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PREDICTIONS OF AUDITORY MASKING IN HELICOPTER NOISE

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One of the more classical problems in detecting and classifying signals in noise is the issue of auditory masking - the effect of raising the threshold of the detection signal due to the presence of noise. Masking is particularly important when threshold listening is involved, that is listening for low level signals under conditions of high noise, and from a military viewpoint it is of great importance when trying to carry out auditory monitoring tasks of sonar signals or electronic warfare returns. Masking, however, is not must a military phenomenum but can be important under civil conditions where aircraft warning sounds or a range of auditory cues are used.

The Human Engineering research at the Royal Aircraft Establishment involves, in part, the problems associated with exposing aircrew to the high levels of noise and vibration inherent in current military aircraft - both fixed and rotary wing. Whilst much of the research encompasses means of reducing noise levels reaching the aircrew's ear, to reduce the problems of poor communication, long and short term hearing damage risk and general lowering of performance, the laws of physics in conjunction with the reality of compromise unfortunately do not prevent some of the high level noise reaching the ear directly, predominantly at low frequencies (below 100 Hz). This is particularly so in helicopters where the majority of the energy is contained in the lower frequencies generated predominantly from the aerodynamic sources (rotor etc) with some mechanical generations (gearbox etc). Figures 1 and 2 show this very clearly. Figure 1, taken from Ref 1 depicts a Lynx noise spectrum measured in the pilots cabin and the contributions from the rotor at the lower frequencies (Rotor 21.2 Hz Tail rotor 123 Hz) and the main acoustic peaks from the gearbox (460 Hz) can be clearly seen. Figure 2 illustrates a Chinook (CH47) helicopter spectrum (Ref 2) which contains even lower rotor frequencies. Due to the heavy loads that the aircraft is assigned to lift, Chinook is a twin rotor design, each rotor having 3 blades. The noise levels produced at the main blade passing frequency (3R : 11.95 Hz) and the interaction between the two rotors (6R : 23.5 Hz) are quite intense and typically are in the region of 120 dB to 125 dB SPL.

This low frequency energy in conjunction with the inability of current generations of passive hearing protectors, headsets and flying helmets to attenuate low frequency energy to any great extent, ultimately means that in a helicopter, even when wearing some form of hearing protection, the levels of low frequency energy experienced at the ear are high. Figure 3 plainly illustrates this point showing in Fig 3(a) the attenuation of the RAF Mk 4 flying helmet (Ref 3) and in 3(b) a helicopter spectrum showing the noise in the aircrew cabin overplotted with the noise level at the aircrew's ear. Quite clearly high levels of low frequency noise are apparent.

It is these high-level low-frequency levels that are liable to cause masking, which is present essentially in 3 forms, direct, upward and downward. Direct masking occurs when the masker is at the same frequency as the signal, and both upward and downward masking are caused by a masker at a given frequency masking signals of higher or lower frequencies (upward or downward respectively). Figure 4 illustrates the point.

In military helicopters using airborne sonar detection equipment, the effects of masking, when using the sonar operator for efficient auditory monitoring of active or passive sonar return signals, may be critical both in the detection phase or in the classification period. Depending upon the level of the detection signal transmitted to the sonics operators ear, the operator may either detect or miss the signal, depending upon the signals level being above or below the masked threshold. Similarly during the classification phase, if the complex signature is partially masked by the cabin noise, then the classification may be in error since only a proportion of the signature is perceived by the operator, effectively changing its characteristic. Similar principles apply to all other aspects of auditory monitoring including aspects of EW signatures, ESM signals and even speech communications (although this is more complex). Figure 5 illustrates the point.

It was with these aspects in mind that RAE embarked upon a research programme to predict to a degree of accuracy the masked thresholds of listeners under high noise conditions, extending and modifying existing models, as required, in both the frequency and intensity range to cover aspects of military operations both in helicopters and fixed wing aircraft.

The programme was structured to become a joint project between the Human Engineering Division of RAE Flight Systems Department, Dr Roy Patterson at MRC/APU Cambridge whose auditory model was utilised and the Auditory Communications and Hearing Conservation Unit (ACHCU) of the Institute of Sound and Vibration Research in the form of Mike Lower and Peter Wheeler. Experimental work was carried out in all these locations and this paper describes the culmination of the research in the application of the auditory model and the conclusions of the research at both APU and ISVR to real-life helicopter noise and operational conditions, using the RAE Helicopter Noise and Vibration Simulator developed by Dr John Chillery and Mr J Collister.

Auditory Model

In 1980, Patterson and Nimmo-Smith (Ref 4) published data on experiments concerned with the auditory filter shape and the asymmetry of such filter shapes, based on previous research by Patterson (Ref 5, 6) and Patterson and Henning (7).

In essence, Patterson (Ref 8) argued that since the rise and fall times of the auditory systems are short with respect to the duration of speech sounds or signals, and since the relative phase of the spectral components has essentially no effect on masking levels, it is possible to predict auditory threshold in noise using a model of auditory masking in which the stimuli are represented by their long term power spectra and the selectivity of the auditory system is represented by an auditory filter. An assumption is made that if the listener is asked to detect a signal in the presence of a noise background he listens for a signal through an auditory filter centred near the peak of the signal spectrum.

Patterson quantified this model in the form

$$Ps = K \int_{-\infty}^{\infty} N(f)W(f)df \tag{1}$$

In other words, the power of the signal at threshold, Ps, is some constant proportion, K, of the integral of the noise spectrum, N(f), times the auditory filter characteristic, W(f). This auditory filter characteristic was determined by Patterson in a series of experiments (Ref 5, 6) which showed that the passband of the filter is virtually symmetric when plotted on a linear frequency scale. The filter has a passband with skirts that fall at around 100 dB/octave, with the passband having a dynamic range in the region of 40 dB. Outside the passband the slope of the filter shape drops rapidly to about 15 dB/ octave. An equivalent rectangular bandwidth of the filter, ERB, may be determined which changes marginally with age and frequency but which for practical purposes may be defined from the equation:

$$ERB = 6.23f^2 + 93.39f + 28.52 \qquad (f \text{ in kHz})$$

The equation is obtained from Ref 9, and is the equation of the curve shown in Fig 6 which is an estimate of how the filter width increases with centre frequency.

From the data the passband may be approximated by a pair of back-to-back exponential functions, and since the filter is roughly symmetric, only one exponential parametor, p, is required.

An adequate first approximation to the filter passband is provided by

$$W(g) = (1 + pg)e^{-pg} \tag{2}$$

where g is the normalised separation from the centre of the filter, fo, to the evaluation point, f.

The parameter, p, determines the width of the passband of the filter, and the term, (1 + pg) rounds off the peaked top of the double exponential. This rounded exponential (ro-ex) is referred to as the ROEX(p) filter.

Further, a dynamic range restriction, r, may be introduced since the auditory filter does have limited skirts.

A useful approximation to the entire filter is then provided by

$$W(g) = (1-r)(1 + pg)e^{-pg} + r$$

The factor (1-r) is introduced to ensure that the value of the filter remains at unity at its maximum point of sensitivity. This is referred to the ROEX (p,r) filter.

This filter shape may now be substituted in the general masking equation, (1), to provide an expression for calculation threshold from an arbitrary noise spectrum. The proportionately constant, k, can be assumed to have a value of 1.0 for practical purposes.

Thus the general expression for threshold becomes

$$Ps = fo \int_{o}^{0.8} N(g)[(1 - r)(1 + pg)e^{-pg} + r]\ dg$$

the constant fo is used to convert from the normalised frequency domain to physical power and since the dynamic range limitation is implemented, the integration is restricted in frequency to 0.8.

Patterson notes (Ref 8) that this expression may be used in the prediction of threshold when the total noise levels do not exceed 95 dB(A), since above this level the auditory filter broadens and corrections must be included.

This, then, was the basic auditory filter model which was to be used in determining the masked auditory threshold from experiments carried out in the helicopter noise simulator.

Helicopter Noise Simulator

The intrinsic aim of the simulator is to faithfully reproduce the noise spectrum of an in-flight helicopter under a variety of flight conditions, retaining enough control over the reproduction system to enable discrete changes in the noise spectrum to be carried out.

A schematic diagram is shown in Fig 7(a). An analogue signal is taken from a recording taken in-flight, fed through an A to D converter, further through the DATS 11 software and stored on disc in time history form. An FFT is now performed on the time history sampling at 32K and stored on the disc in the frequency domain. This produces a 16000 line spectrum with a 1 Hz resolution, this resolution being chosen to provide adequate control of the spectrum when re-shaping is required. The data from the disc is then fed through the array processor, the D to A converter, a digitally controller pre-amplifier and finally ghrough the power amplifiers to the loudspeakers in the simulator. The output of the power amplifier is split into 3 bands, low (10Hz to 400Hz), mid-range (400Hz to 2 KHz) and high 2KHz to 8KHz) and fed into different banks of loudspeakers. In the roof of the simulator 4 low-frequency units are installed (Cetec Gauss 4843:400W) whilst the mid-range units (Cetec Gauss 4281:300W) are arranged in the rear wall with the high frequency units (Cetec-Gauss 2080:60W) at the front and rear walls. With this system levels can be produced which exceed those found in current generation helicopters. Figure7(b) shows the performance envelope of the simulator.

We chose to use a suitably modified real helicopter in which to reproduce the noise, although, of course, the noise control computer will allow the noise field to be reproduced in virtually any space (anechoic rooms etc) with suitable sizes and numbers of loudspeakers . A Lynx helicopter was used which, apart from those modifications necessary to fit the loudspeakers, retains its structural integrity. Control of the noise field, the computer and experimental direction is from a separate control room. A major advantage of the control system is that, apart from reproducing existing helicopter cabin noise, it is capable of manipulating existing aircraft spectra, with their involved changes in level with time at any given frequency, into the predicted spectra of a future helicopter. Experimental research may then be carried out in this future environment to ascertain whether the levels of cabin noise involved in conjunction with specific operational tasks, will cause degradation of operator performance.

For this particular masking experiment three helicopter noise spectra were chosen - Lynx, Chinook and Sea King,all of which have differing spectral characteristics, the spread of which would adequately test the masking model.

Experiment

The basis of the experiment was to measure the auditory threshold of a number of subjects to a range of pure tone frequencies whilst exposing the subjects in the helicopter noise simulator to "real-life" noise conditions. Comparison would then be made with the calculated threshold data from the mathematical model. Ten listeners were used with a series of 17 pulsed pure tones, spaced over the frequency spectrum from 100Hz to 4.5 KHz. In addition, more complex "real-life" electronic warfare returns were used although the results are not included in this paper. Three helicopter noises spectra were used - Chinook, Sea King and Lynx.

Each subject, whose hearing was normal to ISO standards, wore a Mk 4 flying helmet for the duration of the exercise, fitted with experimental PVDF headphones which have a low-frequency response which allows the lower frequency signals to be clearly perceived. A passive acoustic attenuation measurement was made on each subject, using the standard RAE method with miniature microphones, to ensure that helmet fit was acceptable and within normal limits. In addition to the miniature microphone at each ear, placed over the external meatus, a microphone was placed on each side of the helmet to monitor the external noise field. To ensure that any variance due to differences in cabin noise fields between subjects was minimised, each subject adjusted the helicopter seat until his head was in a particular position fixed by sets of cross wires.

Whilst being exposed to the noise, which was measured at both ears, the listener used a Bekesy tracking procedure to measure the thresholds at each of the discrete frequencies, each frequency being exposed for 30 seconds allowing about 10-12 turnarounds in that time. Prior to these detections the audiometer had been calibrated against the sound pressure levels measured at the ear for each frequency. Similarly the audiometer had also been calibrated against artificial ear (Bruel and Kjaer Type 4153) measurements.

From the measurements of the noise levels at each ear the predicted masked thresholds could be calculated, which were then compared with the measured thresholds.

The threshold curves for different listeners had very similar shapes, and whilst one listener may be consistently above or below another, indicating a broader or narrower filter, all of the functions followed the spectrum quite closely and the mean data is thus considered relevant.

During the whole experiment one of the major concerns was predictive efficiency; that is the final model was required to be as complex as necessary for predicting threshold in helicopters, but theoretical complications were not required which would increase the computation time without increasing the predictive accuracy.

As a starting point, the simplest of the theoretical models was used, the Rounded Exponential Filter, having only a single parameter, filter bandwidth. To initially maintain the simple approach, aspects of off frequency listening, broadening of the filter shape at high levels and localised reductions in masked variability were ignored.

The results of the experiment are shown in Fig 8 for Lynx cabin noise, Fig 9 for Chinook noise and Fig 10 for Sea King noise. Each plot shows the subjectively measured and objectively calculated threshold from the noise level measured at the ear. The solid line through the data is the average of ten predicted threshold functions.

It is, incidentally, well worth noting that this calculated threshold represents a true prediction of the data, rather than a fit to the data, in the sense that the parameter values were taken from classical literature rather than being estimated from the experimental data - the value of 'p' being obtained from classical critical ratio research. To obtain this calculated average, each of the 10 subjects' threshold was calculated from the noise level measured at the ear during the course of the experiment. The noise was in fact measured twice, once at the start of the experiment and once at the finish, and measured at both ears. Figure 11 shows the calculated threshold for one subject indicating the variability of noise levels at each ear due predominantly to helmet fit. Figure 12 shows one more consistent set of threshold curves. It must be strongly emphasised, however, that these differences are <u>NOT</u> solely due to error variance but are a correct indication of the variance found not only in experiments of this type but during in-flight measurements, with error variance contributing only nominally to the overall variance figure.

From the data an assumption was made that for detection at each discrete frequency, the listener would use the ear which provides the best signal-to-noise ratio. Thus each of the two left and right ear thresholds was averaged to give a mean left and mean right threshold, and the lower of these (which would give the best signal to noise ratio) was used as the threshold for that particular listener in that particular helicopter noise.

The measured data was taken from the audiometry and it is clear from a comparison of the measured and calculated data that whilst the mean values are surprisingly good, the differences in variance are significant, particularly so in Lynx noise at the higher frequencies (> 3 KHz). There are two predominant reasons for this, the first being an experimental factor that is only apparent in Lynx noise and the second being valid across all helicopter noise spectra. The experimental factor concerns the wide dynamic range of SPLs at the ear when measuring in helicopter noise under a flying helmet. In Chinook, for example, the dynamic range may well be over 100 dB, which is difficult to encompass in measuring equipment - although the ear itself has no problem! To reduce this problem the input spectrum was initially fed through an 'A' weighting filter, which reduced the dynamic range, but for the first 5 subjects that remained some problems on dynamic range above 3 KHz and measurements were running into the noise floor. Thus half of the Lynx data above 3 KHz is contaminated and in its final form will not be used in the calculations. The other factor which causes these differences is that the measured and calculated values are obtained using different - but realistic - parameters. The measured threshold is from the noise levels data at the ear and thus takes into account the helmet fit, the individual subject performance during the audiometry task, his particular criteria for deciding what is detectable as well as the individual differences in age, auditory filter width and characteristic and off frequency listening - to list only a few differences. This is then a relatively true measure of detection. On the other hand the calculation is based solely on classical literature and the variability is only due to the sound pressure levels at the ear, which is then processed for the 'standard' human listener with no allowances made for either the variations found in real-life or individual differences.

At the lowest frequencies the predictive values are consistently above the measured data. This indicates that when the dominant masker component is at very low frequency, the subject is listening for the signal in the troughs between the peaks of the masker wave - and this is a factor which will be taken into account in the modified version of the auditory model.

Both of these factors, at the high and low frequency end of the spectrum, can be seen in Fig 13, which shows the correlation between the measured and calculated thresholds and the regression line. All 48 pairs of points are plotted and the correlation is across all three helicopters- since the correlation should be independent of noise spectrum. The correlation coefficient is 0.990 ($p \ll 0.001$) and the equation of the regression line is $y = 1.013\ x + 1.073$ with neither the slope or intercept being significantly different ($p < 0.001$) from the theoretical $y = x$. The standard error of the estimate is calculated at 2.43 dB which gives a 95% confidence limit of 4.76 dB.

The slight variation at the extremes of the data points, at the low and high sound pressure levels are due to the noise floor and the inter-peak listening respectively (ie at high and low frequency). A minor change in the constants for low frequency listening will correct this minor discrepancy in the model.

Individual correlations for such particular helicopter give virtually identical results to the overall calculation with the correlation coefficients for Lynx, Chinook and Sea King being 0.989, 0.989 and 0.996 respectively - all highly significant ($p < 0.001$).

The general conclusion from this data is that the simple ROEX (p) auditory filter model provides an accurate enough model at present to determine the noise masked threshold in helicopters, with an accuracy which is well within the boundaries of individual differences. Minor modifications to the model to suit the low frequency aspects of helicopter use will enhance accuracy of prediction.

Application to Helicopter Operations

One of the practical problems that is apparent from the masking data is that if threshold listening is required at low frequencies, sonar detections for instance, then the levels of signal that must be produced at the ear to provide adequate detection probabilities may be incompatible with both drive levels on the communication system and some aspects of hearing damage risk. To obtain an effectively 100% detection probability, the signal must be a minimum of 15 dB above the masked auditory threshold. For example, listening to a 200 Hz signal in Lynx would require a 95 dB signal to provide a 100% detection probability. Similarly in Sea King. Rather than attempt to provide equipment which will allow these levels to be attained, it is a better solution to reduce cabin noise levels at these low frequencies, or, at least, the noise levels at the ear, which will lower the masked threshold a proportional amount. Whilst this is practically difficult by passive means, bearing in mind the compromises required in flying helmet design - notably mass and volume, both of which are required for noise reduction and not for helmet use - active acoustic attenuation systems are now being flown in practical form which will reduce low frequency noise. The Ministry of Defence and the Southampton University Institute for Sound and Vibration Research (ISVR) have cooperated in a research project to provide an active noise reduction system (ANR) to work in flying helmets. The system has been flown by RAE in a variety of helicopters (Ref 10) with reductions of some 10-15 dB over that obtained by passive means over a range of frequencies. Figs 14, 15 and 16 show results obtained for 3 helicopters covering light to heavy usage with the aircrew using an RAF Mk 4 helmet fitted with ANR. It can be seen that the system reduces noise over the frequency range of approximately 30 Hz to 1000 Hz, being slightly dependent on helmet fit, and providing some 10 dB or more of additional attenuation over the mid-range frequencies (63 Hz to 500 Hz). Active Noise Reduction is expected to provide not only improvements in communications and reductions in hearing damage risk, but also in the improvement of detection rates, and experiments are planned to provide quantitative support to this hypothesis.

Having improved signal to noise ratios at the ear by reduction of noise levels at the ear, the next step is to improve the signal to noise ratios of signals from the helmet telephone transducer. Again this may be carried out by electronic processing of the signal, and a further research contract between MOD, RAE and ISVR has provided an Adaptive Noise Cancelling System (ANC) which reduces the noise levels of an incoming signal without loss of the primary signal - be it either speech, warning or detection/classification signal. Figure 17 gives an indication of the reduction in noise levels possible. The signal is an output from a boom microphone in helicopter noise and shows microphone output levels before and after ANC is applied, with the subsequent reduction in tonal and broad band noise after processing. The system is, as it needs to be, essentially a real-time processing device. An ANC system is currently being built for flight and will be flight-tested in the RAE experimental helicopter fleet.

Thus the combination of Active Noise Reduction, Adaptive Noise Cancelling, the Mk 4 flying helmet with good passive attenuation characteristics and high quality commercial voice operated switches should go a long way to providing a noise environment at the ear which will allow adequate and comfortable communications and a high probability of excellent detection/classification performance by sonics operators - in addition to the reduction of the real problem of hearing damage risk. The parallel research into the production of an auditory masking model allows the prediction of noise levels which must be achieved in the cabin to be accurately assessed and from that the levels of noise reduction which flying helmet technology and electronic processing must attain.

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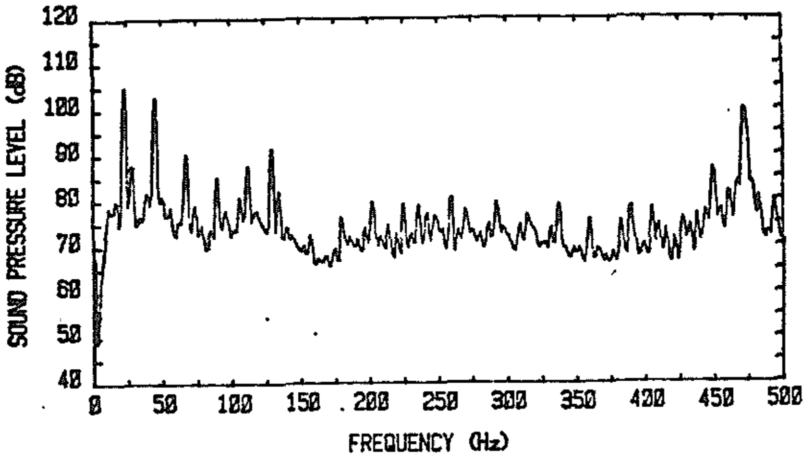


Fig 1 : Lynx cabin noise (1.25 Hz resolution).

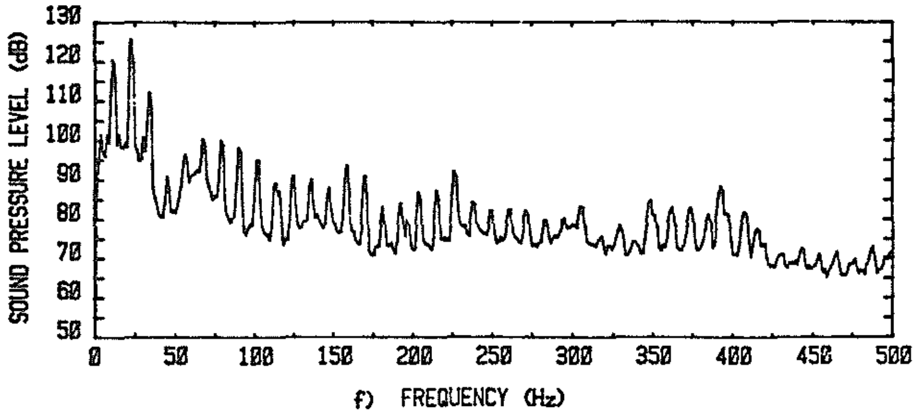


Fig 2 : Chinook cabin noise (1.25 Hz resolution).

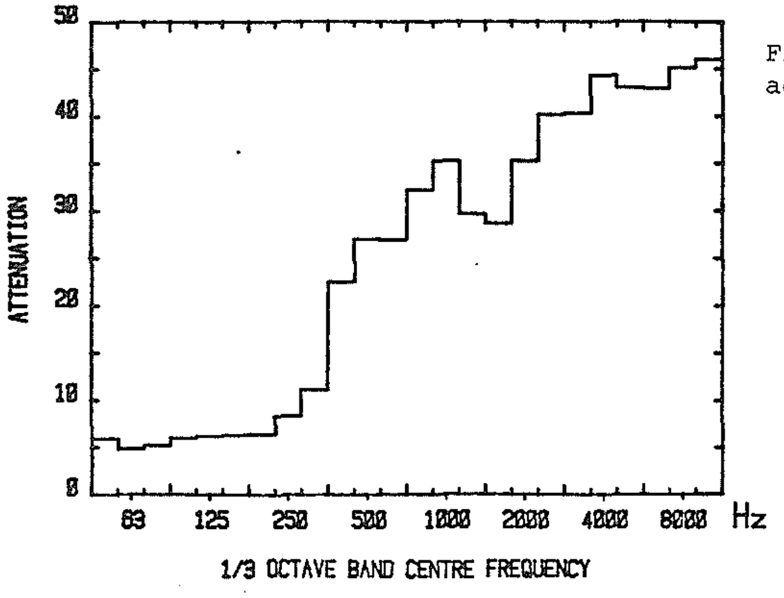
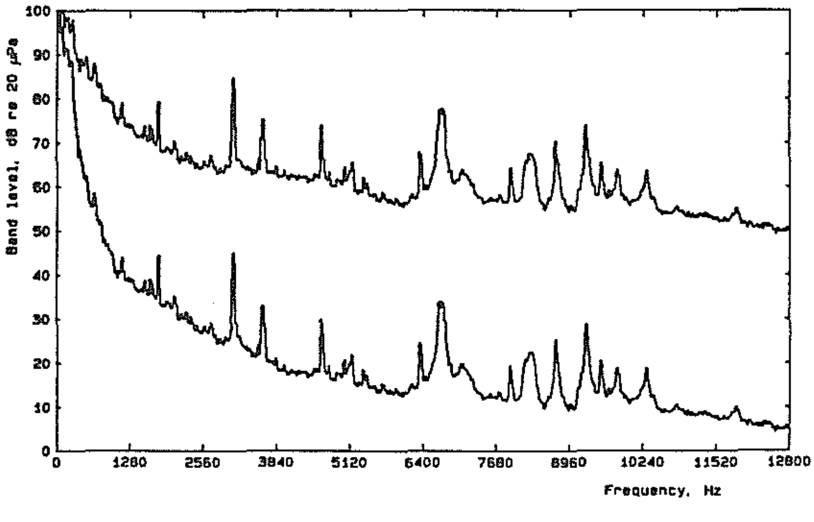


Fig 3(a) : Mk 4 flying helmet acoustic attenuation.



Noise spectra in the cabin and at the ear in a Puma; 16Hz resolution.

Fig 3(b) : Noise levels in cabin and at pilots ear.

Fig 4 : Illustration of masking by a pure tone.

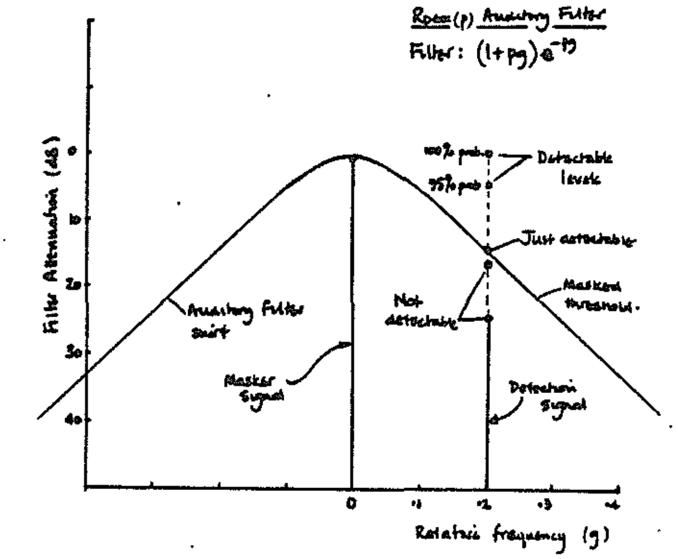
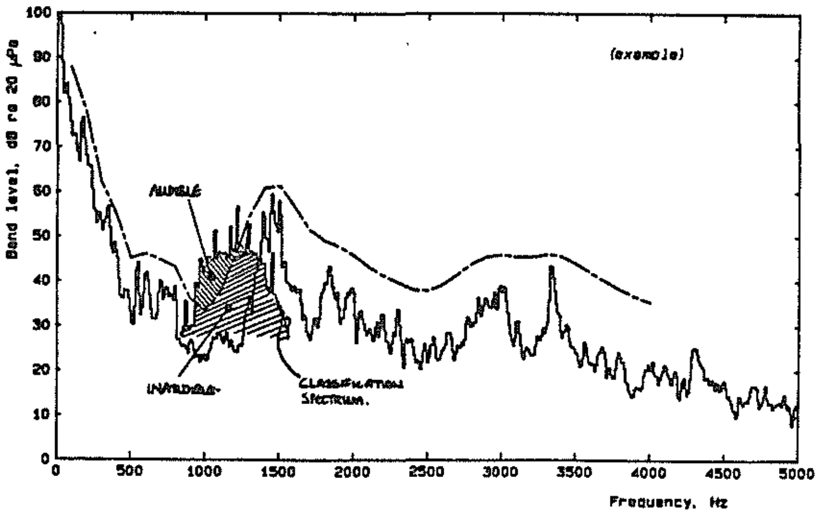
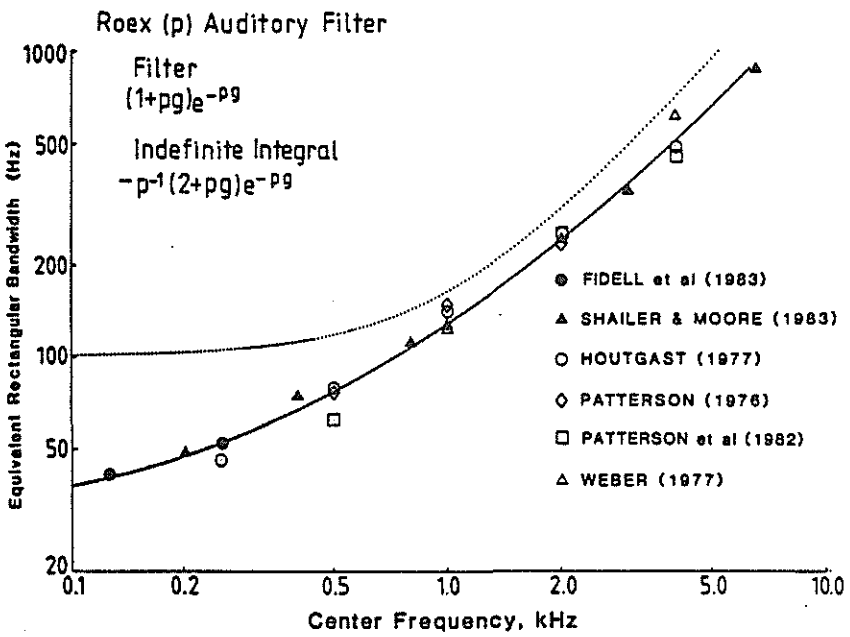


Fig 5 : Masking by helicopter cabin noise of signal signature.



Calculated pure-tone threshold and noise at the ear (10Hz res.) in the Chinook.

Fig 6 : Increase in auditory filter width with frequency.



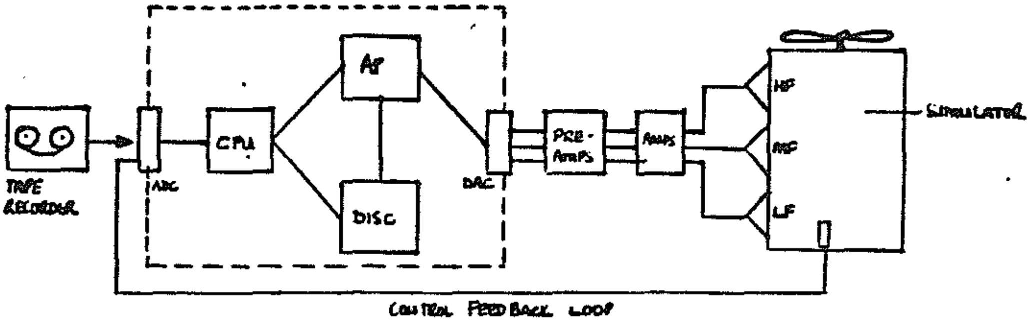


Fig 7(a) : Schematic diagram of helicopter noise simulator.

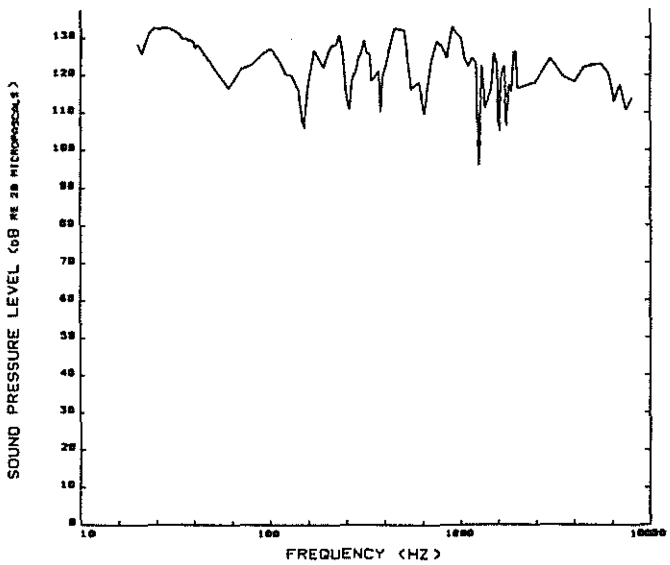
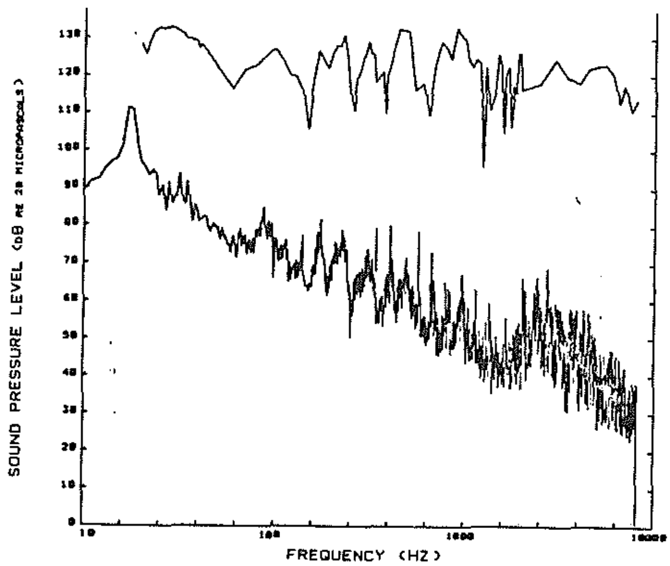


Fig 7(b) : Upper level performance envelope of helicopter noise simulator.

Fig 7(c) : Performance envelope superimposed with Chinook spectrum.



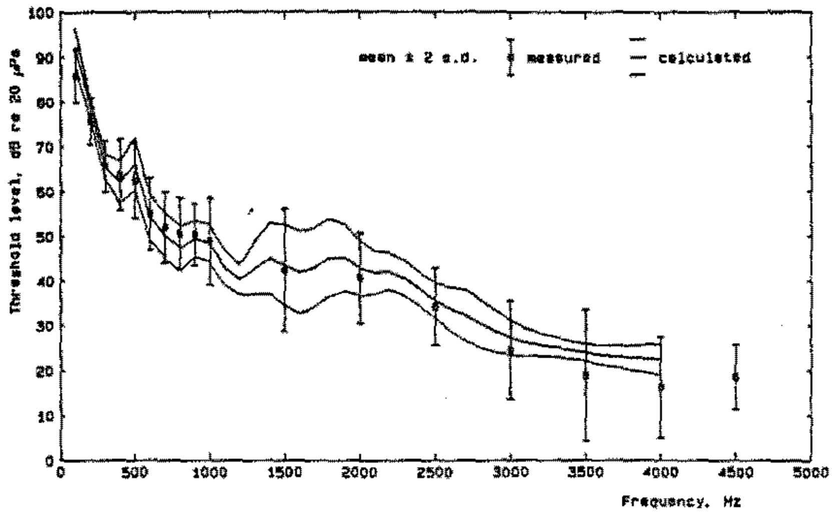


Fig 8 : Measured values compared with calculated mean ± 2 s.d.; Lynx noise.

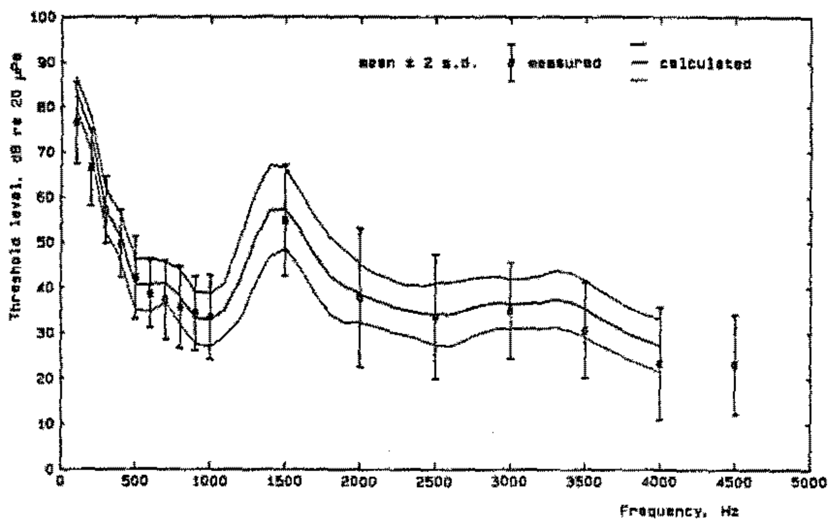


Fig 9 : Measured values compared with calculated mean ± 2 s.d.; Chinook noise.

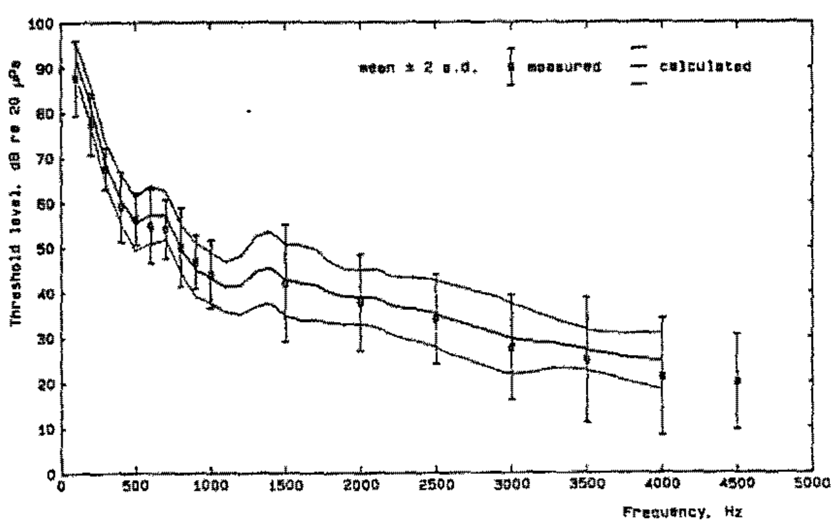


Fig 10 : Measured values compared with calculated mean ± 2 s.d.; Sea King noise.

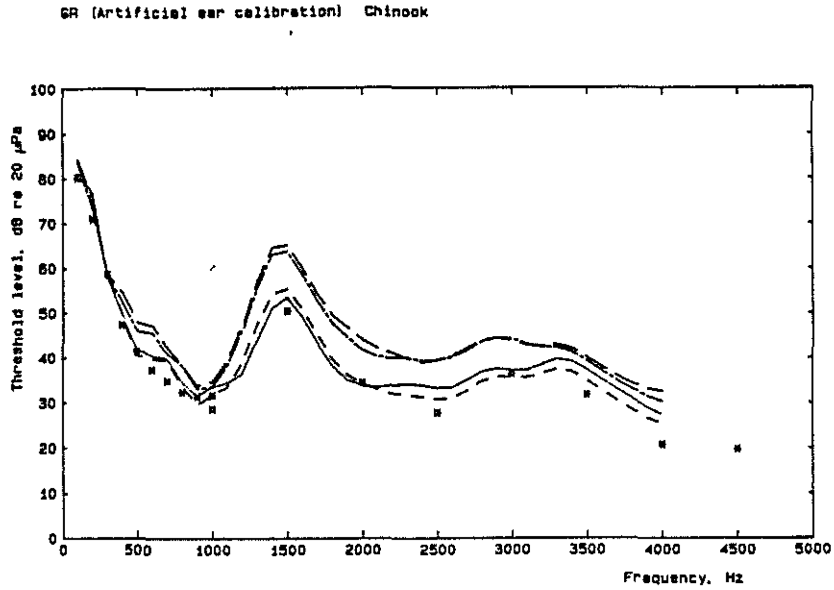


Fig 11 : Examples of the variation of threshold data across ears (single subject).

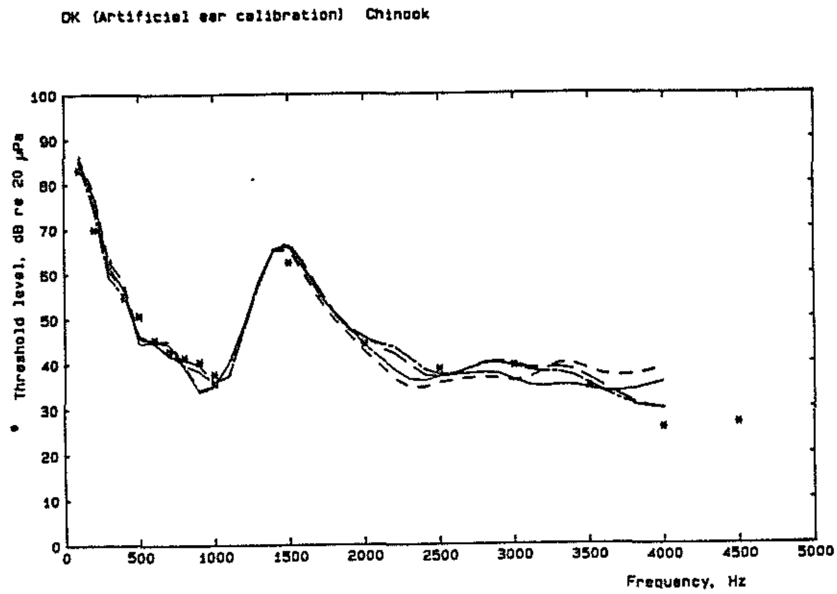


Fig 12 : Examples of the variation of threshold data across ears (single subject).

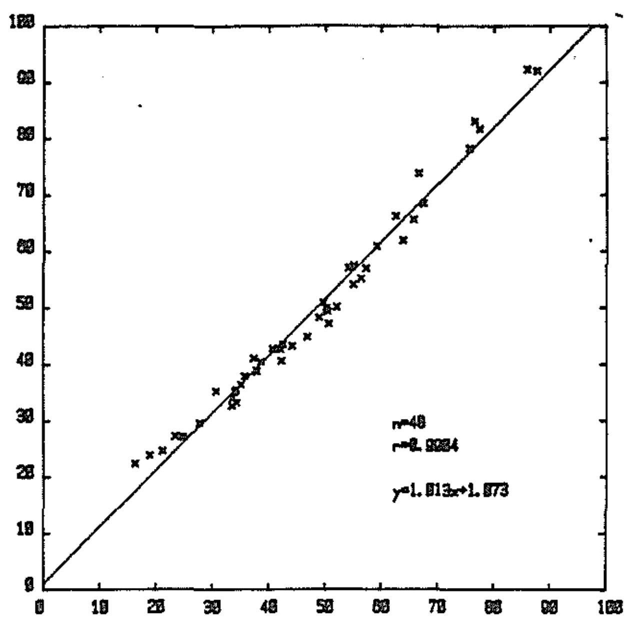
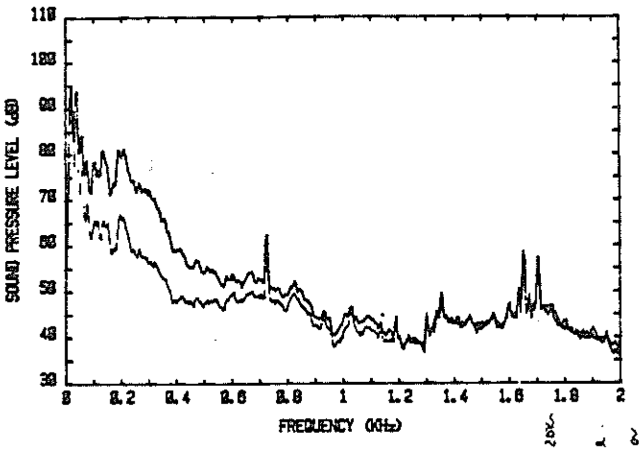


Fig 13 : Correlation between measured and calculated data (from Figs 8 to 10).



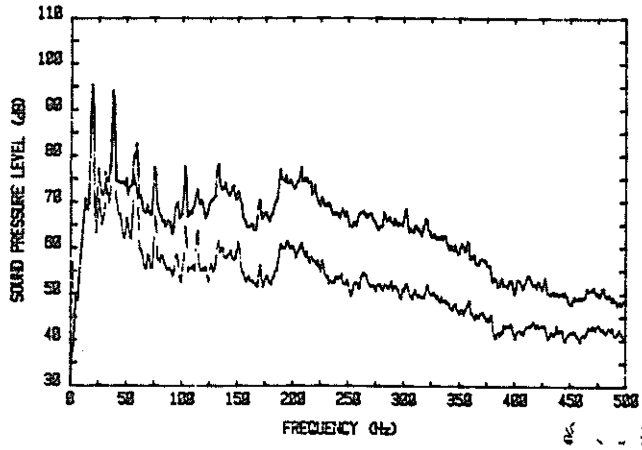
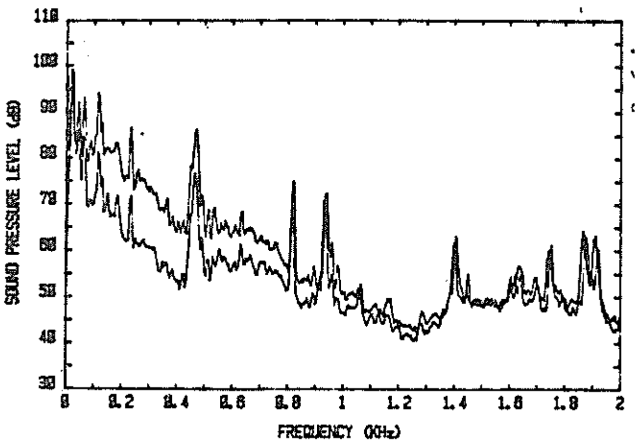


Fig 14 : Active Noise Reduction : Noise at ear; ANR ON/OFF. Gazelle



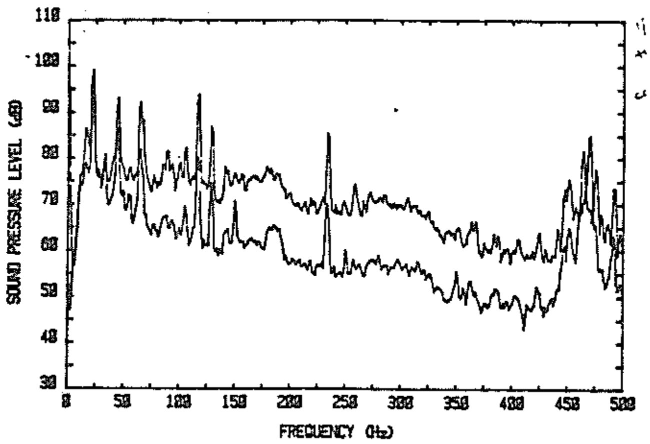
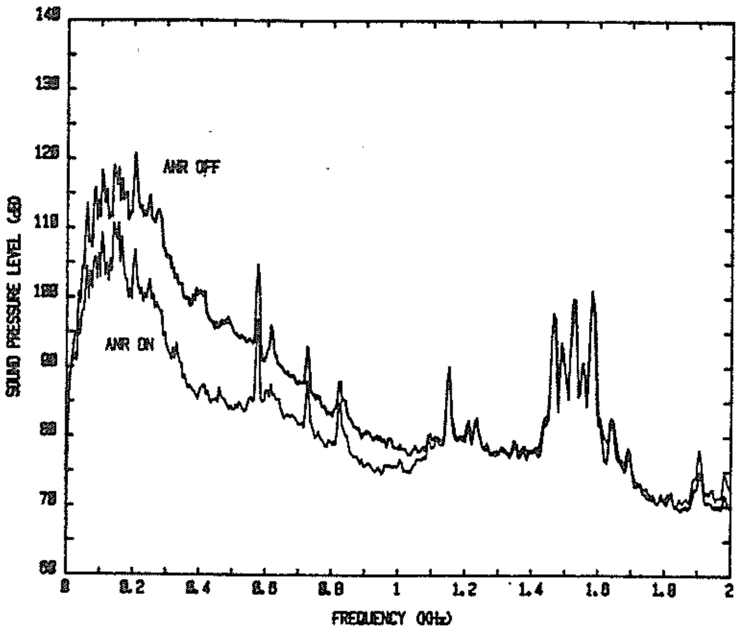


Fig 15 : Active Noise Reduction : Noise at ear; ANR ON/OFF. Lynx



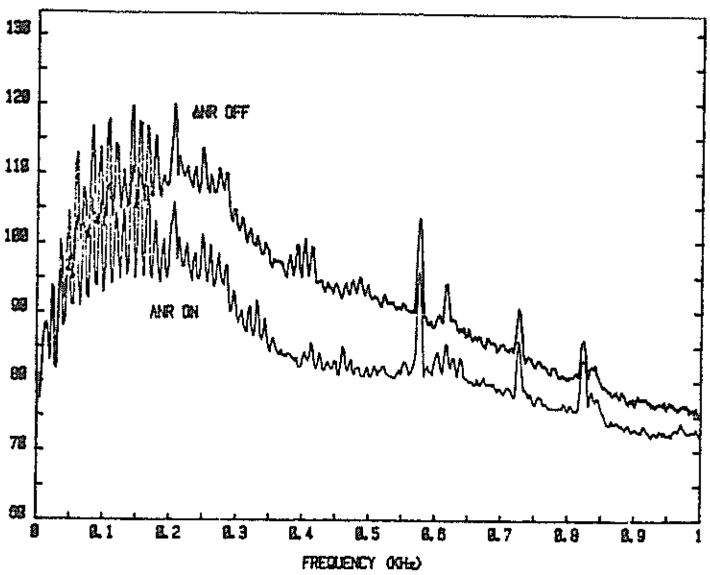
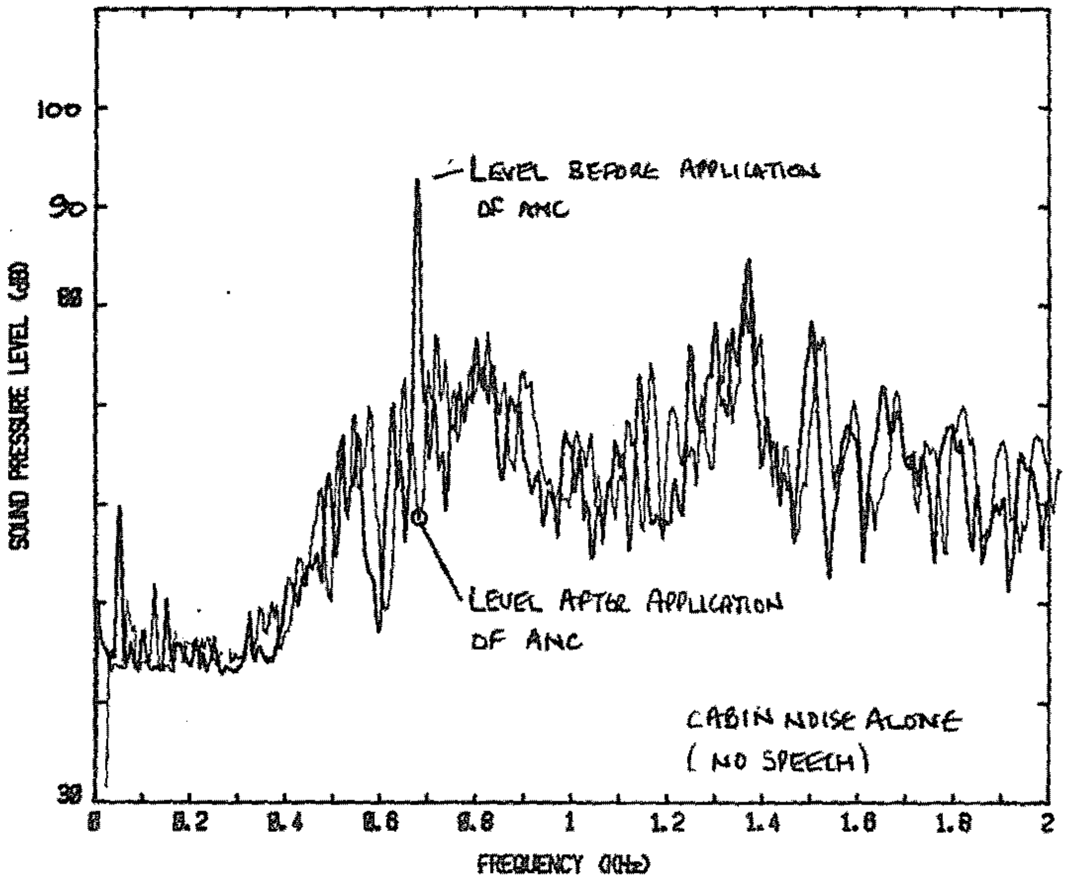


Fig 16 : Active Noise Reduction : Noise at ear; ANR ON/OFF. Chinook



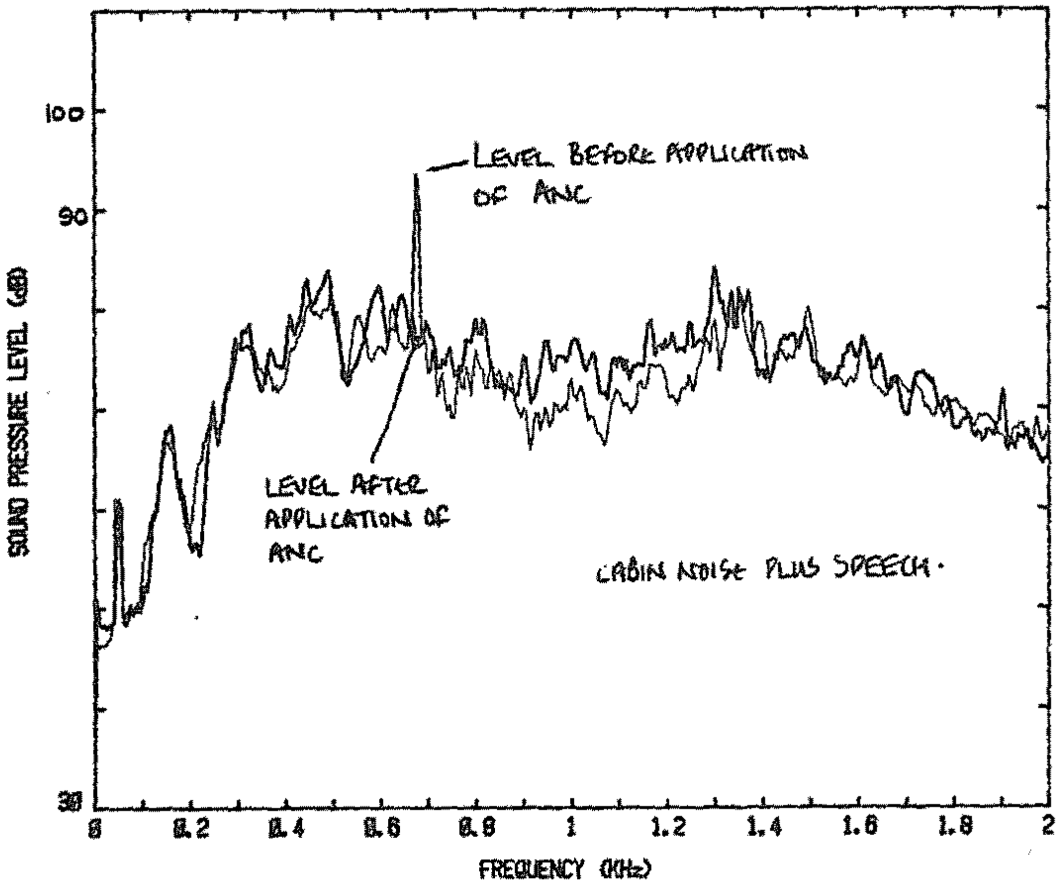


Fig 17 : Use of Adaptive Noise Cancellation in Helicopter Noise (Sea King)