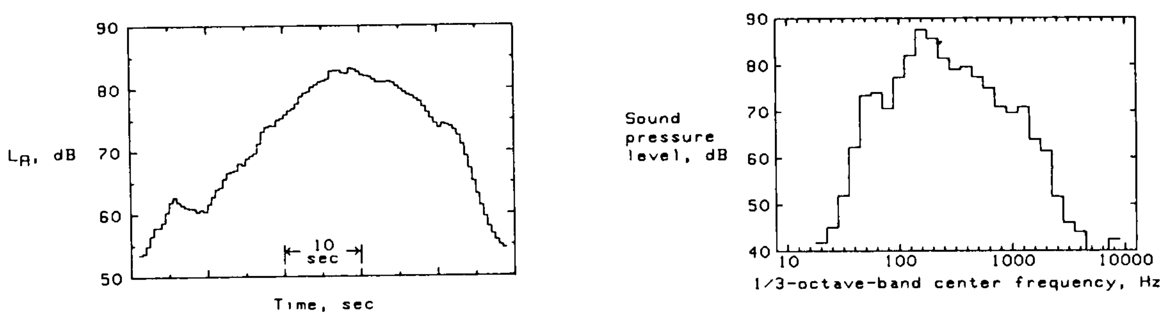
(e) Shorts 330 takeoff.



(f) Airbus Industrie A-300 takeoff.

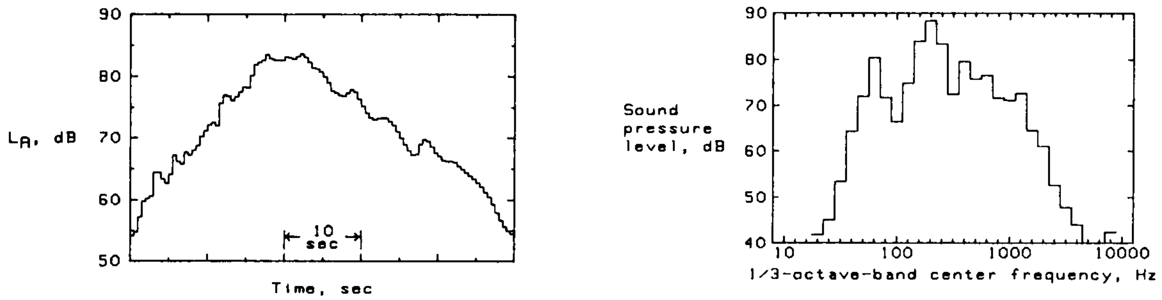


(g) Boeing 707 takeoff.

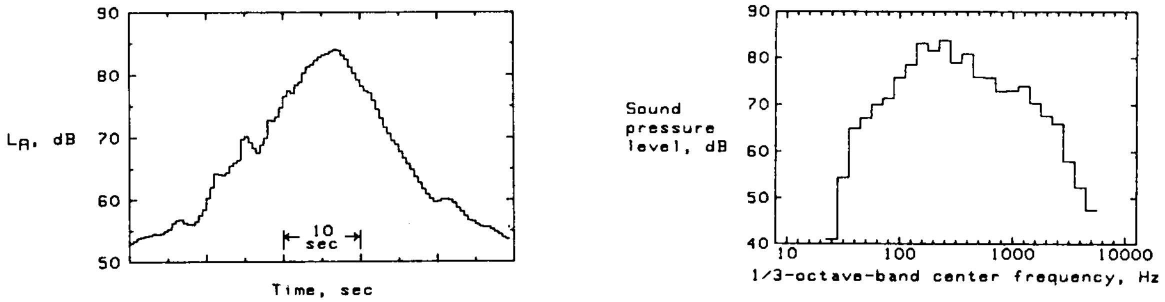


(h) Boeing 727-200 takeoff.

Figure 8. Continued.



(i) McDonnell Douglas DC-9 takeoff.



(j) McDonnell Douglas DC-10 takeoff.

Figure 8. Concluded.

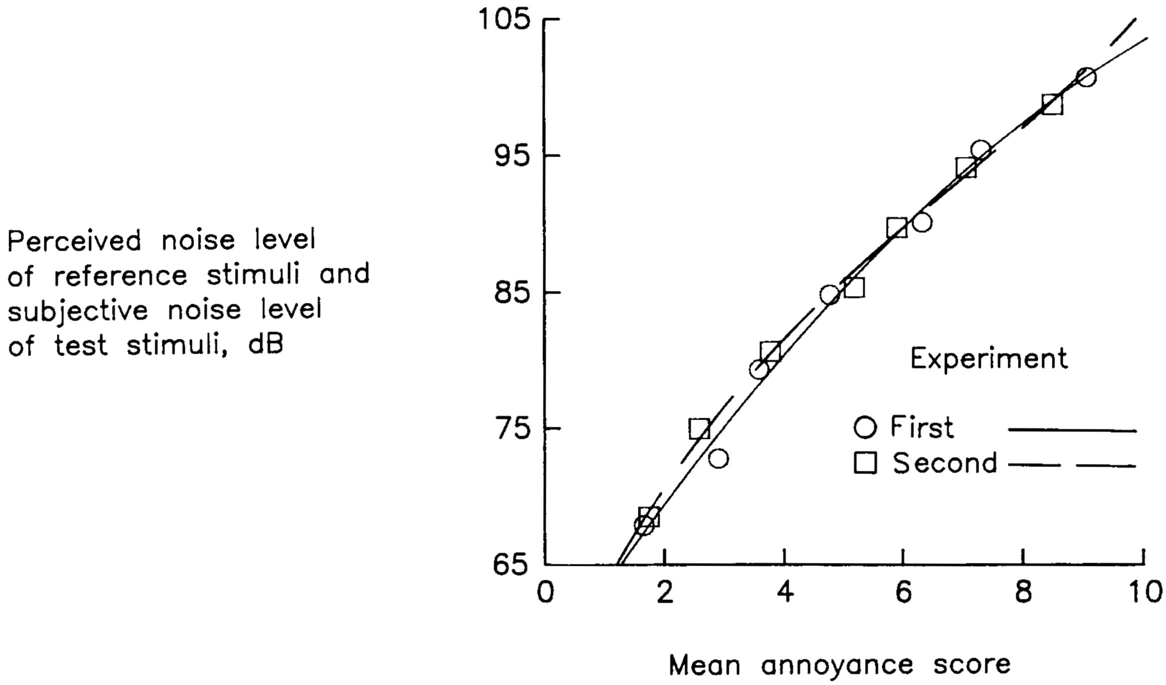


Figure 9. Regression analyses of PNL on mean annoyance scores for Boeing 727-200 takeoff stimuli used to convert annoyance judgments to subjective noise levels L_S.

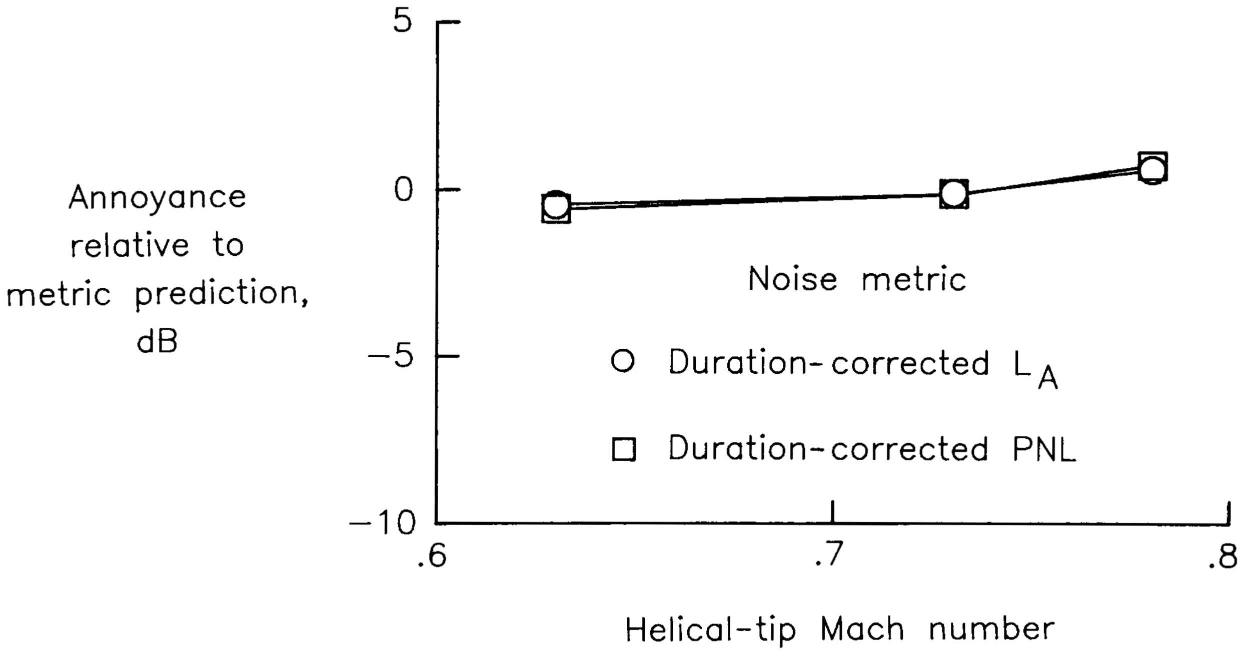


Figure 10. Effect of helical-tip Mach number (frequency envelope shape) on annoyance prediction for duration-corrected L_A and duration-corrected PNL.

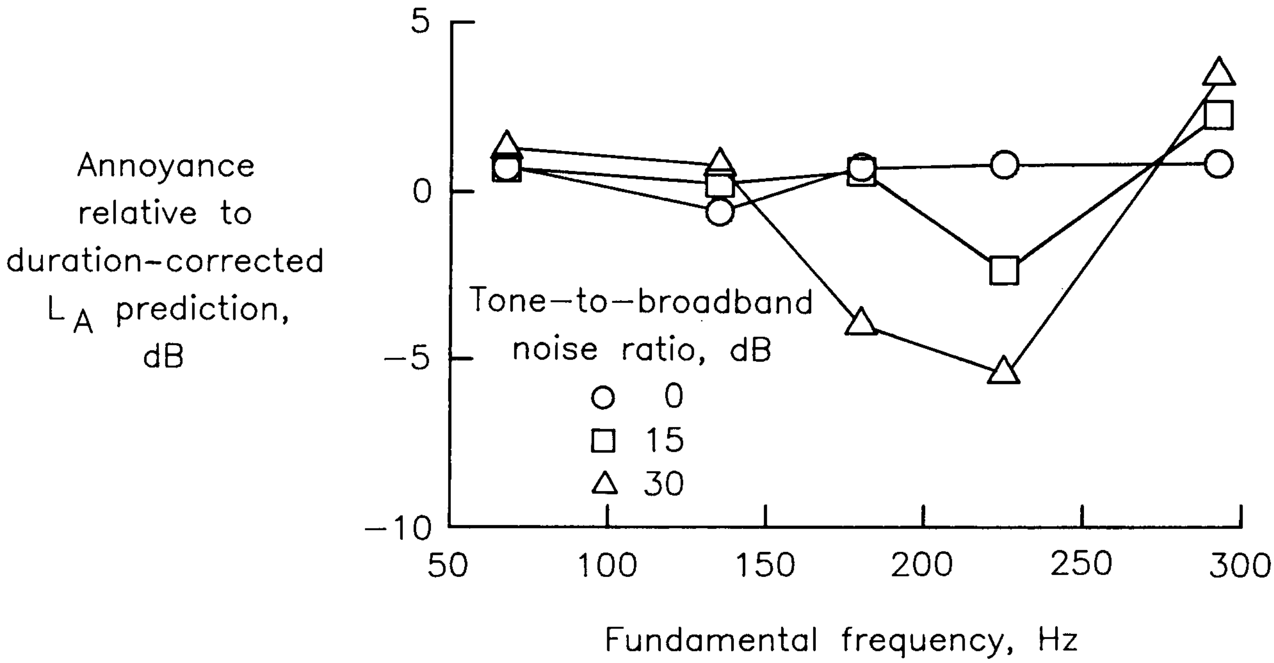


Figure 11. Effect of interaction of fundamental frequency with tone-to-broadband noise ratio on annoyance prediction for duration-corrected L_A in first experiment.

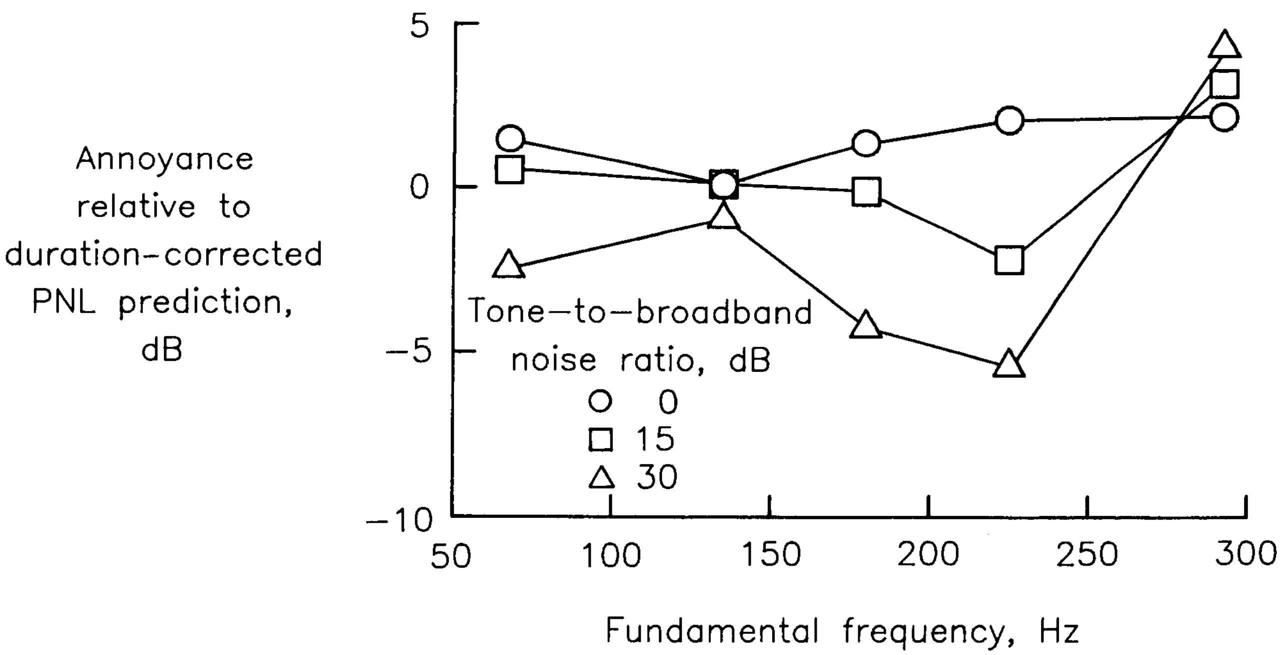


Figure 12. Effect of interaction of fundamental frequency with tone-to-broadband noise ratio on annoyance prediction for duration-corrected PNL in first experiment.

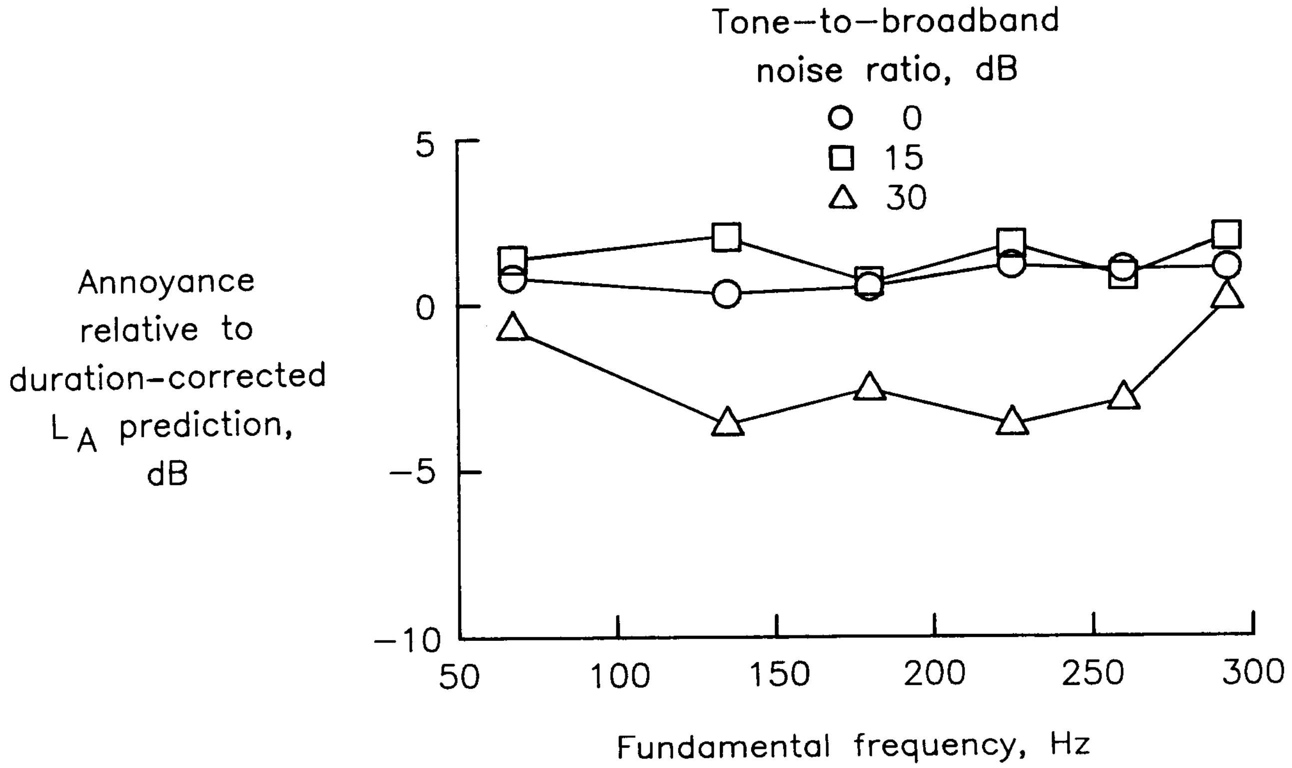


Figure 13. Effect of interaction of fundamental frequency with tone-to-broadband noise ratio on annoyance prediction in terms of duration-corrected L_A for ATP stimuli in second experiment.

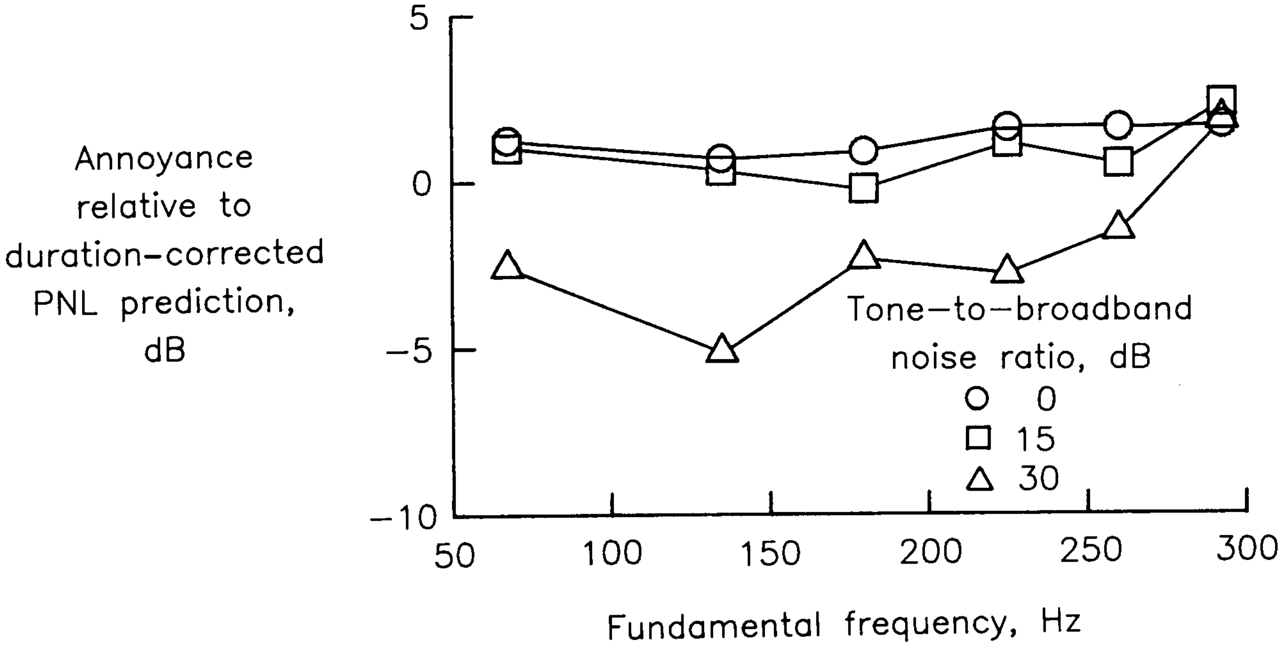


Figure 14. Effect of interaction of fundamental frequency with tone-to-broadband noise ratio on annoyance prediction in terms of duration-corrected PNL for ATP stimuli in second experiment.

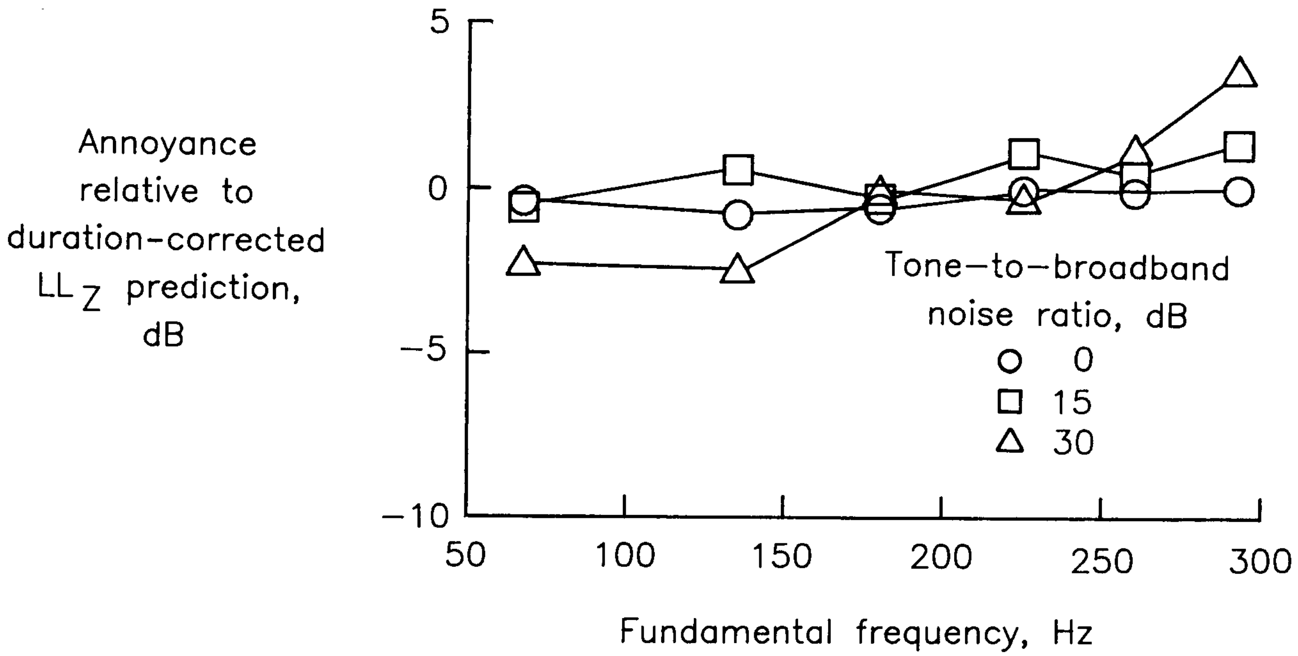


Figure 15. Effect of interaction of fundamental frequency with tone-to-broadband noise ratio on annoyance prediction in terms of duration-corrected LL_Z for ATP stimuli in second experiment.

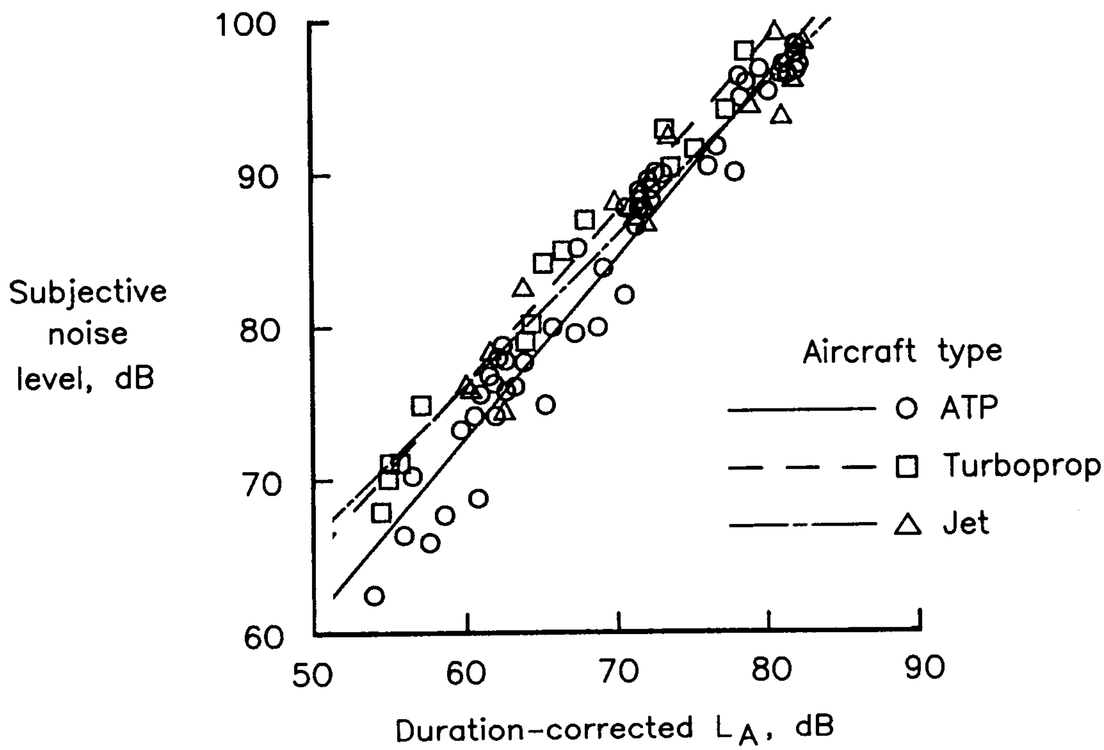


Figure 16. Comparison of annoyance responses using duration-corrected L_A.

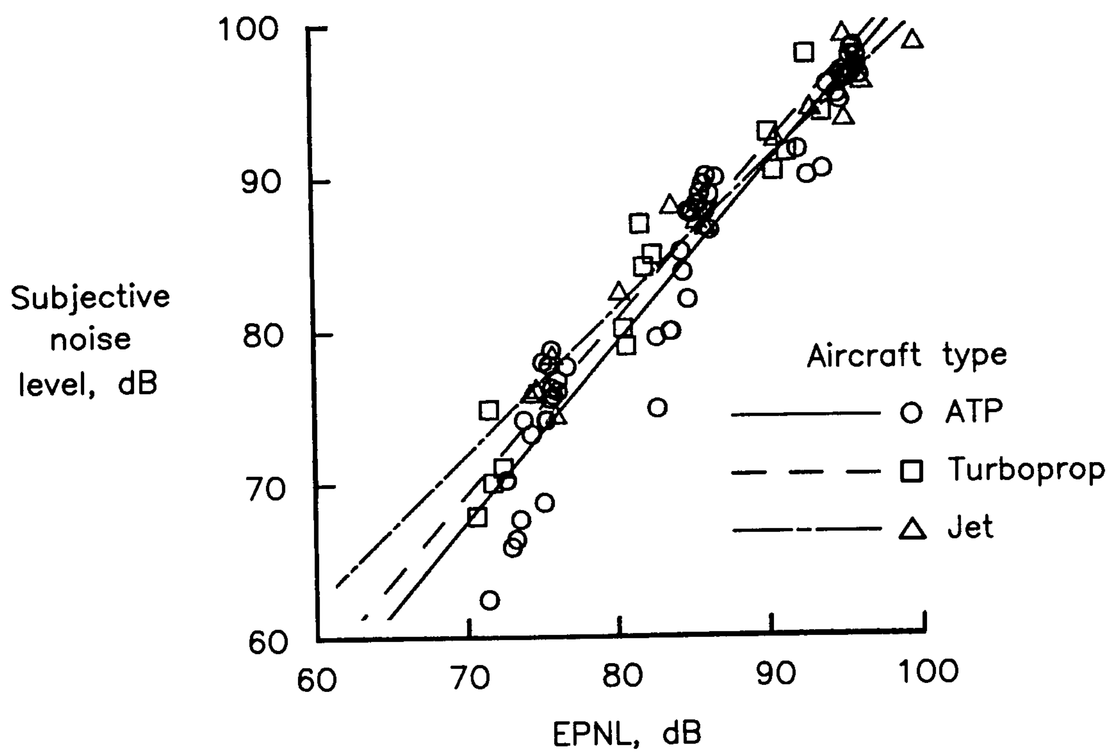


Figure 17. Comparison of annoyance responses using EPNL.

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15. Supplementary Notes

16. Abstract

Two laboratory experiments were conducted to quantify the annoyance of people to advanced turboprop (propfan) aircraft flyover noise. The objectives were (1) to determine the effects on annoyance of various tonal characteristics, and (2) to compare annoyance to advanced turboprops with annoyance to conventional turboprops and jets. A computer was used to synthesize realistic, time-varying simulations of advanced turboprop aircraft takeoff noise. In the first experiment, the subjects judged the annoyance of 45 advanced turboprop noises in which the tonal content was systematically varied to represent the factorial combinations of 5 fundamental frequencies, 3 frequency envelope shapes, and 3 tone-to-broadband noise ratios. Each noise was presented at 3 sound pressure levels. In the second experiment, 18 advanced turboprop takeoffs, 5 conventional turboprop takeoffs, and 5 conventional jet takeoffs were presented at 3 sound pressure levels to subjects. Analyses indicated that the frequency envelope shape did not significantly affect annoyance. The interaction of fundamental frequency with tone-to-broadband noise ratio did have a large and complex effect on annoyance. The advanced turboprop stimuli were slightly less annoying than the conventional stimuli.

17. Key Words (Suggested by Authors(s))	18. Distribution Statement
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