SUBJECTIVE EVALUATION OF HELICOPTER BLADE SLAP NOISE

William J. Galloway
Bolt Beranek and Newman Inc.

SUMMARY

Several methods for adjusting EPNL to account for its underestimate of judged annoyance are applied to eight helicopter flyover noise signatures having various degrees of blade slap. A proposal from an ISO working group for making such adjustments is investigated for these data as well as two sets of data submitted by France to the ICAO Committee on Aircraft Noise, Working Group B. When all data are combined, the ISO proposal is little better than simply adding an arbitrary fixed adjustment of 3 decibels to EPNL.

INTRODUCTION

Means for measurement of the physical characteristics of impulsive noise produced by helicopter blade slap and accounting for the underestimate of judged annoyance by EPNL have been studied by a number of groups in Europe and the USA over the last few years. Working Group 2 on Aircraft Noise of ISO TC43/SC1, Acoustics/Noise, has considered a number of possible measurement and assessment procedures at the request of ICAO/CAN/WGB for use in its development of noise certification procedures for helicopters. A draft proposal for an impulsive noise correction procedure emerged from ISO in January 1978 and has been circulated for comment. The procedure is based on a digital analysis of the flyover signal.

The basic psychoacoustical data used to derive the ISO proposal were obtained from a combination of steady state and simulated helicopter blade slap noises. This paper describes the investigation of the ability of an analog analysis of a number of simulated noises and eight recorded noise signatures from actual helicopters, as well as the use of the ISO and other digitally based procedures, to account for the results of psychoacoustical judgments of these signals. Comparisons of the application of the ISO procedures to the eight recorded helicopter noise signals and to two sets of French data on simulated helicopters are made for the separate data sets and to the aggregated data.

ABBREVIATIONS AND SYMBOLS

Abbreviations

ISO	International Standardization Organization
ICAO	International Civil Aviation Organization
EPNL	effective perceived noise level
PNLT	tone-corrected perceived noise level
Rep.	repetition
TSC	Transportation Systems Center

Symbols

CF	crest factor, decibels
CF_M	maximum value of CF over an event, decibels
$\overline{CF}_{0.5}$	logarithmic average over an event of crest factors obtained for each 0.5 second of the event, decibels
CI	French impulse coefficient
I	ISO impulse factor derived from sampled voltages
r	product moment correlation coefficient
V_i	voltage sampled at ith time increment
Δ_C	calculated additive adjustment to EPNL, decibels
Δ_S	subjective difference between judged and measured EPNL, decibels

MEASURES OF IMPULSIVENESS

The psychoacoustical study reported in reference 1 investigated the use of several analog and digital measures of impulsiveness that had been proposed in the ISO working group. Since the time of that report the ISO proposal has emerged as a coalescence of two proposals, one from the National Physical Laboratory in England and the other from France. The two computational procedures results in impulse measures that differ only by a subtractive constant of unity when based on the same digital sampling intervals and integration times. In this paper both the ISO proposal and the last French proposal are used, since the transfer functions between the impulsiveness measures and the subjective corrections to EPNL are different. In addition to the digital techniques, several analog measures of crest factor were used in the analysis of the subjective data in reference 1.

In all the procedures the basic concept is to derive an adjustment factor, for each 0.5 second interval of the flyover, which is added to the measured value of tone-corrected perceived noise level (PNLT) for that 0.5 second interval, before integrating (summing) over the event to obtain EPNL. The differences between the impulse adjustment procedures lie in how the adjustment increment is determined for each 0.5 second interval.

Digital Analyses

The noise signal voltage is A-weighted, passed through a 2000 Hz low pass anti-aliasing filter, then digitally sampled at 5000 (or an integer multiple of 5000) samples per second. In the French proposal the 2500 samples in each 0.5 second interval are combined to determine an impulsiveness coefficient CI (ref. 2):

$$CI = \frac{\frac{1}{2500}\sum_{i=1}^{2500} V_i^4}{\left[\frac{1}{2500}\sum_{i=1}^{2500} V_i^2\right]^2} \qquad (1)$$

Note that the denominator is the square of the mean-square voltage during the time interval, denoted in the ISO procedure as "S". In the ISO procedure, the impulsiveness quality I is calculated from the same sampled data (ref. 3):

$$I = \frac{1}{2500} \sum_{i=1}^{2500} \left[\frac{V_i^2 - S}{S} \right]^2 \tag{2}$$

Thus, CI = I + 1.

The values of CI and I are converted through transfer functions to decibel adjustments, Δ, which are added to the PNLT values in the same time interval. The form of these transfer functions has varied at different times during their evolution. In each case the aim was to develop a function that would empirically fit the then available subjective data and, at the same time, have a zero adjustment for "non-impulsive" noise, such as that produced by conventional jet aircraft. The current forms (refs. 2 and 3) of the transfer functions may be expressed as:

$$\begin{aligned} \text{French:} \quad & \Delta = -6.875 + 13.75 \log_{10} CI \\ \text{ISO:} \quad & \Delta = -2.4 + 8 \log_{10} I \end{aligned} \tag{3}$$

where Δ is restricted to $0 \le \Delta \le 5.5$.

Analog Analysis

A classical way to describe the impulsiveness of a signal is through its crest factor, its peak-to-rms ratio. Expressed in decibels, where L_{pk} is the peak sound pressure level, and L is the mean square sound pressure level, crest factor $CF = L_{pk} - L$. For random noise CF is of the order of 12 decibels and, for severe helicopter blade slap, may be as high as 20 or more decibels, depending upon what, if any, frequency-weighting is employed. As a measure of helicopter blade slap, Leverton has proposed the crest factor measured in the 250 Hz octave band, while a number of different investigators have used A-weighted sound level crest factors.

In this study A-weighted sound level crest factor in decibels is used, as measured with a B&K 2209 sound level meter. In making peak measurements the instrument uses a 10 microsecond RC detector with a resetable peak hold circuit and provides accurate sound level measurements for crest factors of more than 30 decibels. Two different crest factors have been used in the study. The simplest is the maximum crest factor measured during a flyover, irrespective of when it occurred, and is abbreviated as CF_M. A more complex measure is the mean-square average of the separate maximum crest factors obtained in each 0.5 second interval of the flyover, abbreviated as $\overline{CF}_{0.5}$.

SUMMARY OF SUBJECTIVE TESTS

A complete description of these experiments is provided in reference 1. A brief summary is provided here.

Steady-State Synthesized Signals

Eight different signals were constructed for judgement against two different non-impulsive signals. All signals had durations of 10 seconds at constant level, with 0.5 second on and off ramps. Three different non-impulsive noise spectra were used to represent different helicopter spectra. The first non-impulsive noise was a replica of the signal reported by Fuller in experiments at the National Physical Laboratory (NPL), in England (ref. 4). The other two were representative of the spectra of large multi-bladed and smaller two-bladed helicopters. Impulsive noise simulations were made by mixing single sine wave pulses, repeated at a specified repetition rate, with the broad-band non-impulsive "background" spectra. The signals may be described by the "background" non-impulsive spectrum, the fundamental frequency of the sine pulse, the frequency of the pulse repetition rate, and the level difference in decibels between the peak sound pressure level of the sine pulses to the overall sound pressure level of the non-impulsive spectrum. (Note that this is not the crest factor for the combined signals.)

Time-Varying Synthesized Signals

Six of the steady-state signals were modified to become time varying simulations of flyover signals by use of a variable gain amplifier to provide a trapezoidal time pattern in which the overall signal level was increased at a rate of 2 decibels per second to a maximum level, held for 2 seconds, then decreased in level at a decay rate of 2 decibels per second (providing signals 12 seconds wide at the points in the time pattern that are 10 decibels below the maximum level).

In order to simulate the effect of directivity on impulse noise during a flyover, two of the signals were further modified to fadeout the impulsive part of the signal during the 2 second maximum level portion of the time pattern. Thus these signals had impulsive content on the increasing level portion of the signal and no impulses on the decaying portion of the signal, as in the case with most actual helicopter noise signatures.

Recorded Helicopter Noise Signals

Nine recorded helicopter signals were selected from those obtained in a comprehensive measurement program conducted by FAA/TSC to define the noise characteristics produced by a variety of helicopters during level flyover and approach maneuvers under consideration for noise certification. The signals used in the psychoacoustical tests were chosen to represent the range of helicopter designs and sizes currently in operation that produce significantly audible blade slap, with one signal having negligible blade slap chosen as a comparison signal (S-61 in level flight). The general characteristics of the signals selected and the operational conditions under which they were produced are described in detail in reference 5. The events used in this study are listed in table 1.

Experimental Facilities

All stimuli were presented to subjects seated, one at a time, in an anechoic chamber. The individual test signals were recorded on individual magnetic tape loops that could be selected at will through computer control. The playback system frequency response was equalized so that the signal as measured at the listener's head position reproduced the signal spectrum of the original recording. The signal levels used in all presentations were measured in EPNL, as calculated from real-time analyses of the signals obtained at the listener's head position, using the procedures of FAR Part 36/ICAO Annex 16. Particular attention was paid to insure that the analysis system properly measured the rms levels of the signals with high crest factors.

Test Subjects

Twenty college students between the ages of 18 and 32 were used as subjects. Half of these were women and half were men. All subjects were audiometrically screened to assure that they were within 20 decibels of ISO defined normal hearing.

Test Procedure

Each listener was asked to choose which of two sequentially reproduced signals was more annoying. For each test stimulus the experimental procedure, called PEST (Parameter Estimation of Sequential Testing), in an iterative manner controlled by a computer, varied the level of a comparison stimulus in a succession of trials until the subject's responses indicated that the test stimulus was subjectively equal to the standard stimulus. The computer program randomizes the order of presentation of the two signals and varies the level of the test stimulus in both increasing and decreasing fashion to obtain a convergence in the judgements from the subject. The convergence criterion used in these tests was 1 decibel, and the allowed upper limit in number of trials was 30. The 20 subjects used an average of approximately 10 trials each to reach stable judgements for the subjective equality between the test and standard stimuli. The difference in EPNL between the test and comparison stimuli, averaged over all subjects, was used as the measure of the subjective underestimate of blade slap by EPNL.

Although the order of presentation of the different test stimuli was randomized between subjects, all subjects were given a pretest training session during which they were asked to judge one of the NPL test noises against itself. The average difference in judgements for this test was 0.4 decibels, with a standard error in the mean of 0.3 decibels.

In all tests the fixed level signal was reproduced at a nominal EPNL value of 80 decibels. The comparison signal level could be varied as much as 30 decibels above and below this level.

SUMMARY OF RESULTS

The subjects, on average, judged impulsive signals to be more annoying than non-impulsive signals by up to 7 decibels. On the other hand, non-impulsive signals of substantially different spectral shape were equated on an EPNL basis within 0.1 to 0.4 decibel, on average. The standard errors in the mean (20 subjects) ranged from 1.0 to 1.8, for all signals, and from 1.0 to 1.4 for just the helicopters. For the small number of subjects, these standard errors are very acceptable.

A physical analysis of each signal was made to calculate the various impulsiveness measures. Adjustment factors for PNLT were computed according to the proposed transfer functions, added to PNLT values, and EPNL re-computed for each signal. The difference in EPNL with and without the impulse adjustment was then compared to the judged differences. The differences between EPNL computed with crest factors added to PNLT and without were compared directly with the judgements.

The results of the comparisons between calculated and judged values were discouraging when all signals were compared as a set. In essence, the comparisons were uncorrelated, with the best measure accounting for less than 20 percent of the variance in a linear regression analysis ($r^2 = 0.18$). When only the eight helicopters were considered as a subset the picture improved, for the French CI proposal, with $r^2 = 0.69$. The crest factor measures did not improve, with $r^2 = 0.17$. Scatter diagrams and the regression lines of Δ_S on Δ_C are shown in figure 1 for the French procedure and in figure 2 for $\overline{CF}_{0.5}$.

In some other tests on the judged annoyance of impulsive sounds we have found preliminary evidence that annoyance increases with crest factor when pulse repetition rate is held constant, while with crest factor held constant annoyance varies with repetition rate. The shape of the sensitivity curve is very much like a visual flicker sensitivity curve, little sensitivity at low (≈ 5 Hz) and high (≈ 80 Hz) repetition frequencies (flicker fusion in the case of vision) with a maximum in sensitivity of repetition frequencies of the order of 30 to 40 Hz. Using the zero airspeed blade passage frequency as a measure, the product moment correlation between Δ_S and frequency accounts for 65% of the variance in the eight helicopter signals ($r^2 = 0.65$); however, for the entire signal set little correlation resulted ($r^2 = 0.10$).

In an attempt to improve the picture, multiple regressions of Δ_S on a linear combination of calculated adjustments, Δ_C (or CF) and repetition frequency were computed. Typical results for the helicopters were improvement in r^2 for the French adjustment from 0.69 to 0.87 and improvement in r^2 for $CF_{0.5}$ from 0.17 to 0.77. Standard errors for the regression improved from 0.8 decibels to 0.5 decibels for the French adjustment, and from 1.4 to 0.7 decibels for $\overline{CF}_{0.5}$.

CONFLICTING VIEWS

The possible use of analog measures of crest factor to assess impulsiveness has not met with much enthusiasm in ISO, particularly on the basis of analyses reported from France. Wright and Damongeot (ref. 6) argue that crest factor is a poor measure since, in their tests, it provided poor resolution for low impulsiveness signals. Our contention is that they did not follow the specified measurement procedure, since in their paper they determined crest factor from visual analysis on an oscilloscope.

In another analysis Berry and Robinson (ref. 7) found good correlation with their data using a crest factor determined from the largest value of their digitally sampled voltages used to compute CI or I. In the one case where we can compare their analysis directly with one of ours, their digital method correlates well (r^2 of 0.91), for seven samples of synthesized blade slap noise, with our analog analysis. Further, the slope of the regression line is 1.01, although there is a 1.7 decibel offset at CF = 0.

A more basic disagreement exists over the use of repetition rate in an adjustment process. The primary issue is the repetition rate to be attributed to a helicopter with dual main rotors. If one takes the repetition rate as that due to the blade passage rate of one rotor only, the correlation with repetition rate is low. If one takes the repetition rate as twice this number, the correlation is retained. The fact is, a dual set of pulses exists, not quite uniformly spaced (constant repetition time overlap of two sets), with one set somewhat weaker than the other, their relative crest factors varying with operating conditions.

The second fact is that this kind of helicopter is judged to be twice, in decibels, as annoying as other helicopters having essentially the same degree of impulsiveness, as calculated by any of the impulsiveness measures. See figures 1 and 2 for examples.

ISO ADJUSTMENTS AND COMPARISONS OF DATA

Of major interest at this time is how well the proposed ISO adjustment procedure works on judged data. Analyses of two sets of French data and of a dubbed recording of our eight helicopter signals, provided by us, have been reported by Aerospatialle in an ICAO working paper (ref. 8). The following discussion is based on the data reported in reference 8.

Consider first the ISO procedure applied to the eight helicopters. The scatter diagram showing the relationship between Δ_S and Δ_C is plotted in figure 3, along with the regression line. A positive correlation exists, with r^2 of 0.60, intercept of 0.2, and slope of 1.23.

The French judgement data are derived from one set of time-varying signals and from one set of steady-state signals. Consider first the data for the time-varying signals, as plotted in figure 4. In this case, $r^2 = 0.38$, but the values of Δ_S are negatively correlated, the regression line slope being - 0.49. Combining these data with the eight helicopters to obtain all the time-varying signals results in the plot of figure 5. Here the correlation is meaningless, with $r^2 = 0.04$.

The relationship between Δ_S and Δ_C for the French steady-state signals provides a better picture, as seen in figure 6. This should be better, since these data are basically those used to derive the CI and ISO transfer functions in the first place. Here $r^2 = 0.85$ and the slope is 1.04.

Finally, combining the three sets of data, as in reference 8, the plot in figure 7 results. In this figure the 6 signals used as comparison standards have been omitted since the subjective differences for the impulsive signals are judged relative to these standards. In this combined case $r^2 = 0.34$ and the slope is 0.69.

CONCLUDING REMARKS

It seems clear that at this point our knowledge of a good general predictor of subjective response to impulsive noise is poor. It is also clear that EPNL does underestimate annoyance due to blade slap. For these data the average underestimate is about 3 decibels for single main rotor aircraft and about 6 for the dual main rotor aircraft. Considering the variability in the data, one might arbitrarily use these constant values and ignore any more elaborate approach. One could simply apply these additive values to any helicopter that had a maximum A-weighted crest factor of more than 14 decibels.

REFERENCES

1. Galloway, W. J., "Subjective Response to Simulated and Actual Helicopter Blade Slap Noise," BBN Report No. 3573, December 1977.

2. Anon., "Impulsivity Indicators--Effect of Integration Time on NPL Indicator," ICAO/CAN/WG B WP 16 (France), June 1977.

3. "First Draft Proposal for Amendment to ISO 3891 'Acoustics-Procedure for Describing Aircraft Noise Heard on the Ground' Measurement of Noise From Helicopters," ISO/TC43/SC1 (Secretariat-254) 356, January 1978.

4. Fuller, H. C., "Rating Helicopter Noise: A Study of Subjective Reaction to Impulsive Sound," ISO/TC43/SC1/WG2 N 77, November 1976 (B&R 3).

5. True, H. C. and Rickley, E. J., "Noise Characteristics of Eight Helicopters," Report No. FAA-RD-77-94, July 1977.

6. Wright, S. E. and Damongeot, A., "Psychoacoustic Studies of Impulsive Noise," Paper No. 55, Third European Rotorcraft and Powered Lift Aircraft Forum," September 1977.

7. Berry, B. F. and Chew, A. J., "Helicopter Noise: Analysis of Various Descriptors of Impulsiveness," ISO/TC43/SC1/WG2 N 81, February 1977 (B&R 4).

8. Anon., "Analysis of the Effect of "Pulse Repetition Rate' on the Annoyance of Helicopter Impulsive Noise," ICAO/CAN/WGB WP 8 (France), April 1978.

TABLE 1

HELICOPTER SIGNALS USED IN
SUBJECTIVE RESPONSE STUDY

BBN No.	Aircraft Type	TSC Event	Operating Condition	Static Rep. Rate, Hz
214	S-61 (ref.)	34	115 knot level	17
215	S-64	50	60 knot level	18.6
216	CH-47C	28	150 knot level	25
217	CH-47C	18	60 knot level	25
218	212	36	105 knot level	11
219	212	31	61 knot level	11
220	47 G	19	6° Approach	12
221	S-61	20	6° Approach	17
222	206 L	46	6° Approach	13

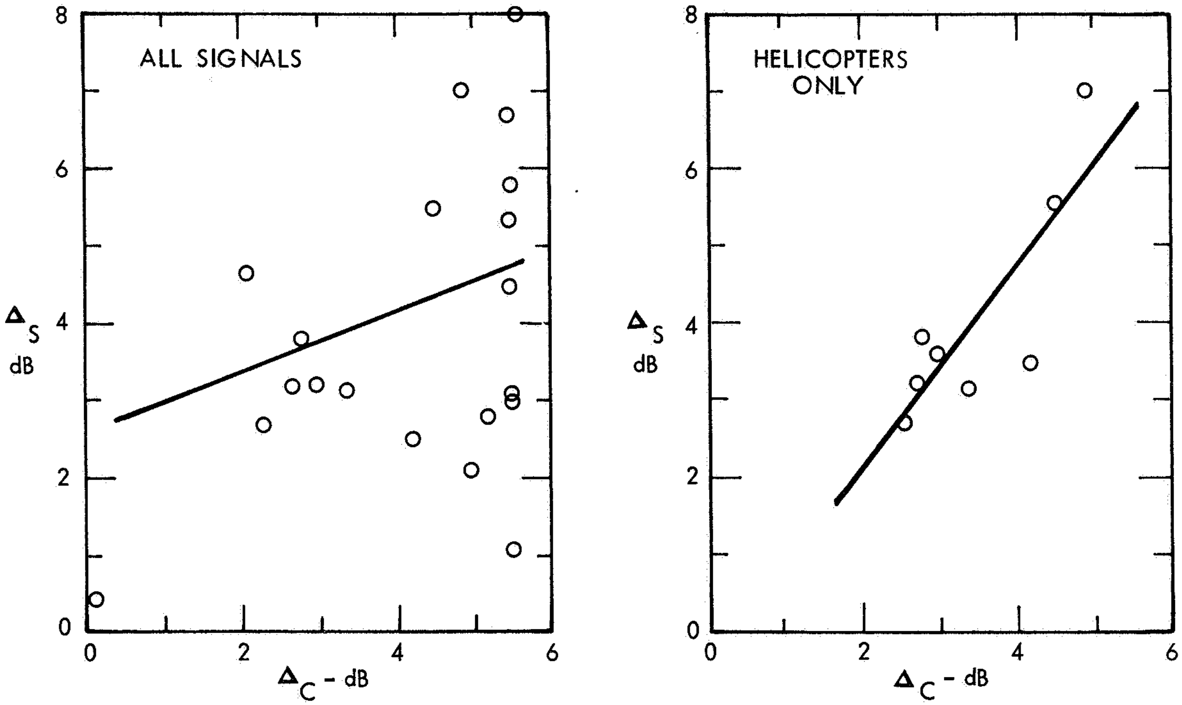

Figure 1.- Comparison of judged difference in EPNL between impulsive and non-impulsive signals and calculated impulse adjustment using French measure CI_A.

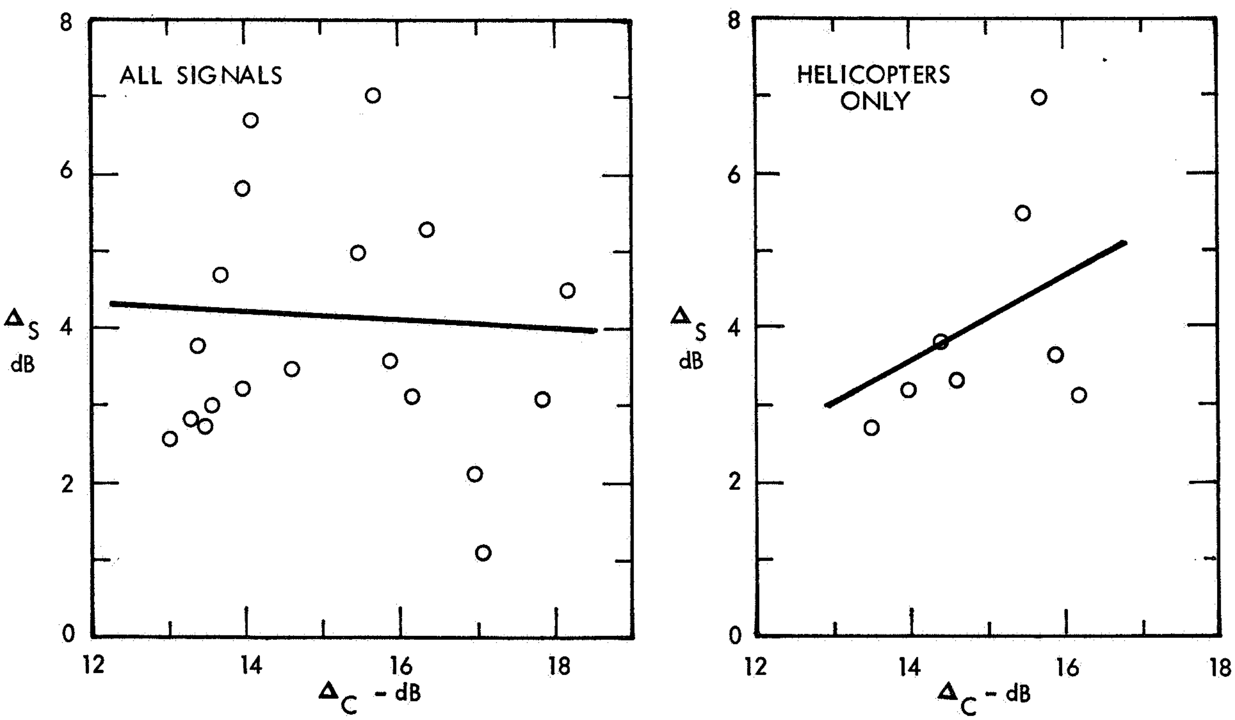

Figure 2.- Comparison of judged difference in EPNL between impulsive and non-impulsive signals and calculated impulse adjustment using $\overline{CF}_{0.5}$.

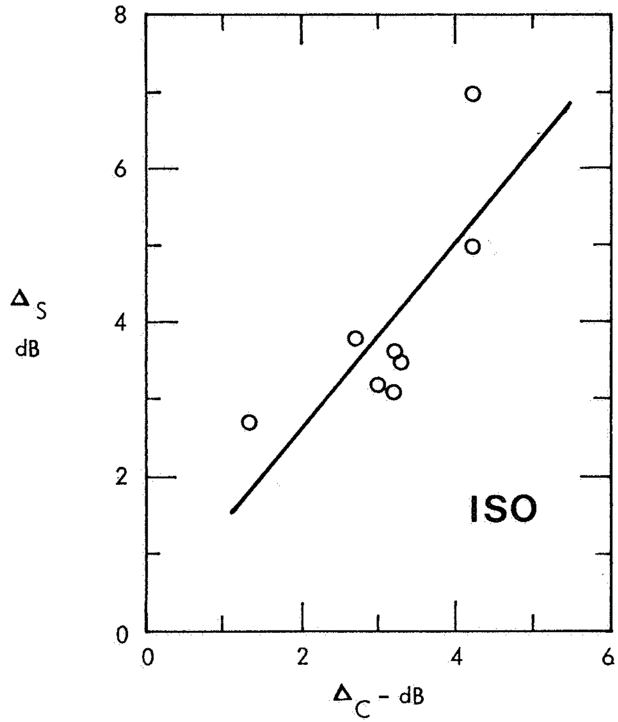

Figure 3.- Correlation between judged and calculated adjustment to EPNL for BBN helicopters.

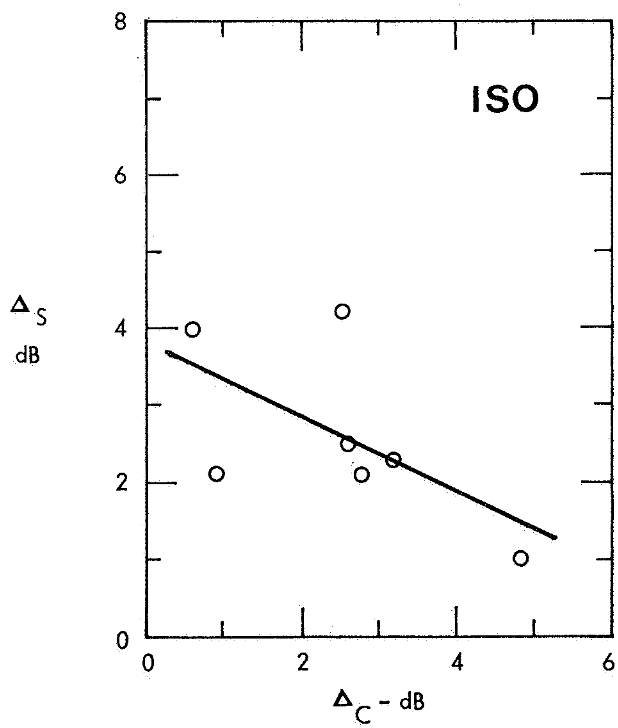

Figure 4.- Correlation between judged and calculated adjustment to EPNL for French time-varying simulations.

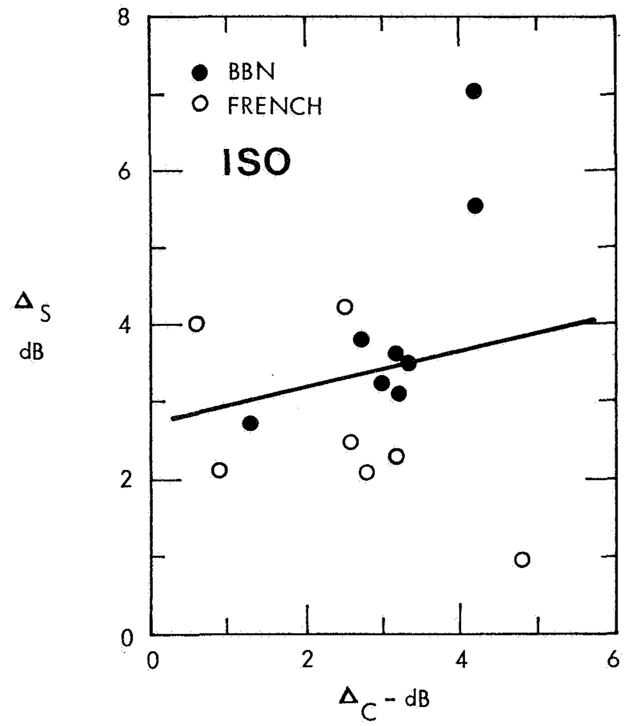

Figure 5.- Correlation between judged and calculated adjustment to EPNL for BBN and French time-varying signals.

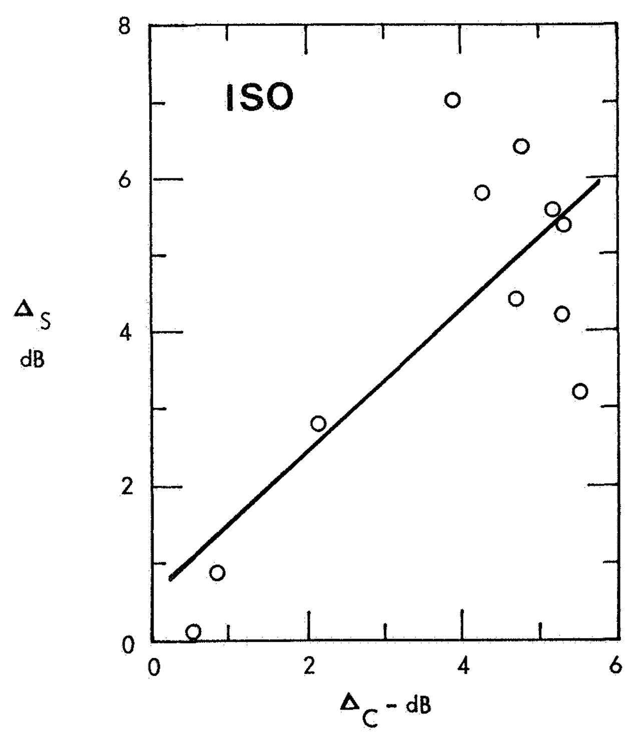

Figure 6.- Correlation between judged and calculated adjustment to EPNL for French steady-state signals.

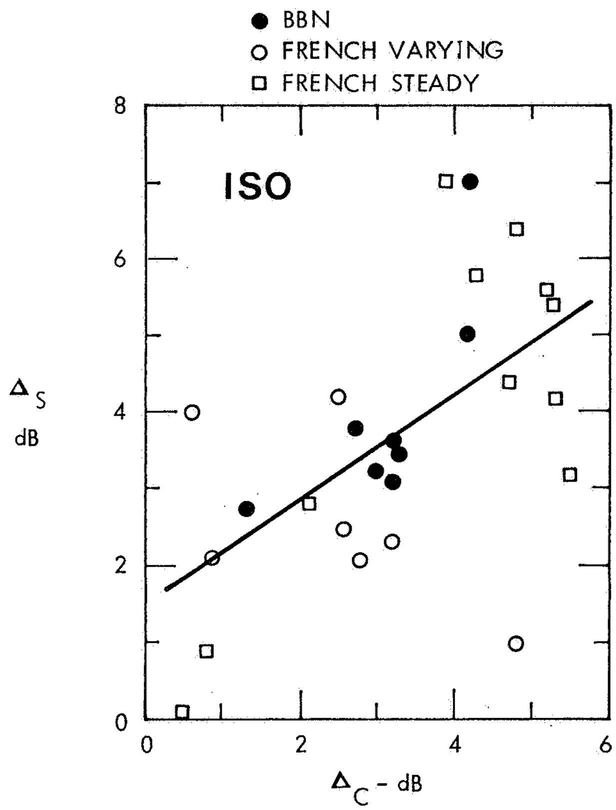

Figure 7.- Correlation between judged and calculated adjustment to EPNL for combined signals.