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Psychoacoustic Testing of Modulated Blade Spacing for Main Rotors

Bryan Edwards
Bell Helicopter Textron Inc., Fort Worth, Texas

May 2002

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1. BACKGROUND/INTRODUCTION

The growing commercial reliance upon the rotorcraft industry has increased the need for noise reduction technology. The occurrence of rotorcraft operations in and near population centers is increasing, causing more public awareness of the noise associated with these operations. Because of this increased awareness, rotorcraft operations are being constrained by local governments and by regulatory bodies in the form of more stringent noise specifications. These specifications are a requirement for civil certification of rotorcraft.

The increasing market sensitivity to rotorcraft noise has fueled the search for rotorcraft design innovations that will reduce noise without placing impractical penalties on cost or performance. This report describes an investigation of one potential noise reduction design feature.

1.1 Modulated Blade Spacing Concept

The National Aeronautics and Space Administration (NASA) has an ongoing program to develop technology which will reduce rotorcraft noise. NASA's overall Technology Enterprise goals are to reduce perceived noise levels of future aircraft by a factor of 2 from today's subsonic aircraft within 10 years and by a factor of 4 within 20 years. The current study supports these goals specifically for future helicopters and, by similarity, for future tiltrotor aircraft.

In September 1998, NASA requested proposals for innovative, high-risk design features to reduce helicopter main rotor noise. Bell responded with a proposal to evaluate the noise reduction potential of Modulated (uneven) Blade Spacing (MBS) as applied to helicopter main rotors. The primary characteristic of this non-traditional 5-blade rotor concept is that the blade spacings, rather than being a constant 72° as in a traditional 5-blade rotor, had five unique spacings: 72°, 68.5°, 79°, 65°, and 75.5°. Bell's Model 427 helicopter, illustrated in Figure 1-1, was chosen as a baseline for comparison. The contracted Phase 1 effort (Reference 1) consisted of an analytical study of this MBS design concept to predict its acoustic and dynamic properties, and determine its practicality. The conclusion of this Phase 1 study was that the MBS concept as applied to main rotors offers significantly reduced noise levels at many flight conditions and the potential for a breakthrough in how a helicopter's sound is perceived and judged. Although the MBS rotor concept was found to be feasible in terms of dynamic loads and practical design criteria, the noise level reductions were not found at every flight condition. In fact, the MBS rotor was found to increase noise levels at some conditions. The subjective test described in this report was devised as a means of resolving this anomaly and defining the potential of this innovative main rotor.

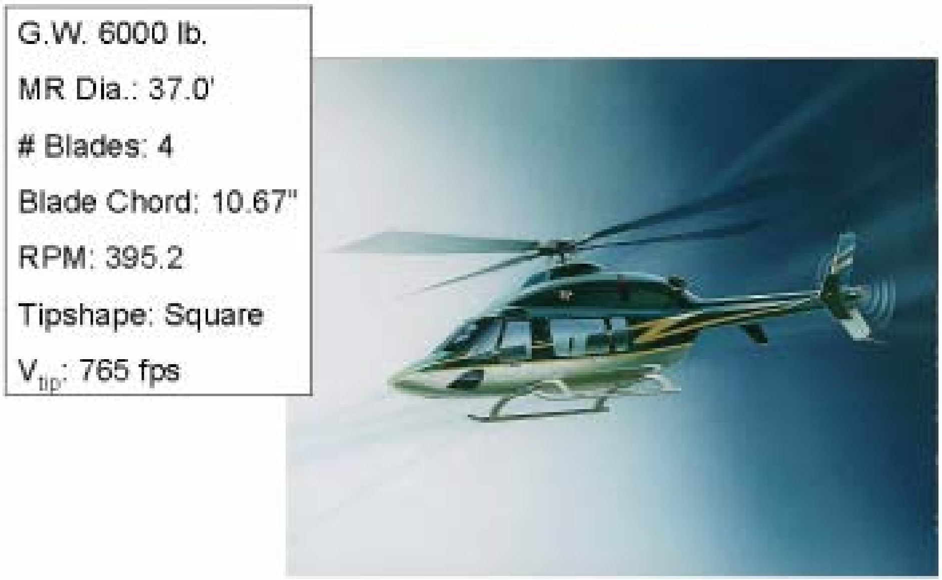


Figure 1-1. Baseline: 427 main rotor

Helicopter main rotors have traditionally been designed with equally spaced blades. In the acoustic spectrum of a main rotor, as many as 20 or 30 harmonics are commonly present, each of which is a multiple of the fundamental blade-passage frequency. In a typical spectral plot, these frequencies appear as pronounced, ordered "peaks" spread regularly across the acoustic spectrum. Since the acoustic frequencies associated with the rotating blades are directly related to the blade spacing, the use of unevenly spaced blades holds the potential for affecting sound levels and perceptibility.

The acoustic effect of uneven or modulated blade spacing is to modify the distribution of energy during each revolution. For the 5-blade even-spaced rotor, the acoustic spectrum is characterized by high-amplitude noise "spikes" at the blade passage frequency and its harmonics. For the unevenly-spaced rotors, the amplitude of these spikes, particularly those in the higher frequency region, is reduced, and rotor rotational frequency (1/rev) and its harmonics dominate. The total acoustic energy is thereby spread more broadly, rather than being concentrated at one blade-passage frequency and a single set of harmonics.

The candidate MBS rotor used in the Phase 1 analysis had five blades, and is sketched in Figure 1-2. This design concept was considered a candidate for substantially reducing perceived noise. Although the acoustical analysis had indicated mixed results in the Phase 1 study, the dynamic analysis did indicate that such a rotor could be designed and flown, although it would likely require some form of active transmission mount to reduce dynamic loads to the fuselage.

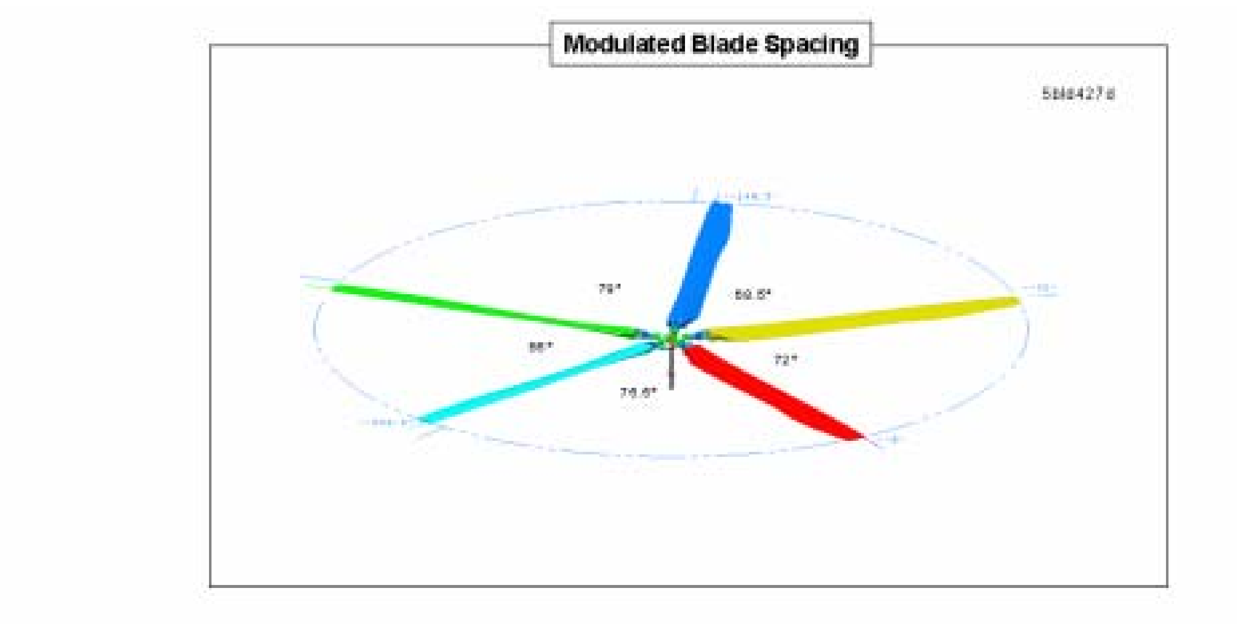


Figure 1-2. Modulated blade spacing

The testing and analysis described in this report is the Phase 2 evaluation, a psychoacoustic test of the modulated blade spacing (MBS) as applied to helicopter main rotors.

1.2 Previous Experience With Modulated Blade Spacing at Bell

The MBS concept was proposed originally because of the success of an earlier research program at Bell having to do with an anti-torque rotor design in which a 5-blade Ducted Tail Rotor (DTR) had been flight tested at Bell, demonstrating a significant reduction in tail rotor noise (References 2 through 4). This concept had previously been used to reduce anti-torque noise in European helicopters (Reference 5). The noise reduction achieved in the DTR was due not only to the duct that surrounded the tail rotor, but to significant design features incorporated in the rotor itself, one of which was modulated blade spacing.

The MBS effect is evident in the measured DTR spectra shown in Figure 1-3. The spectrum of a baseline 5-blade evenly-spaced rotor, was characterized by a series of well-defined noise “spikes” at harmonically related frequencies. Another tail rotor configuration, identical except that the blades were unevenly spaced, was subjectively much more pleasing. Its spectrum showed the acoustic energy to be distributed more uniformly throughout the audible frequency range, with lower amplitude spikes in the range of the human ear’s greatest sensitivity (1,000 to 3,000 Hz). This uneven spacing provided a 5.4 dBA reduction in the model tests, and dramatically changed the sound quality, making the tail rotor sound like a broadband “hum,” rather than a tonal “buzz.”

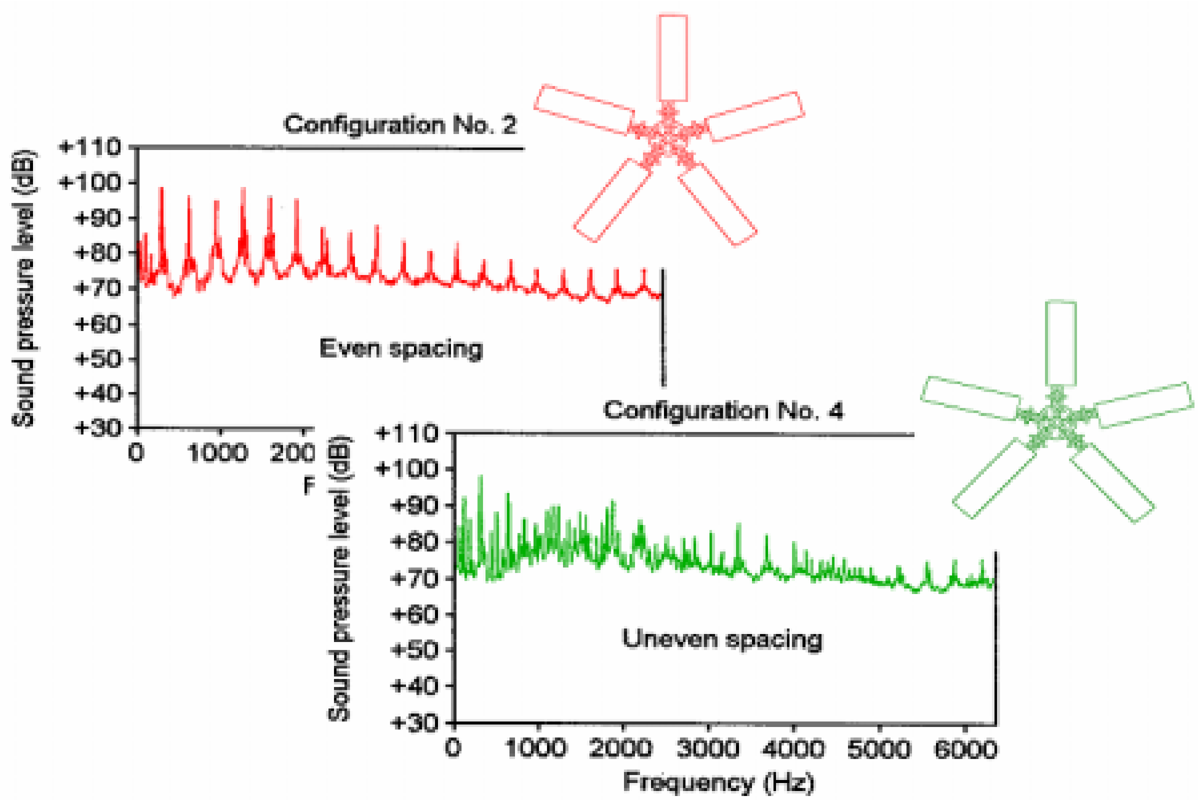


Figure 1-3. The MBS effect in the measured DTR spectra

Because of this positive experience with the MBS concept for tail rotors, the Phase 1 study was undertaken to define its benefits for the lower frequencies characterizing main rotor noise.

1.3 Previous Acoustic Analysis (Phase 1 Study)

The Phase 1 study, completed in March 2001, consisted of analytical noise predictions of the baseline 4-blade 427 rotor, a 5-blade evenly-spaced rotor, and a similar 5-blade MBS rotor. The acoustic signature for each rotor was analytically predicted for the approach, flyover, and takeoff conditions. This study and its results are described briefly below. Details can be found in Reference 1, as mentioned previously.

1.3.1 Analysis of SILENT Rotor

In the Phase 1 analysis of the MBS main rotor, three observer locations and three flight conditions were considered. The three locations were those required for helicopter noise certification. Location 1 was nominally 150 meters on the left (port) side of the aircraft, location 2 was below aircraft centerline and location 3 was nominally 150 meter on the right (starboard) side of the aircraft. At time t equal to zero (start time), the aircraft was specified to be 150 meters above location 2 for both the flyover and takeoff conditions, while for the approach condition the aircraft was only 120 meters above microphone 2 at time equal to zero. Likewise, the flight conditions were the flyover, takeoff, and approach conditions as defined for certification. The three flight conditions evaluated are shown in the Table 1-1 below. For each, the velocity was assumed to be constant throughout the duration of the flight.

Table 1-1. Flight conditions used in noise predictions

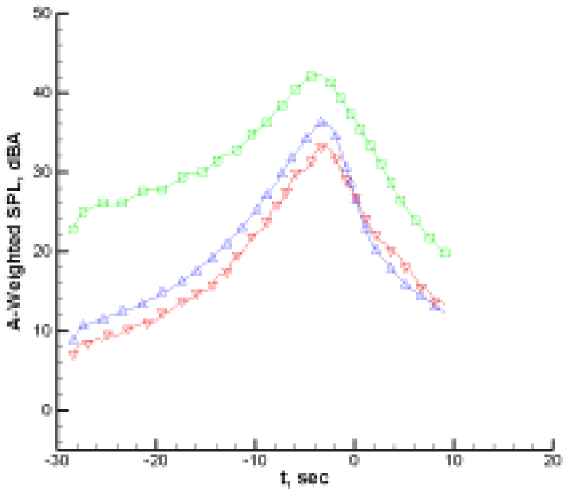
	Airspeed (m/s)	Ascent Angle (deg)	Nominal Height at t=0 (m)
Flyover	58.7 (114 kn)	0.	150
Take Off	32.1 (62 kn)	18.2	150
Approach	30.7 (60 kn)	-6.0	120

1.3.2 Phase 1 Results Leading to Subjective Test

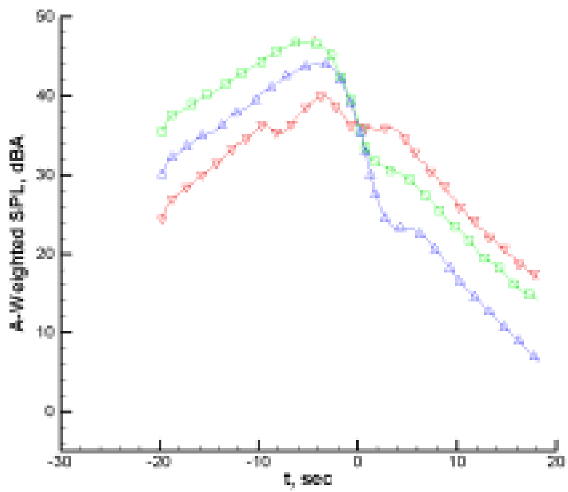
The Phase 1 study indicated promising noise benefits at some flight conditions and observer locations, in terms of the dBA metric. Because of the inherent limitations in this and other metrics, it was felt that additional information was needed before a decision could be made to:

a) develop the MBS design concept further by building and testing a model rotor, or

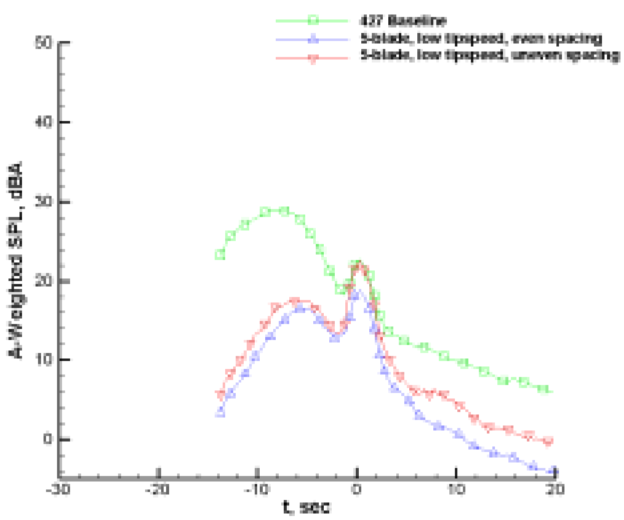
b) eliminate the concept as a potential means of reducing main rotor noise.



(c) Flyover



(b) Approach



(a) takeoff

Figure 1-4. Predicted noise levels from Phase 1 study

To provide this additional information, a subjective test was proposed in which analytically-derived sounds of the MBS rotor would be evaluated by a panel of listeners. Three rotors were to be included in the evaluation—the baseline 4-blade Model 427 rotor, a comparable 5-blade evenly spaced rotor, and a comparable 5-blade MBS rotor. Their subjective ranking would then indicate whether the MBS concept would actually reduce perceived noise of a helicopter main rotor. This subjective testing is the topic of this report, and is described in the following sections.

2. TEST DESCRIPTION

To evaluate the acoustic benefits of the MBS main rotor, a subjective test was conducted in June 2001 at the NASA –Langley Research Center test facility in Hampton, Virginia. Bell Helicopter was responsible for generating the rotor sound simulations, and NASA Langley personnel designed and conducted the subjective test. Since the earlier Phase 1 study laid the analytical groundwork, this test program has been designated as Phase 2.

2.1 Rotor Designs Tested

In addition to the three Phase 1 rotor designs, three more MBS rotor designs were developed and included in the Phase 2 testing, each of which had a different set of angular offsets. These additional configurations were added to provide a broad range of modulation within the subjective study, rather than limiting it to a single MBS configuration. Table 2-1 lists the blade-spacing characteristics of each rotor tested. Included in the table is the shorthand designation used during data analysis and carried throughout this report.

Table 2-1. Main rotor configurations tested, with blade spacings shown for each

Designation	**“M427”**	**“SE”**	**“MO”**	**“C1”**	**“C2”**	**“C3”**
Rotor Description	**4-Bl**	**5-Bl Even Spacing**	**5-Bl “Optimum” Modulated**	**5-Bl Modulated Candidate #1**	**5-Bl Modulated Candidate #2**	**5-Bl Modulated Candidate #3**
Angular blade spacing (degrees)	90 90 90 90	72 72 72 72 72	79 68.5 72 75.5 65	79.3 52.9 95.6 52.9 79.3	86.6 68.2 63.5 89.6 52.1	83 63 75.5 75.5 63
Tipspeed m/sec (ft/sec)	233 (765)	203 (665)	203 (665)	203 (665)	203 (665)	203 (665)

As noted earlier, the 4-blade evenly-spaced rotor was based on the main rotor of the Bell Model 427 helicopter. The 5-blade main rotor with regular spacing was designed to approximate the performance of the 427, but at reduced tip speed. Four modulated rotors – one with “optimum” spacing developed during the earlier Phase 1 testing and three with alternate spacing configurations – were designed to the same performance targets.

2.2 Preparation of Sound Files

2.2.1 Flight Conditions and Observer Locations

Sound simulations were prepared for the flyover, takeoff, and approach conditions described previously in Table 1-1 for the Phase 1 analysis. To keep the number of test stimuli within a manageable number, only the centerline observer position was simulated for the subjective test. For each rotor configuration, then, the goal was to replicate the sound of a 427-size helicopter passing over an observer at an altitude of 150 meters (flyover and takeoff) or 120 meters (approach). The sound was set up to begin as the hypothetical aircraft was approaching the observer position, continue through the overhead position, and end during the downrange portion of the overflight.

2.2.2 Analytical Noise Predictions

As a first step in the noise prediction process, rotor airloads were analytically predicted at the specific flight conditions desired. As in the Phase 1 analysis, these predictions were made by utilizing Bell's airloads program known as COPTER. The airloads were then input into a modified version of the WOPWOP noise prediction program to calculate the acoustic time histories. This was done for each rotor configuration and flight condition used in the subjective testing. A total of 18 such time histories were produced (6 rotor configurations times 3 flight conditions).

The analytically-derived time histories were converted to ".wav" files for playback on an audio system. An empirically-based high frequency component, based on measured M427 data, was added to increase the realism of the test stimuli. The amplitudes of these added high-frequency components were adjusted subjectively so that a realistic sound was achieved while still allowing the main rotor characteristics to be clearly audible to the test subjects.

Overflight time histories of the final test stimuli are presented in Figure 2-1 for the flyover, approach, and takeoff conditions. To illustrate the waveform differences characterizing each of the rotor configurations, an example of their pressure time histories is shown in Figure 2-2. These examples were taken from the initial (uprange) portion of the flyover simulations.

Additional information as to the analytical production of the sound stimuli is given in Reference 1 and in Appendix A of this report.

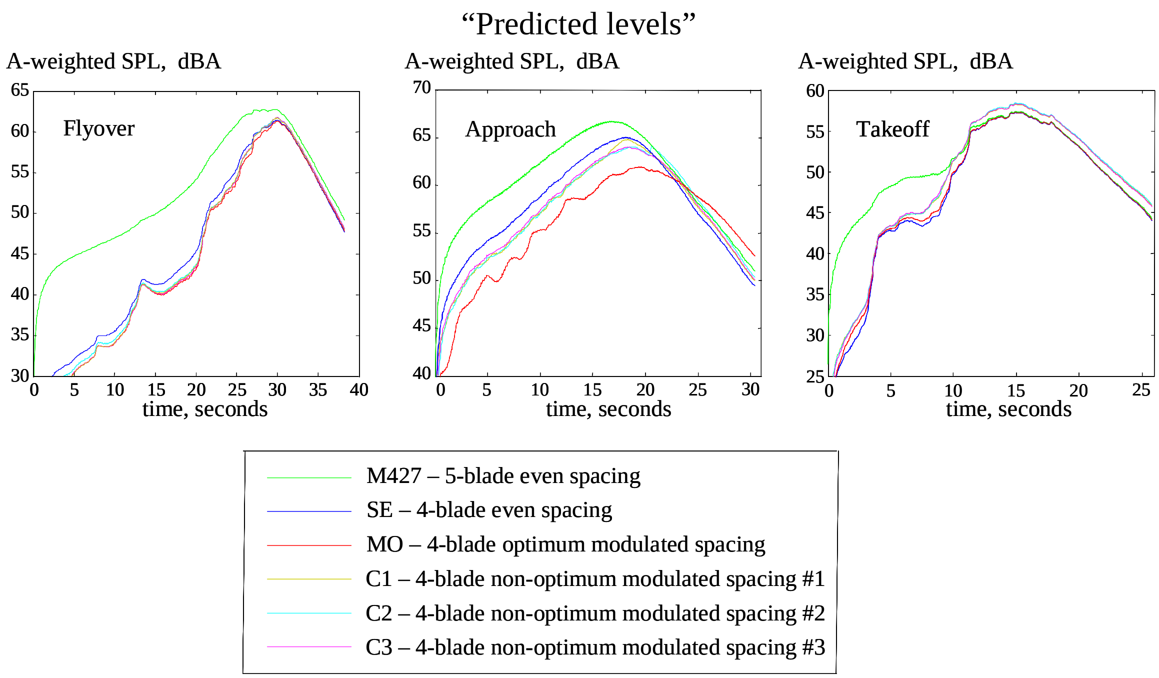


Figure 2-1. Predicted time histories of test stimuli

2.3 Test Procedures

The eighteen test stimuli, corresponding to the six rotor configuration and three flight conditions, are identified using their shorthand notation in Table 2-2. Each sound was played to forty test subjects for evaluation.

Table 2-2. Shorthand notation for the stimuli used in subjective tests

	Flyover	Takeoff	Approach
Model 427 Baseline	M427fo	M427to	M427ap
5-blade Even Spacing	SEfo	SEto	SEap
5-blade MBS	MOfo	MOto	MOap
5-blade MBS Candidate #1	C1fo	C1to	C1ap
5-blade MBS Candidate #2	C2fo	C2to	C2ap
5-blade MBS Candidate #3	C3to	C3fo	C3ap

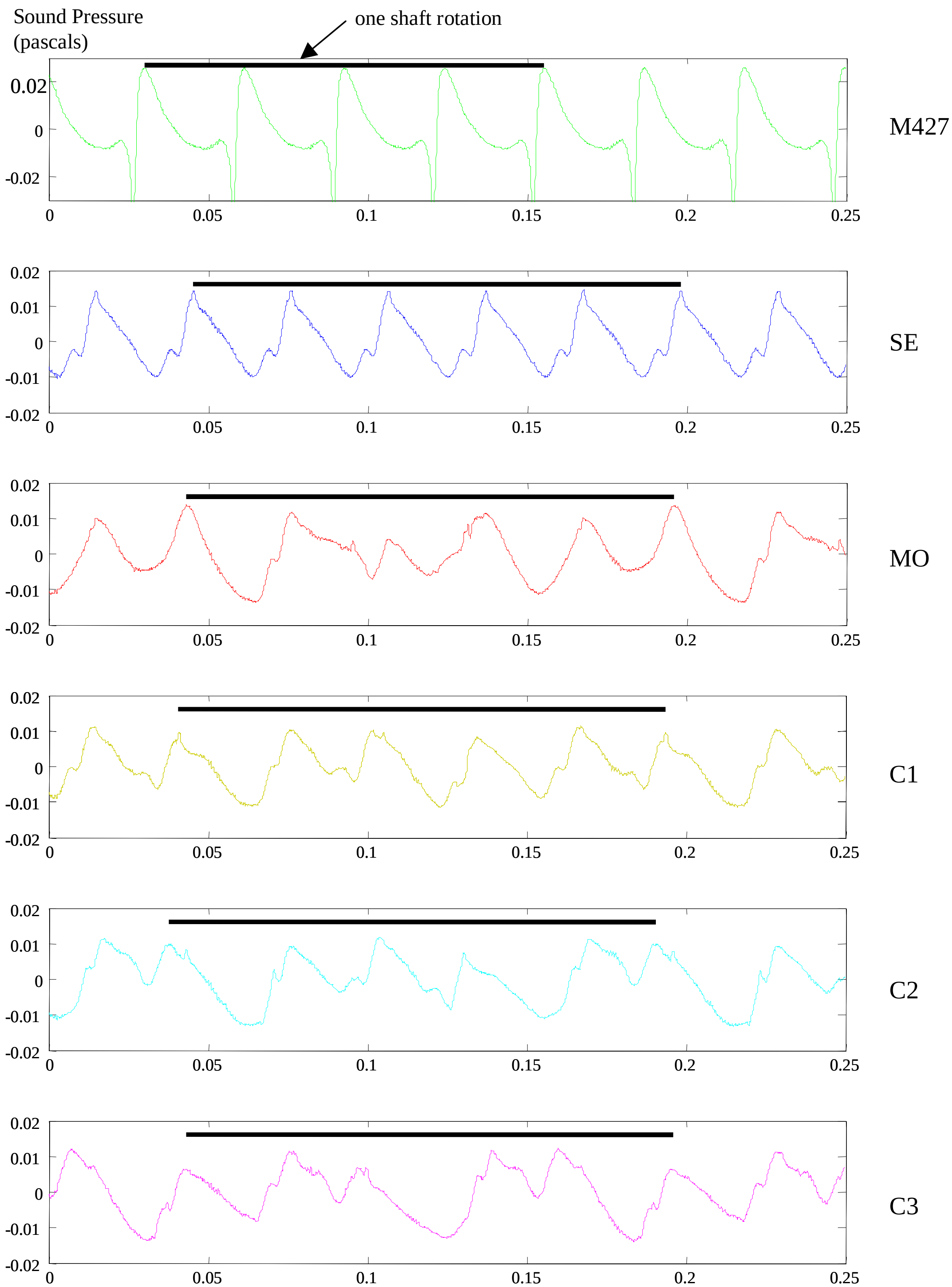


Figure 2-2. Time histories of sounds from main rotors with even and modulated blade spacings

2.3.1 Test Setup

Two psychoacoustical test designs were used:

- The numerical category scaling (NCS) method, in which the subject was asked to rate the noisiness of each overflight sound on a scale of 0 to 10, and

- The "paired comparison," or constant stimulus differences (CSD) method, in which short portions of each overflight sounds were played in pairs, and the subject was asked to identify which of the two he or she preferred.

A discussion of the metrics used in evaluating and setting up the sound stimuli is given in Appendix B.

2.3.1.1 Test Facilities

The test was conducted in an anechoic room at NASA Langley Research Center, building 1208. Three loudspeakers were used: (1) a Velodyne FSR-18 subwoofer system, used to present the components of the test signals below 80 Hz, (2) a Mackie HR824 studio monitor, used to present the components of the test signals between 37 Hz and 650 Hz, and (3) a Mackie HR824 studio monitor, used to present all the components of the test signals above 37 Hz (see Figure 2-1). An Ashly XR2001 electronic crossover was used to filter the low frequency portions of the signal. Subjects were seated in two chairs in the room for the test sessions (see Figure 2-2). The signals received by microphones placed at the equivalent subject head positions, in the absence of subjects and chairs, were measured, and a digital filter was designed to equalize the loudspeaker responses at those positions. The actual sound levels at the subjects' head positions are discussed in Appendix A.

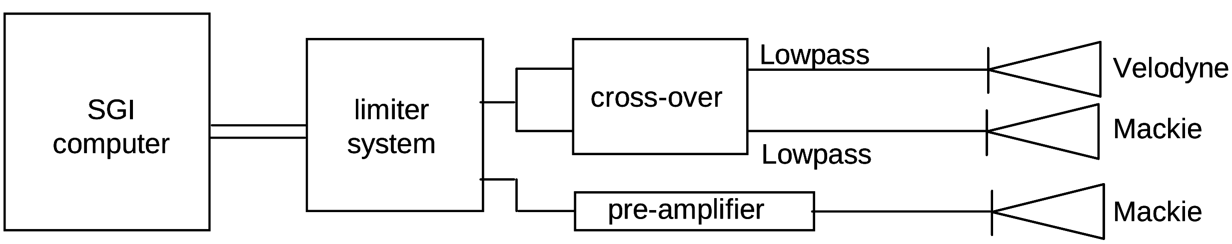


Figure 2-3. Playback system used in presenting the test sound stimuli

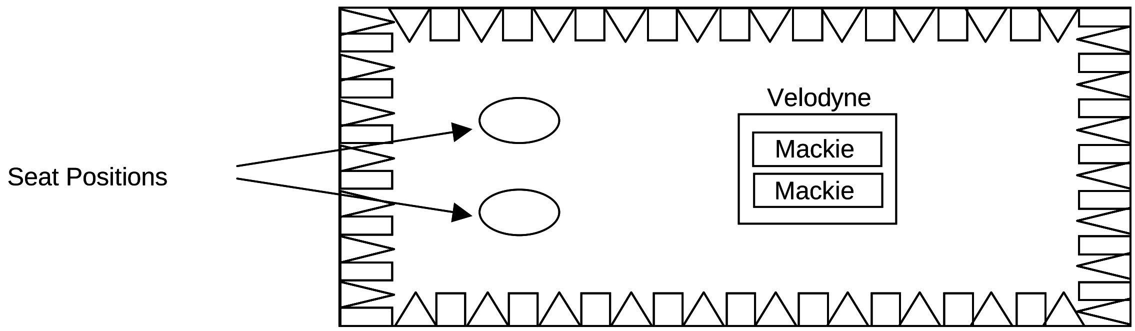


Figure 2-4. Relative positions of test subjects and speakers in anechoic room

Instructions being given prior to test — Testing underway

Figure 2-5. Photograph of two test subjects

2.3.1.2 Selection and Screening of Subjects

Forty subjects were used in each test design. The subjects were chosen from volunteers in the community, and were paid for their participation. Instructions to the recruiter were to identify and screen 40 subjects over 18 years old with at least 1/3 of them male and 1/3 to be female. The population of test subjects was distributed as in Table 2-3 below. These subjects were chosen from the general population, and were each given audiograms prior to testing. They were required to have hearing acuity within 40 dB of the ISO threshold.

Table 2-3. Test subjects' gender and age distribution

	Age Range	Average Age	Median Age
Females	23-68	41.8	41.0
Males	19-65	38.1	35.0
Total Population	19 - 68	40.3	38.0

2.3.1.3 Instructions to Subjects

Prior to testing, each subject was given information as to the purpose of the test and a broad description of the sounds they would hear. These general instructions and the voluntary consent form that all subjects were required to complete are presented in Appendix C. Each subject first completed the NCS test, then was allowed a rest break, and finally completed the CSD test. Specific test instructions were developed for the NCS test and the CSD test, and were given to the subjects just prior to the start of each. A short practice session prior to actual testing provided each subject a chance to hear some sample sounds and become familiar with the test procedure.

2.3.2 Numerical Category Scaling Tests

In the first of the tests, numerical category scaling, subjects were asked to rate the noisiness of each sound they heard. The rating was to be identified on a continuous line, numbered from 0 to 10. The instructions given to each subject and an example response sheet are shown in Appendix D. The descriptor "noisy" was rather than "annoying" as annoyance may be difficult to judge in a test situation when the only occurrence in the subject's environment is the playing of the test signals.

In the NCS test, all 18 test stimuli were used. They were presented to the subjects at levels corresponding to those predicted to occur in reality. In addition, the SEfo (5-blade, even spacing) stimulus was presented at three other levels (-5dB, +5 dB, and +10 dB). These added stimuli were intended to relate the subjective scale results to intensity. The resulting 21 stimuli were each repeated for a total of 42 test sounds. These sounds were presented to the subjects in a randomized order in two sessions of 21 sounds each. A total of 20 different presentation orders were used for the 40 subjects.

2.3.3 Paired Comparison, or Constant Stimulus Differences, Testing

In the second test design, constant stimulus differences, subjects were asked to listen to two signals and to "indicate which member of the pair you preferred" by circling A or B on a response score sheet. No further instructions as to the criteria to be used for the basis of the preference were made to give the subjects the greatest possible freedom to decide on their preference. The test instructions presented to each subject and an example response sheet are given in Appendix E.

In the CSD test, only a brief portion of the entire flyover was used. It would have been difficult for a subject to compare the entirety of a 30 second-long stimulus with another, since there can be a tendency to compare the end of the first stimulus with the start of the second. Instead, a 3.6 second segment was taken from each of the approach and flyover stimuli. For the approach stimuli, the segment was taken from 9.6 to 6.0 seconds before the position of overhead; for the flyover stimuli, the segment was taken from 8.2 to 4.6 seconds before the position of overhead. These specific segments gave a reasonable main rotor noise amplitude while avoiding excessive variations due to Doppler shift. The lower priority takeoff condition was eliminated from this portion of the testing to reduce testing time. During the selected segment, it was considered that the sound remained fairly steady from the start to the end, and might be considered "steady-state." Especially important was that the added high frequency components from the recorded 427 helicopter were nearly constant during each of the short segments. Twelve segments were thus created, each of which was ramped at start and end over a 0.3 second period.

The M427, MO, C1, C2 and C3 segments were designated "target" stimuli and were each played at the same level as they occurred in the time history. Each of the approach ("ap") segments was paired with the SEap segment. Each of the flyover ("fo") segments was paired with the SEfo segment. The SEap and SEfo segments were designated the "variable" stimuli. A pilot study was conducted to find the approximate level for the variable at which it was considered equally preferable to the target stimulus. Each pairing of target and variable stimuli was presented five times with the variable stimulus varying in steps of 3 dB, so that the total range of the variable was ±6 dB about the approximate level of equal preference. Each pairing/variable-level combination was presented twice, once with the target following the variable, and once with the variable following the target. Results from the two presentations were combined to minimize within-pair order effects.

The resulting 100 pairs (5 target sounds, 2 flight conditions, 5 variable levels 2 within-pair orders) were randomly ordered five times. The random orders were modified to remove any close recurrences of the same target stimulus, and split into two sessions of 50 pairs each. A total of 20 different presentation orders were used for the 40 subjects.

3. TEST RESULTS

Scores were entered into Microsoft® Excel 2000 spreadsheets, reordered and read into SPSS® for Windows version 10.1, which was used for all statistical calculations. Some mathematical calculations were performed using MATLAB® version 6.0.

3.1 Numerical Category Scaling Test Results

In the numerical category scaling test, the positions of the subjects' marks along the 1 to 10 scaling line were measured to quantify the subjective score. Values for the scores for each sound were averaged across all presentations and all subjects. The surrounding 95% confidence interval (C.I.) was also calculated (that is, the range with a statistically 95% confidence of containing the true value of the mean). Some subjects scored consistently low, some scored consistently high but taken as a group, the scores were normally distributed (as indicated by the statistical calculations of skewness). Student's t-tests were applied to the mean values to determine which sounds could be considered statistically different in their subjective rating at the 95% level.

The SEfo stimulus was presented to the subjects at a total of four levels, the level equivalent to that predicted for the flyover case, and that level –5dB, +5dB and +10dB. The average scores for these four events were used to calibrate the subjective scale in terms of equivalent SEfo stimuli. A polynomial fit of the levels of the four presentations of SEfo on the scores was derived in MATLAB®, and equivalent levels were calculated from the scores for the other events (see Figure 3-1). The levels of the SEfo presentations were expressed in dB so the resulting equivalent levels are in dB. Thus, for example, a stimulus that received the same scale value as SEfo at the –5 dB SEfo event was given a value of –5 dB relative to the SEfo at its predicted level. In this way, all events could be converted to Equivalent Subjective Levels (ESL) relative to SEfo at its predicted level. These relative levels are effectively the change in level of SEfo from its predicted level that is required to make it subjectively equivalent to the test stimulus, and are designated DESL. The bounds of the 95% C.I. were also converted to DESL in the same way. In dB, the 95% C.I. for the 18 test stimuli ranged from 2.2 to 4.1, with a mean of 3.0. These relative levels are in dB because the original polynomial fit was calculated using levels of SEfo expressed in dB. If phons or other loudness units had been used, then the DESLs would be expressed in those units. The DESL increases as the scale rating increases (that is, the sound is rated more noisy).

For compatibility with the results from the CSD tests, the DESL values were normalized on the SE events for each flight condition. Thus DESL is zero for each SE event.

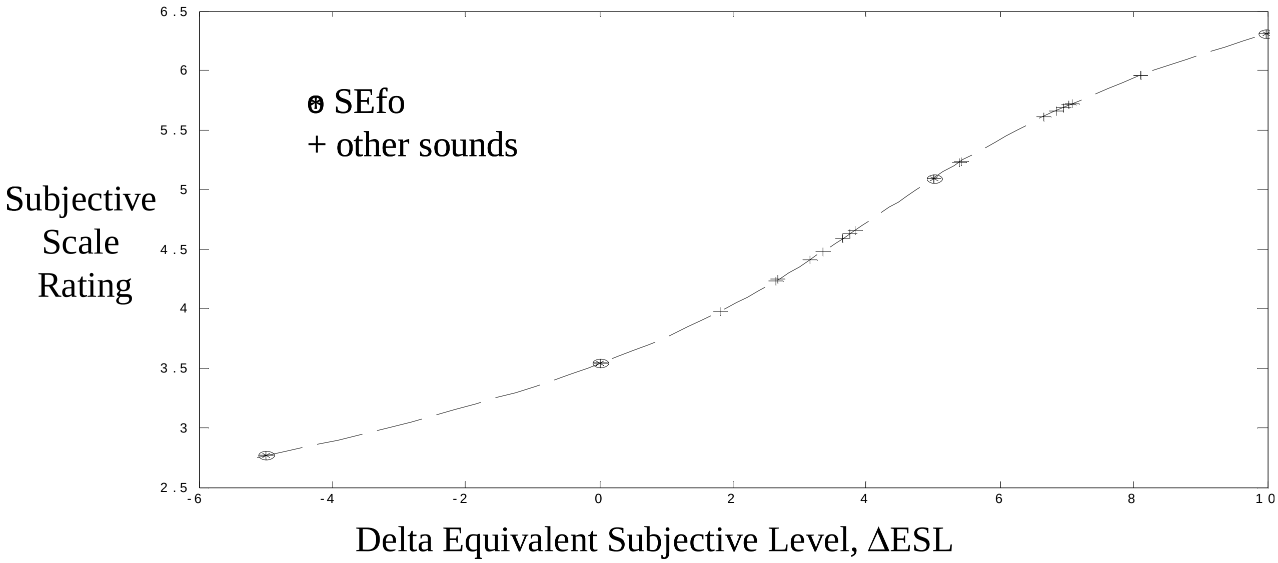
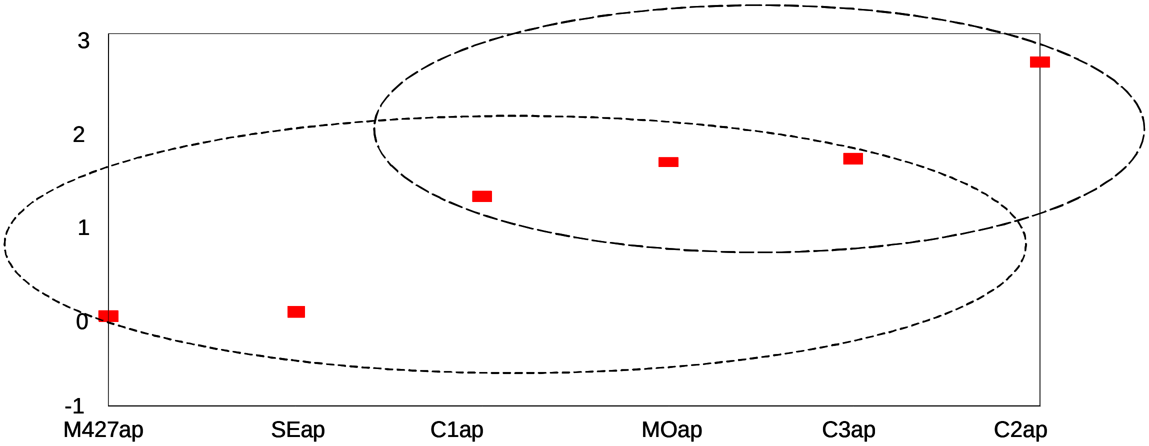


Figure 3-1. Polynomial fit through the subjective scores for the SEfo stimulus

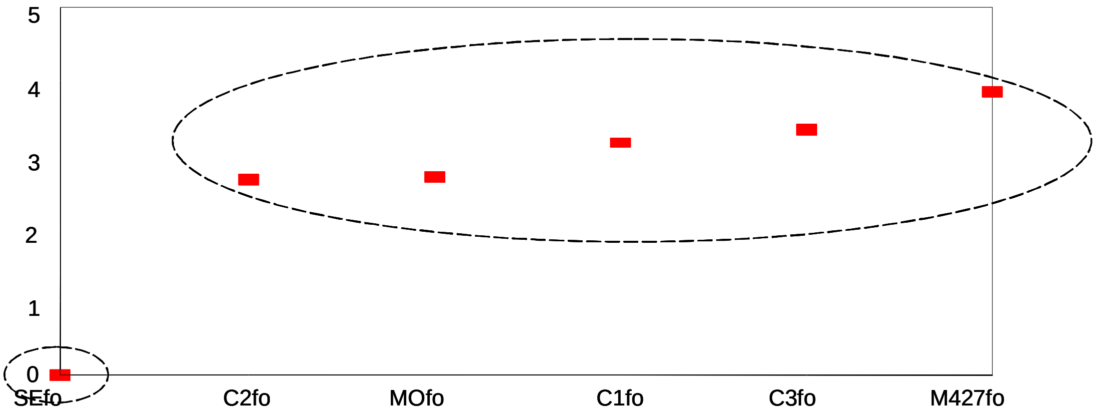
Figure 3-2 shows the scores converted to DESL for the three flight conditions, approach, flyover and takeoff. The groupings indicate those sounds that could not be shown to be subjectively different at the 95% probability level. Thus for the approach flight condition, two overlapping groups of sounds were formed, one containing all the sounds except for the C2 case, and another containing all the sounds except SE and M427. Thus C2 was found subjectively noisier than the rest, and SE and M427 were found less noisy. For the flyover condition, the evenly spaced 5-bade configuration (SE) was shown to be subjectively different from the other configurations (in this case, less noisy). For the takeoff condition, SE was found less unpleasant than MO and M427, which in turn were less noisy than the C1, C2 and C3 configurations.

3.2 Paired Comparison Results

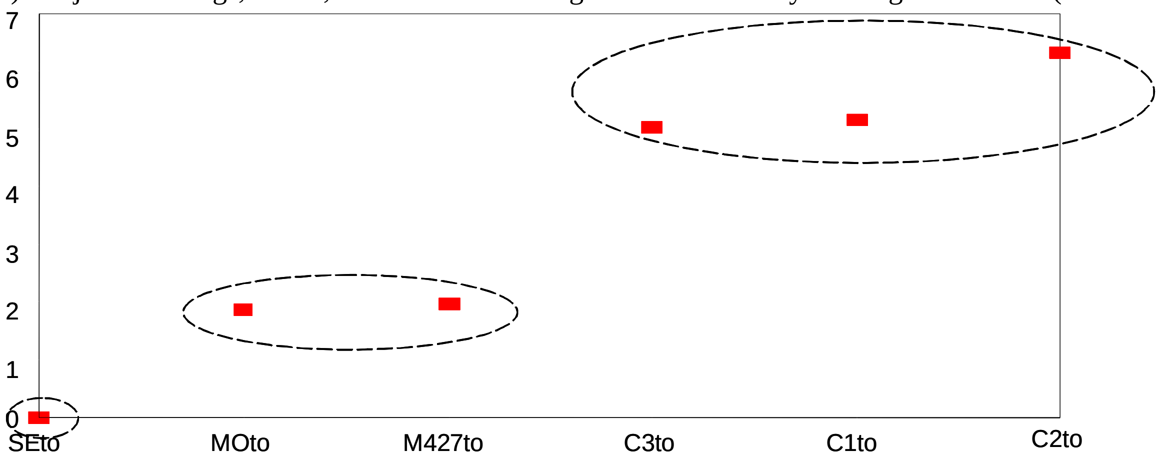
For the Paired Comparison test, the subjects' choices of which sound they preferred in each pair of presentations were combined to give the total number of times the target sound was selected over the variable sound. As expected, the variable was selected less often as its level was increased. A probit analysis of the combined scores for the different levels in dB of the variable was performed as described in Reference 6. From this, the point of subjective equality (at which there is an equal chance that the target or the variable would be selected) was estimated. At the point of subjective equality the variable is judged subjectively equal to the target. Thus the level of the variable is the Equivalent Subjective Level (ESL) of the target. The 95% Confidence Interval about this point was calculated. These values were all in dB, as dBs were used to define the levels of the variable.



(a) Subjective ratings, ΔESL, for the 6 rotor configurations for the approach flight condition (NCS test)



(b) Subjective ratings, ΔESL, for the 6 rotor configurations for the flyover flight condition (NCS test)

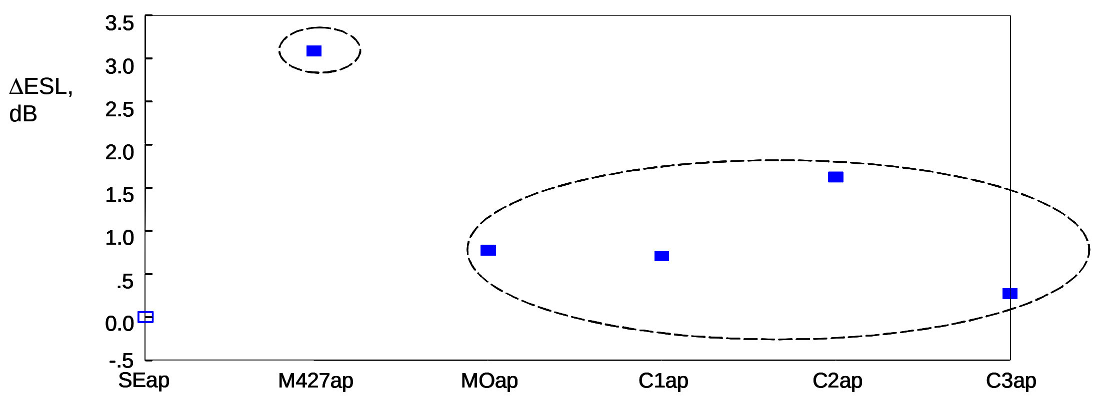


(c) Subjective ratings, ΔESL, for the 6 rotor configurations for the takeoff flight condition (NCS test)

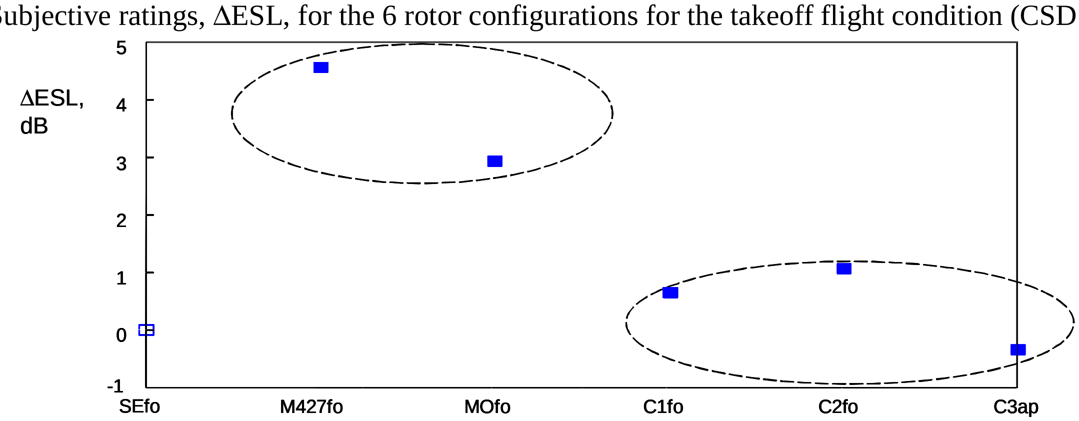
Figure 3-2. Subjective ratings, ΔESL, for the 6 rotor configurations

Using the Relative Median Potency (RMP) method (as described in Reference 6 and implemented in SPSS®), the significance of the differences in the ESLs for the different sounds was estimated. As in the NCS test, ΔESL values were calculated by subtracting the level of the variable at its predicted level. Subjects judged which sound they preferred, so the target sound is judged more preferable as the ΔESL decreases. As the variable used was different for each flight condition, these ΔESL values were defined in terms of the SEap sound for the approach stimuli and the SEfo sound for the flyover stimuli. No comparison could be made between approach and flyover conditions. (In the NCS test, all rating scale values were initially converted to SEfo levels. For flight conditions other than the flyovers, the SEfo values were normalized to SEap and SEto for the approach and takeoff conditions respectively in order to compute ESL and DESL.) As the variable sound was the SE event, by definition ΔESL would be zero.

Figure 3-3 shows the ΔESL values in dB for the approach and flyover conditions. The groupings are based on the RMP results and show sounds that could not be shown to be subjectively different at the 95% probability level. Thus for the approach flight condition, all other (5-bladed, low tip speed) configurations were preferred to the 4-bladed M427 baseline configuration. For the flyover condition, C1, C2 and C3 were preferred to M427 and MO. Simulated ΔESL for the SE segments are indicated by hollow symbols. No RMP results were available for the SE cases, but from the plots, it would seem probable that SEap would fall in with MOap, C1ap, C2ap and C3ap, and SEfo would fall in with C1fo, C2fo and C3fo.



(a) Subjective ratings, ΔESL, for the 6 rotor configurations for the takeoff flight condition (CSD test)



(b) Subjective ratings, ΔESL, for the 5 rotor configurations for the takeoff flight condition (CSD test)

Figure 3-3. Subjective ratings, ΔESL, for the 6 rotor configurations

3.3 Combined Results

Table 3-1 shows ΔESL values in dB, with 95% confidence interval limits and widths, for both tests and the 18 test stimuli. It was expected that the width of the Confidence Interval would be smaller for the CSD test because it is easier to select one of two sounds than to rate a sound on a scale; on average, the Confidence Interval is 2.02 dB for CSD and 2.99 dB for NCS.

The sounds were more clearly separated into statistically different groups in the CSD test than in the NCS test for the approach flight condition; otherwise, groupings were well defined in both tests. However the groupings differed greatly between the two tests. The CSD test was based on 3.6-second segments of the sounds, whereas the NCS test was based on the entire 30-sec event. For example, when A-weighted time histories of the approach events are plotted, it is evident that M427 has a higher level than the other events before overhead. As the segment used in the CSD test was taken at around 7 seconds before overhead, it would be reasonable to suppose it might be rated noisier and thus less preferable relative to the other segments than the entire event was relative to the other entire events.

The NCS results indicate that the SE configuration (even spacing) is generally judged to be better than any of the modulated spacings; within the modulated spacings, MO is perhaps better than C1, C2 and C3 but not strongly so. C2 is generally least preferred of the modulated spacings. The CSD test results would lead to different conclusions, but these are affected by the fact that the segments used could be considered unrepresentative of the complete time history.

Table 3-1. Numerical category scaling and constant stimulus difference test results

Flight condition	Rotor	Numerical category scaling test			
		Δ ESL	95% C. I.		Width of C.I.
Approach	SE	.00	-1.13	1.37	2.50
Approach	M427	-.04	-1.26	1.45	2.71
Approach	MO	1.62	.09	3.70	3.61
Approach	C1	1.24	-.14	3.06	3.20
Approach	C2	2.69	1.05	5.17	4.12
Approach	C3	1.66	.10	3.79	3.69
Flyover	SE	.00	-2.28	1.69	3.98
Flyover	M427	3.84	2.58	5.05	2.47
Flyover	MO	2.68	1.36	3.77	2.40
Flyover	C1	3.16	1.90	4.25	2.35
Flyover	C2	2.64	1.12	3.87	2.75
Flyover	C3	3.34	2.07	4.47	2.40
Takeoff	SE	.00	-1.72	1.32	3.04
Takeoff	M427	1.96	.83	3.02	2.19
Takeoff	MO	1.85	.72	2.90	2.17
Takeoff	C1	5.14	3.71	7.05	3.34
Takeoff	C2	6.31	4.61	8.60	3.99
Takeoff	C3	5.03	3.78	6.63	2.86
Level check	SEfo1	-5.00	-8.48	-2.29	6.18
Level check	SEfo2	.00	-2.28	1.69	3.98
Level check	SEfo3	5.00	3.87	6.31	2.44
Level check	SEfo4	10.00	7.80	12.99	5.19

Table 3-1. Numerical category scaling and constant stimulus difference test results (continued)

Flight condition	Rotor	Constant stimulus difference test			
		Δ ESL	95% C. I.		Width of C.I.
Approach	SE	.00			
Approach	M427	3.08	2.10	4.11	2.01
Approach	MO	.77	-.17	1.71	1.88
Approach	C1	.70	-.20	1.62	1.82
Approach	C2	1.62	.67	2.58	1.91
Approach	C3	.27	-.57	1.14	1.70
Flyover	SE	.00			
Flyover	M427	4.55	3.31	5.89	2.58
Flyover	MO	2.92	1.80	4.11	2.31
Flyover	C1	.62	-.36	1.68	2.03
Flyover	C2	1.07	.01	2.16	2.14
Flyover	C3	-.36	-1.31	.63	1.94

4. CONCLUSIONS AND RECOMMENDATIONS

No strong subjective differences among the predicted helicopter test sounds were found in either test performed in this study. These subjective differences were expected to be more dramatic, since the Phase 1 analytical results had indicated relatively large noise level differences of 4 to 8 dBA_{max} among the sounds. Taken together, these results suggest that, for these sounds, the simple dBA_{max} metric is not strongly indicative of subjective response.

Considering all flight conditions, the subjective results indicate there is a tendency for the evenly-spaced 5-blade configuration to be preferred, especially for the NCS test which used long time samples (30 seconds or so in duration). Little difference among the four modulated blade-spacing configurations was shown. The accuracy of the subjective tests was found to be 2-3 dB, and a change of 3 dB produces only a small change in subjective response.

4.1 Recommendations for Perceived Noise Reduction

The subjective test results indicate that main rotors with modulated blade spacing do not offer significant improvements in perceived noise as had been originally hoped. Based on these results, no hardware testing (wind tunnel or full-scale flight testing) of this main rotor design concept (as a means of reducing perceived noise of helicopters) is recommended.

Although the MBS concept has been successfully applied to a helicopter tail rotor, its application to main rotors showed no benefits, probably because of the much lower blade passage frequencies common in main rotors. The author's subjective observations support this assumption, and a general rule of thumb may be that MBS improves rotor noise if the blade passage frequency is sufficiently high so that individual blade pulses are not distinguishable. Below that frequency, the staccato sound of the individual pulses becomes objectionable, overriding the "blending" effect which benefited Bell's ducted tail rotor.

4.2 Recommendations for Acoustic Detection Investigation

One alternate application for the MBS main rotor may be in reducing a helicopter's acoustic detection range. The acoustic signature of this unusual rotor concept tends to change with viewing angle more than a standard evenly-spaced main rotor. Also, the blade passage frequencies are broadly distributed, as opposed to the single blade passage frequency of the main rotor with evenly-spaced blades. Each of these characteristics could potentially make the MBS rotor more difficult to detect, either aurally or electronically. It should be noted that the present test was not designed to investigate any such effects on acoustic detection, so no such conclusions can be drawn from these test results.

To investigate the potential for the MBS rotor to reduce acoustic detection range, an analysis may be possible using the sound files that have already been generated. Alternatively, additional files can be generated fairly efficiently, using the same methodology and techniques employed in the subjective test. In any case, groundwork has been laid which would possibly allow for assessing the acoustic detection without going to the complexity of an extensive flight test.

4.3 Possible Applications for UAV Main Rotors

Another alternative application for the MBS main rotor is in small rotorcraft such as many Unmanned Airborne Vehicles (UAV's). One example of such a rotorcraft is Bell's "Eagle Eye" tiltrotor UAV design, shown in Figure 4-1. The blade passage frequency of the Eagle Eye's rotor is 75 Hertz, which is similar in frequency to that of many helicopter tail rotors. For example, the Model 427 helicopter has a main rotor blade passage frequency of 26 Hertz and a tail rotor blade passage frequency of 79 Hertz. Because the blade passage frequencies of these small UAV main rotors is so much higher than that of the larger piloted vehicles, the sound should be similar to that of a tail rotor. For this reason, the MBS rotor concept as applied to a UAV (tiltrotor, helicopter, or any small rotor configuration) could provide acoustic benefits similar to that experienced in Bell's Ducted Tail Rotor program discussed earlier in this report.

At this point, UAV's are used in military, rather than in commercial applications. As these relatively new machines become more common, perceived noise and detection range may become more important. The use of the MBS rotor concept has the potential to reduce perceived noise as well as acoustic detection range for these vehicles. Again, it should be noted that these are general comments, not supported by specific results generated in the present test.

Figure 4-1. UAV photos

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APPENDIX A

SOUND FILE PREPARATION AND DEMONSTRATION

The sound simulations used in the subjective test were based on analytical noise predictions, with an added high-frequency component based on measured M427 data. Rotor geometric parameters for all rotor configurations were modeled analytically for inclusion in the noise prediction program known as WOPWOP (Reference 7). For each blade, the radial properties (chord, thickness, twist) were curve fit and included in the FUNE2 subroutine of WOPWOP. The chordwise thickness and camber distribution was also determined from the discrete airfoil section data and modeled analytically for each airfoil section along the radius of the blade in subroutine FUNE2Q. Thus WOPWOP utilized a mathematical description of the blade for all the noise computations. All measurements for WOPWOP were converted to metric units. To ensure that the blade coordinates were input properly, a modification to WOPWOP was made which output the surface grid used by WOPWOP in the numerical integration. The blade geometry was verified visually to correspond to the geometrical information of each blade.

Blade flapping, collective, and cyclic pitch were included in the WOPWOP noise predictions. Only the constant and first harmonics of these motions were included. No lead-lag motion was modeled for these predictions. The forward shaft tilt of the rotor was input into WOPWOP to account for the orientation of the rotor in each of the cases. Although WOPWOP is unable to accommodate lateral mast tilt, the 427 rotor system’s net lateral (left) mast tilt of 0.94 degrees was included by adjusting the positions of the microphone locations on the ground.

The section lift and drag from COPTER calculations was provided in the form of a Microsoft Excel spreadsheet. The spreadsheet was modified slightly so that it could be read by WOPWOP at the beginning of each case. In WOPWOP, the forces were converted to metric units and the time derivatives of section forces were computed using the standard 2nd order central finite difference approximation. Both section forces and the time-derivatives of section forces were interpolated first in the radial direction and later in the chordwise direction in the process of the noise prediction in WOPWOP. Linear interpolation was used in each interpolation of the data (i.e., radial, chordwise, and azimuthal). The section force data was given with an azimuthal resolution of one degree. The data was assumed to be periodic for the acoustic predictions – therefore only one rotor revolution was needed. Linear interpolation was also used for the azimuthal interpolation needed to provide blade loads at the retarded time of the center of each surface element in the numerical integration.

The section forces were assumed to act at the quarter chord of each radial station along the blade. A compact chordwise model for the loading (Reference 8) was utilized for this work. In this model, the compact chordwise loading is simulated in WOPWOP with a triangular loading distribution in the chordwise direction, extending from 5 percent before to 5 percent after the quarter chord location. The peak amplitude of the loading is chosen such that the integral of the triangular loading gives the correct section lift and drag when integrated. Although section drag is often neglected in computations of this type, both lift and drag forces were used in all of the present WOPWOP noise predictions.

Two types of modifications to WOPWOP were required. The first modification required was to enable long observer time runs (typically 10 –30 seconds of observer time). The standard version of WOPWOP only allows up to 1024 points in the acoustic-pressure time history. While this is appropriate for cases that include up to a few rotor revolutions, it was not sufficient for the predictions of an entire overflight required for this task. The needed modifications were relatively minor – they consisted mainly of increasing array sizes and modifying the algorithm for updating the observer time and position. For a 30 second segment of observer time, as many as 135,000 points were computed in the acoustic pressure time history (nominally 128 points per blade passage period).

The second modification to WOPWOP – enabling modulated rotor blade spacing – was more extensive. WOPWOP was modified to allow user input of the angles between the blades. In the standard version of WOPWOP the angle between the blades is assumed to be constant. In the modified version of WOPWOP, the angles are input by the user instead. Another aspect of modulated blade spacing is that the loading on each of the blades may be different from the others at a give azimuth angle. Therefore, WOPWOP was also modified so that the each blade would utilize a unique loading dataset. To implement this feature, the code added a global variable to keep track of which blade was currently generating the noise. Then the input subroutine FUNPSI was enhanced to use the correct loading from the current blade. The blade flapping and pitch angles, which are functions of azimuth, were assumed to be the same functions of azimuth for all the blades. The updated version of WOPWOP was tested thoroughly to ensure that results for a rotor with equal blade spacing were identical to the standard version of WOPWOP.

For the relatively long runs (30 seconds) specified in this analysis, it is impractical to use the acoustic pressure time history to directly characterize the noise or make comparisons between the noise of different rotors. Hence, the WOPWOP acoustic pressure time histories were post processed. The post-processing consisted of applying a Hanning window to each one-half second interval of the discrete acoustic pressure time history. A Fourier transform was then performed on each half second interval and the Overall Sound Pressure level (OASPL) and the A-Weighted Sound Pressure Level (SPLA) were computed for the interval. A “slow-time weighting” of the form

$$L_{slow}\left(k\right) = 10\ln\left[0.13\times10^{0.1\mathrm{L}(\mathrm{k}\text{-}3)} + 0.21\times10^{0.1L(k-2)} + 0.27\times10^{0.1L(k-1)} + 0.39\times10^{0.1L(k)}\right]$$

effectively takes the SPL levels at four different times and smoothes the time history of SPL. This is approximately equivalent to what is done during certification flight testing. In that case, however, each third-octave band is “slow-time weighted” rather that the integrated SPL metric (OASPL or SPLA). The “slow-time weighted” SPL value is plotted versus the time corresponding to interval k, which is the center of the last of the four half-second intervals.

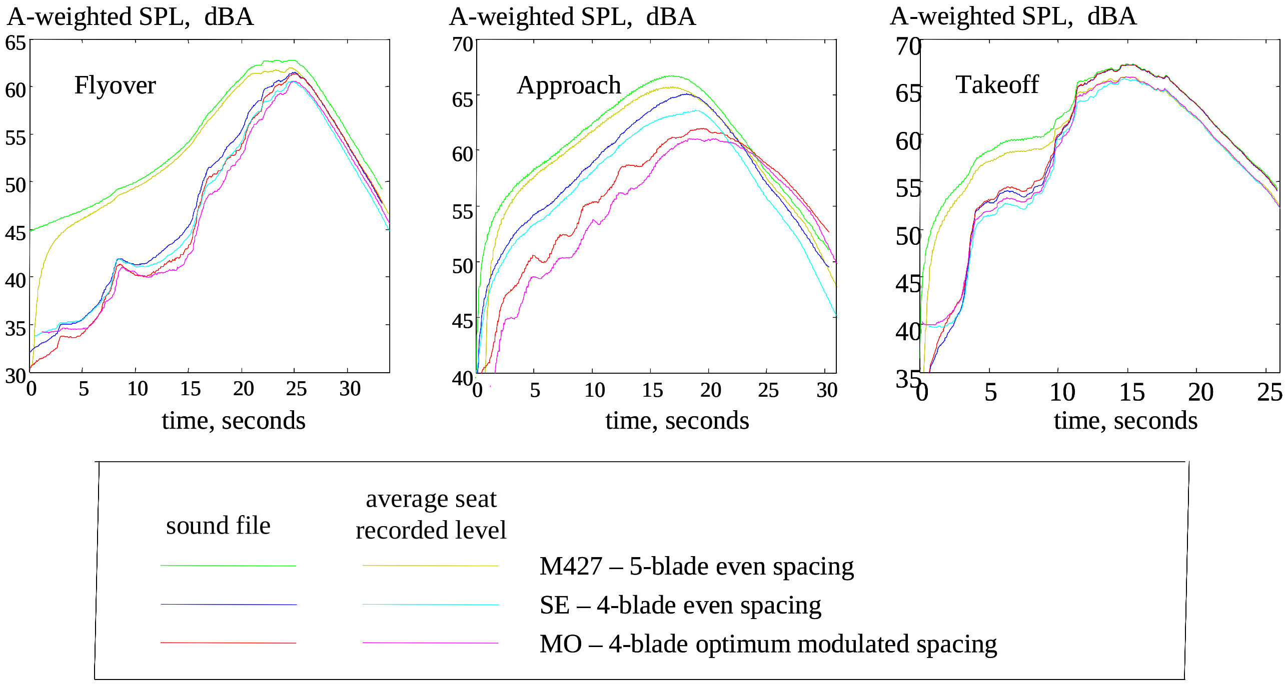
Sound Simulations

For each test condition, a time history was predicted for the main rotor sound, lasting about 30 seconds. To increase the realism of the sounds, recordings from an actual Model 427 time history were high-pass filtered at 820 Hertz and mixed with the predicted low frequency main rotor noise that had been low-pass filtered at 800 Hertz. The mixed sound files became the 18 test stimuli. Energy below 17 Hz was removed from the sounds using a digital filter, as this part of the spectra was not reproduced by the playback system. Each signal was ramped in and out over a period of .6 seconds to prevent any startle effects from abrupt sound events. The approach stimuli were each of 28.8 seconds duration, the flyover stimuli were each 33.4 seconds, and the takeoff stimuli were each 25.8 seconds long.

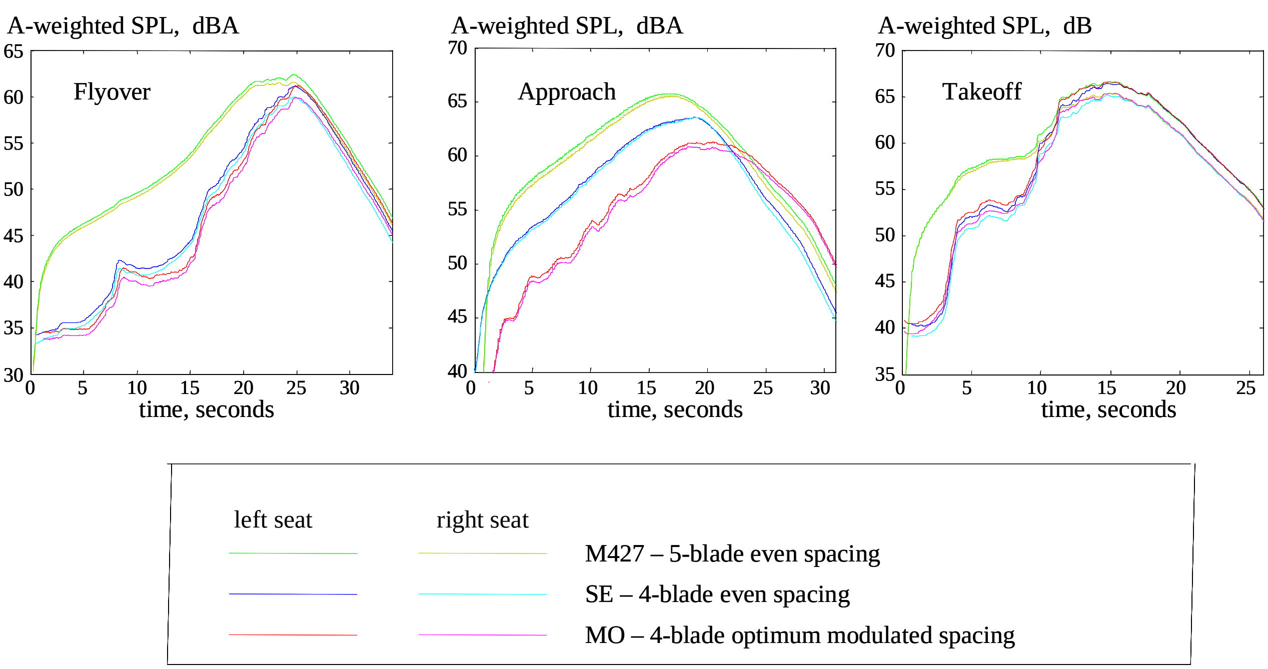
Presentation to Test Subjects

The sound levels in the test chamber were adjusted to replicate the predicted levels as closely as possible. Figure A-1 illustrates the time histories for the predicted, or “target” levels, compared with the measured levels at the head positions of the test subjects within the chamber. These are given for only three of the six test stimuli, but are representative of all.

The 40 test subjects were tested two at a time in the anechoic test chamber. The relative positions of the test subjects and the speakers were adjusted prior to the test to ensure that both test subjects heard the same sound, as nearly as possible. Figure A-2 shows these levels for comparison, indicating that the test subjects were subjected to very nearly identical sounds.



A-1. Predicted time histories compared to those recorded at test subjects head position



A-2. Levels from left and right seat recordings

APPENDIX B

METRICS

Several metrics were calculated for the test stimuli from recordings made in the subject seat positions with one inch B&K 4145 microphones. The performance of each metric was assessed by correlating its value with the Equivalent Subjective Levels as defined in the subjective tests.

For the time-varying sounds used in the Numerical Category Scaling test, any of the complex non-linear loudness-type metrics such as Perceived Loudness (PL), Perceived Noise Level (PNL), and Loudness Level (LL) performed well. Those with a 10-down duration correction, as used in the calculation of Effective Perceived Noise Level (EPNL) in Federal Aviation Regulation-36, improved the correlation between subjective result and predicted metric, but a tone correction as specified in FAR-36 degraded the metric performance.

For the steady-state sounds, the Sound Quality metric called "roughness" would seem to be the most effective. However, no strong correlations are shown, because of the small range of differences between the test events, especially within the 5-blade configurations. Considering both tests and all flight conditions, no single metric performed very well in predicting subjective response.

<u>Metrics for the NCS Test</u>

The NCS stimuli, being time varying, were suitable for EPNL-style metrics, that is metrics with tone and duration corrections based on 1/3 octave band spectra calculated every 0.5 second. FAR36 tone corrections and 10-dB down duration corrections as used in the calculation of EPNL, were applied to a selection of metrics, including overall Sound Pressure Level (OASPL), A-, B- and C-weighted (A-WT, B-WT, C-WT), Perceived Noisiness (PNL), Stevens' Perceived Loudness (PL), and Zwicker's Loudness Level (LL). Pearson Correlation Coefficients between ESL and the metric values for the 18 test stimuli were calculated, and are shown in Table B-1. These metrics are described in References 9 and 10. ESL was used to allow inclusion of all flight conditions into one regression calculation. ΔESL, being dependent on SEap, SEfo or SEto, depending on flight condition, cannot be mixed across conditions.

In general, the tone correction degraded the ability of the metric to predict the subjective response. This is not surprising, as it was designed for the tonal content of jet aircraft noise, rather than the much lower frequencies present in helicopter sounds. The duration correction did improve the metric over the maximum 0.5-second level. The complex non-linear metrics (PL, LL and PNL) all gave good results with PNL superior for the uncorrected metrics, and duration-corrected PL superior overall. Inspection of the data showed that the high correlations were in part driven by the high level and thus high ESL of the M427 events. The correlations were repeated without the M427 results. The data are shown in Table B-2. As can be seen, the correlations are much lower, but the same trends are visible – the duration correction improves and the tone correction (in the main) degrades the correlations; the non-linear metrics perform best, with duration-corrected PL slightly superior. Uncorrected LL is slightly more highly correlated with ESL than PNL.

Table B-1. Pearson correlation coefficients between ESL and metrics for NCS test, including all main rotor configuration for three flight conditions

Metric	Correlation Coefficients			
	No tone correction		FAR36 tone correction	
	No dur^n. corr.	10-dB dur^n. corr.	No dur^n. corr.	10-dB dur^n. corr.
PL (dB)	0.863(**)	**0.889(**)**	0.852(**)	0.856(**)
LL (phons)	0.848(**)	0.876(**)	0.784(**)	0.830(**)
PNL (dB)	**0.878(**)**	0.863(**)	0.842(**)	0.827(**)
A-weighted (dB)	0.611(**)	0.763(**)	0.566(**)	0.725(**)
B-weighted (dB)	0.709(**)	0.716(**)	0.642(**)	0.672(**)
C-weighted (dB)	0.477(*)	0.586(**)	0.430(*)	0.541(**)
Unweighted (dB)	0.467(*)	0.582(**)	0.419	0.536(*)
Max. Roughness	-0.033			
Ave. Roughness	-0.244			

** Correlation is significant at the 0.01 level (2-tailed)

* Correlation is significant at the 0.05 level (2-tailed)

Table B-2. Pearson correlation coefficients between ESL and metrics for NCS test, considering only the 5-blade main rotor events

Metric	Correlation Coefficients			
	No tone correction		FAR36 tone correction	
	No dur^n corr.	10-dB dur^n. corr.	No dur^n. corr.	10-dB dur^n. corr.
PL (dB)	0.700(**)	**0.843(**)**	0.722(**)	0.790(**)
LL (phons)	**0.778(**)**	0.830(**)	0.692(**)	0.752(**)
PNL (dB)	0.763(**)	0.812(**)	0.738(**)	0.751(**)
B-weighted (dB)	0.621(*)	0.667(**)	0.538(*)	0.599(*)
A-weighted (dB)	0.258	0.585(*)	0.182	0.513
C-weighted (dB)	0.316	0.481	0.258	0.420
Unweighted (dB)	0.298	0.472	0.238	0.408
Max. Roughness	-0.112			
Ave. Roughness	-0.088			

** Correlation is significant at the 0.01 level (2-tailed)

* Correlation is significant at the 0.05 level (2-tailed)

The performance of the simple, linear metrics is reduced to below significance at the 1% level, except for duration corrected B-weighted SPL. The improved performance of B-weighting over A-weighting is probably due to A-weighting underestimating the importance of the low frequency components of the sound.

Metrics for the CSD Test

The CSD stimuli, being effectively steady state, were unsuitable for duration corrections. However, some of the newer Sound Quality metrics, that have no procedure for application to time-varying sounds, were included in the analysis of the CSD stimuli. Pearson Correlation Coefficients between DESL levels and metrics (with no tone or duration corrections) are given in Table B-3 for the two flight conditions. H-weighting is a weighting developed by Dr. Clemans A. Powell in a study of helicopter noise, Reference 11. The final five metrics in the table are Sound Quality metrics, Reference 12, used extensively in the automobile and appliance industries. Because there were only five target sounds for each flight condition, high correlation values are required for statistical significance. Thus significant correlations only exist at the 5% level between DESL and Roughness for the approach condition and between DESL and Overall SPL for the flyover condition. Overall SPL performs poorly for the approach condition; Roughness performs well (though not at a statistically significant level) for the flyover condition.

Table B-3. Pearson correlation coefficients between ΔESL and metrics for CSD test

Metric	Correlation Coefficients	
	Approach	**Flyover**
Unweighted (dB)	-0.071	**-0.953(*)**
A-weighted (dB)	-0.847	-0.800
B-weighted (dB)	-0.767	-0.743
C-weighted (dB)	-0.368	-0.842
D-weighted (dB)	-0.782	-0.773
E-weighted (dB)	-0.782	-0.749
H-weighted (dB)	-0.797	-0.760
PL (dB)	-0.799	-0.780
PNL (dB)	-0.740	-0.763
LL (phons)	-0.767	-0.720
LL (sones)	-0.793	-0.736
Roughness (aspers)	**-0.935(*)**	-0.867
Sharpness (acums)	-0.777	-0.772
Fluctuation .strength (vacils)	-0.169	-0.432
Tonality	-0.510	-0.409
Kurtosis	-0.878	-0.365

* Correlation is significant at the 0.05 level (2-tailed)

Metrics that do relatively well for both flight conditions include Roughness and A-weighted SPL, which are correlated with each other at the 5% significance level. The Roughness metric, References B-4 and B-5, developed by Aures, is designed to measure the amount of modulation of a signal, for modulation frequencies between 15 and 300 Hz. Fluctuation Strength, References 12 and 14, measures the amount of modulation for modulation frequencies below 15 Hz. From these results Roughness would appear to be more effective in predicting human response to helicopter noise than Fluctuation Strength. In view of this finding, Roughness was calculated for the sounds in the NCS test. As the sounds are not steady, Roughness varies throughout the sound. Average Roughness and Peak Roughness were calculated and correlated with ESL. The results are included in Tables B-1 and B-2, shown previously, where it can be seen that neither of these versions of Roughness predicts subjective response.

Table B-4 shows the correlations between DESL and metrics for the CSD test, omitting the M427 events and considering only the 5-blade main rotor sounds. Roughness is the only metric to perform fairly well for both flight conditions. Fluctuation strength gives good results for the flyover events.

Table B-4. Pearson correlation coefficients between ΔESL and metrics for CSD test, considering only the 5-blade main rotor events

Metric	Correlation Coefficients	
	Approach	**Flyover**
Unweighted (dB)	-0.361	-0.902
A-weighted (dB)	-0.060	-0.243
B-weighted (dB)	-0.125	-0.720
C-weighted (dB)	-0.315	-0.549
D-weighted (dB)	-0.133	-0.494
E-weighted (dB)	-0.132	-0.724
H-weighted (dB)	-0.093	-0.815
PL (dB)	-0.056	-0.319
PNL (dB)	-0.137	-0.703
LL (phons)	-0.061	-0.885
LL (sones)	-0.071	-0.882
Roughness (aspers)	**-0.748**	-0.827
Sharpness (acums)	-0.085	-0.059
Fluctuation .strength (vacils)	-0.061	**-0.960(*)**
Tonality	-0.140	-0.089
Kurtosis	-0.315	-0.729

* Correlation is significant at the 0.05 level (2-tailed)

APPENDIX C

GENERAL INSTRUCTIONS TO TEST SUBJECTS AND VOLUNTARY CONSENT FORM

Human Response to Aircraft Noise

Conducting Organization: Structural Acoustics Branch, Aerodynamics, Aerothermodynamics & Acoustics Competency, NASA Langley Research Center

Principal Investigator: Ms. Brenda Sullivan.

General Information and Instructions

Description And Purpose: This research will study human reaction to aircraft sounds. This research will provide valuable information to help aircraft manufacturers improve aircraft design.

Type of Study and Volunteer Participation: The study will require you to hear various sounds played over loudspeakers. The sound level involves noises no greater than those experienced on a daily basis in an ordinary community. You will experience a maximum A-weighted sound level of no more than 95 decibels (dBA). A noisy home vacuum cleaner or lawn mower will normally equal the 95 dBA level. The actual testing will take about an hour. Before the actual test begins, you will participate in a demonstration session and a short practice session, which will cover the range of levels that will be used in the test.

The study will involve a number of test sessions, each of which usually lasts 10 to 15 minutes. During each session, you will hear various sounds. You will be given a set of test instructions that you agree to follow during the testing. You may ask questions about the testing to clarify any concerns you may have. The principal investigator will also provide you with additional written and oral instructions and information regarding the test.

Foreseeable Risks, Discomfort, or Benefit: You will experience no undue physical or psychological risk or discomfort. In particular, the study will subject you to minimal risk of loss or discomfort to your hearing. You must complete a health questionnaire prior to participating in the study, and you must take a hearing test before and after the study. The benefit to you from participating in the study is discussion of the test results and knowledge of their possible assistance to improving aircraft design.

Confidentiality: Any information obtained about you from the research will be kept strictly confidential. Data from the research could be used in reports, presentations, or publications; but you will not be identified. Such information would, however, be subject to subpoena by court order or may be inspected or reviewed by federal regulatory authorities. Any data stored electronically will not enjoy strict confidentiality protections due to the nature of computers; but you will not be personally identified in any event.

Withdrawal Privilege: You understand that you are free to refuse to participate in this study or to withdraw at any time without penalty or loss of benefits to which you may be entitled. You may withdraw at anytime simply by speaking out that you wish to stop; however, you must still take the post-study hearing test.

Points of Contact: If you have any questions regarding this research or your rights, you may contact the above investigator at (757) 864-3585. If you have any questions regarding a research-related injury, you should contact the NASA Langley Occupational Medical Clinic at (757) 864-3193. The clinic is staffed by professional nurses, and the center has two full-time medical doctors to address any injury concerns you may have. An ambulance service is also within approximately 1/2 mile of the test facilities.

VOLUNTARY CONSENT FORM

I understand the objectives of the Human Response to Aircraft Noise and Sonic Boom Research Testing in which I am participating as a test subject. The testing procedures have been clearly presented, and I fully understand my participation in the study as explained above and in further oral and written instruction I received.

I have been briefed on the reasonable risks involved with the testing procedures. I will adhere to the safety requirements as specified by the Principal Investigator(s), and I will obey any and all regulations.

I understand that I may withdraw from the study at any time without penalty or loss of benefits. Without regard to my consent, the Principal Investigator(s) may terminate my participation if I cannot participate correctly or the testing must stop for some reason.

I understand that some personal data from the testing may be collected, and that the test will be monitored on closed circuit television and microphone. I further understand that my name will not be associated with these collected data. I consent to the use of these data in any form deemed appropriate by the Principal Investigator(s).

I affirm that, to my knowledge, my state of health has not changed since I completed my health questionnaire and the Langley physician approved my participation in the testing.

I understand that I may contact the Principal Investigator(s) for more information related to this research, although I was afforded an opportunity to ask questions and all questions asked were answered. I understand that I may elect to receive a copy of the test report. If I have concerns after the testing about the manner of conducting the testing, the Principal Investigator(s) will inform me of how to contact the oversight committee, The Institutional Review Board.

I do hereby voluntarily consent to participate as a test subject in the Human Response to Aircraft Noise Research to be conducted at NASA Langley Research Center during ______________, 2001.

______________________ ________________________

Date Signature

____

Print name

______________________ ______________________

Date Investigator

APPENDIX D

TEST INSTRUCTIONS – NOISE CATEGORY SCALING TEST

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

Today there will be 2 test sessions, each lasting 10 to 15 minutes. During each session, you will hear 21 sounds. Each sound will last a few seconds. Before each session you will be given 2 scoring sheets, each containing 10 or 11 rating scales like the one shown below.

Extremely noisy

Not noisy

0 1 2 3 4 5 6 7 8 9 10

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

The scales on the first sheet are numbered 1 through 11, those on the second sheet are numbered 12 through 21. A voice message will be heard every 5 sounds to help you keep track of which sound is being presented. In case you lose track, please tell the test conductor at the end of the session and part of the session will be repeated. Please listen carefully and make your rating at the end of each sound. Again, there are no right or wrong answers; we just want a measure of your own personal reaction to these aircraft sounds. For this reason, we ask that you do not talk during the tests nor make any sounds or express any emotion that might influence the response of the other person in the room. Before we start the actual test, we will play 6 sounds to give you the opportunity to hear the range of sounds. We will then have a practice session with 6 sounds. This will let you become familiar with the scoring and give you the opportunity to ask us any questions about the test.

Thank you for helping us with this investigation.

Subject Number :_________ **Test Name :** **MRT**

Session Name :_________ **Date :**______________

After each sound please indicate how noisy you judge the sound to be by placing a slash mark along the scale.

Not noisy **Extremely noisy**

1 0 1 2 3 4 5 6 7 8 9 10

2 0 1 2 3 4 5 6 7 8 9 10

3 0 1 2 3 4 5 6 7 8 9 10

4 0 1 2 3 4 5 6 7 8 9 10

5 0 1 2 3 4 5 6 7 8 9 10

6 0 1 2 3 4 5 6 7 8 9 10

7 0 1 2 3 4 5 6 7 8 9 10

8 0 1 2 3 4 5 6 7 8 9 10

9 0 1 2 3 4 5 6 7 8 9 10

10 0 1 2 3 4 5 6 7 8 9 10

11 0 1 2 3 4 5 6 7 8 9 10

APPENDIX E

TEST INSTRUCTIONS – PAIRED COMPARISON TEST

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

Today there will be 2 test sessions, each lasting 10 to 15 minutes. During each session, you will hear 50 pairs of aircraft sounds. Each sound in the pairs will last a few seconds. Your job will be to score each pair of sounds on a response sheet in the following manner:

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

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

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

Thank you for helping us with this investigation.

Sample Sheet for CSD test

Subject Number: __________ **Test Name:** **MRT**

Date: __________ **Session Name:**

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

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

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

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

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13. ABSTRACT ***(Maximum 200 words)***
Psychoacoustic testing of simulated helicopter main rotor noise is described, and the subjective results are presented. The objective of these tests was to evaluate the potential acoustic benefits of main rotors with modulated (uneven) blade spacing. Sound simulations were prepared for six main rotor configurations. A baseline 4-blade main rotor with regular blade spacing was based on the Bell Model 427 helicopter. A 5-blade main rotor with regular spacing was designed to approximate the performance of the 427, but at reduced tipspeed. Four modulated rotors – one with “optimum” spacing and three alternate configurations – were derived from the 5 bladed regular spacing rotor. The sounds were played to 2 subjects at a time, with care being taken in the speaker selection and placement to ensure that the sounds were identical for each subject. A total of 40 subjects participated. For each rotor configuration, the listeners were asked to evaluate the sounds in terms of noisiness. The test results indicate little to no “annoyance” benefit for the modulated blade spacing. In general, the subjects preferred the sound of the 5-blade regular spaced rotor over any of the modulated ones. A conclusion is that modulated blade spacing is not a promising design feature to reduce the annoyance for helicopter main rotors.

14. SUBJECT TERMS
Helicopter main rotor, acoustics, noise, blade spacing, psychoacoustic, subjective response, modulated blade spacing, even, uneven, community impact

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