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APPLICATIONS OF HUMAN PERFORMANCE MODELS TO SYSTEM DESIGN

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Applications of Human Performance Models to System Design

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MODELLING OF AUDITORY MASKED THRESHOLDS IN HUMANS

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INTRODUCTION

In order to be able to predict the probability of detection of an acoustic sound in noise, it is necessary to be able to define the masked threshold of that noise along with the level of the sound required to be detected. The phenomenon of obscuring the detection of one sound by another is defined as auditory masking and is one of the more classical problems of the detecting and classifying of signals in noise. Auditory masking is particularly important when threshold listening is involved, that is listening for low level signals in conditions of high noise, and from a military viewpoint it is of great importance when attempting to complete auditory monitoring tasks of sonar signals or electronic warfare returns. Masking, however, is not solely a military problem, but is important wherever a human is required to listen, detect and classify.

The origin of this research grew from the high noise levels in helicopters and the necessity for the human operator to listen for low level sonar returns from helicopter-borne sonar systems. The returns could be active or passive, but relied upon the operator aiding the sonar processing equipment both visually and aurally. As in most systems which use a human operator in the loop, the system should be designed such that human operator and the processing equipment both complement each other and interact such that the combination provides an improved performance over the two constituent parts. For instance, in sonar operations, the human provides a better detector of transient sounds and the classification of those sounds than the processor, whilst the processor provides other benefits - mainly in long term detection of low level sounds in noise - at which the human is less efficient.

Whilst airborne sonar operators are protected from the high levels of noise by a flying helmet, such helmets are unable to prevent some noise reaching the ear, and it is these noise levels which are liable to mask the incoming detection signals. Fig. 1 shows typical cabin noise in an airborne helicopter and clearly shows the low frequency content of the noise spectrum. Generally the helicopter rotor noise is at the lower frequency end of the spectrum, typically 16 Hz to 20 Hz, and at levels of up to 125 dB SPL, whilst gearbox and associated mechanical noise is in the region of 400 Hz to 600 Hz at slightly lower levels (Lucas 1982, 1984). Due to the inability of the flying helmet to attenuate the cabin noise to any great extent at frequencies below 300 Hz or so (Rood 1978), the lower frequency noise levels experienced at the ear are high. Fig. 2 shows a helicopter cabin noise spectrum with the noise at the ear overplotted. Quite clearly high levels of low frequency noise are apparent.

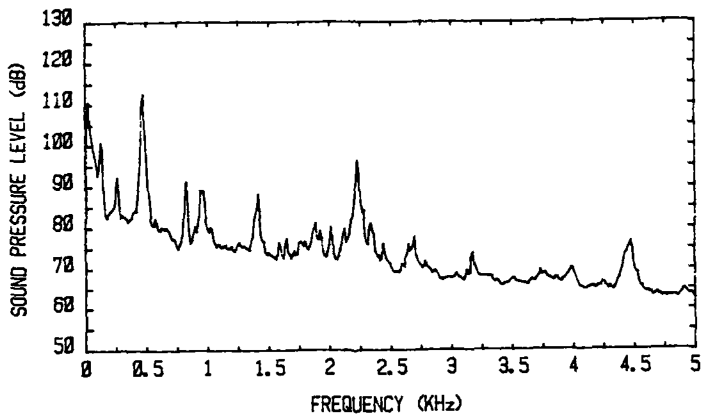


Fig. 1. Helicopter cabin noise spectrum (12.5 Hz resolution)

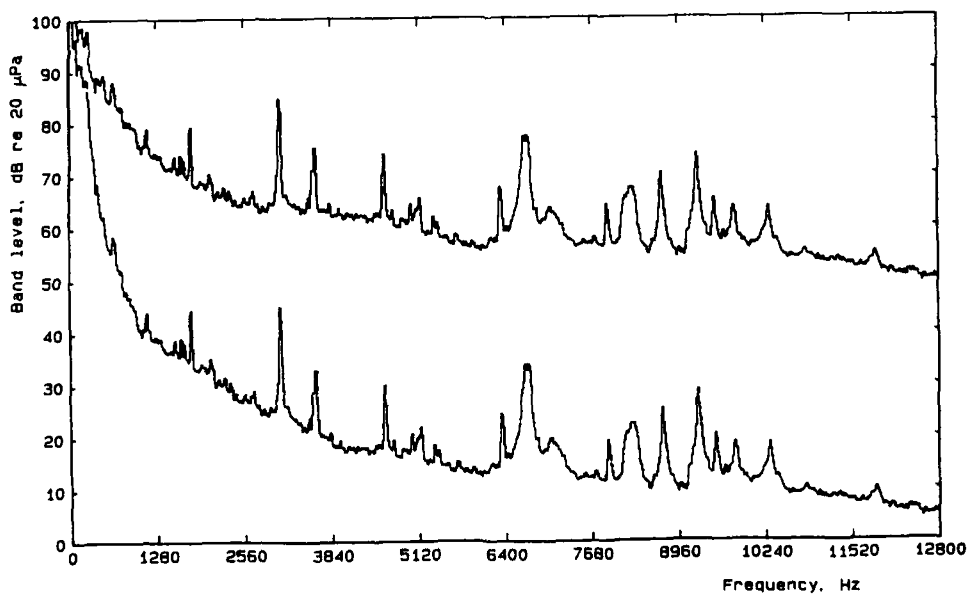


Fig. 2. Helicopter cabin noise spectrum and noise levels at the ear measured under a flying helmet (16 Hz resolution)

Whilst masking is caused by all noise levels, it is the combination of the masking noise and the masked detection signal and their relative positions in the frequency spectrum that are important. Masking is essentially present in three 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 noise at a given frequency masking signals of higher or lower frequencies (upward or downward, respectively).

Thus, in order to optimise the positioning of signal returns in the frequency domain and to be able to transmit signals at levels that are adequate for a 100% detection rate, but no louder; or to predict the auditory detection rate for a given signal strength in noise, a research programme was initiated by MOD(PE) and the Royal Aerospace Establishment, Farnborough to develop a mathematical model of auditory masking. The project was structured to become a joint project between Human Engineering Division of RAE Mission Management Department, MRC/Applied Psychology Unit, Cambridge - whose auditory model was utilised and developed - and Dr Mike Lower of the Institute of Sound and Vibration Research, Southampton University with funding from MOD(PE)DA Radio in London. Experimental work was carried out at all of these locations and this paper describes the validation of the model in the RAE Helicopter Noise Simulator.

THE AUDITORY FILTER MODEL

Patterson and Nimmo-Smith (1980) published data on experiments concerned with the auditory filter shape and the asymmetry of such filter shapes, based on previous research by Patterson (1974, 1976) and Patterson and Henning (1977).

In essence, Patterson argued that since the rise and fall times of the auditory systems are short with respect to the duration of speech sound or signals, and since the relative phase of the spectral components has essentially no effect on masking levels, it is possible to predict auditory thresholds 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 (Patterson 1982). 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

$$P_S = K \int_{-\infty}^{\infty} N(f)\, W(f)\, df \qquad (1)$$

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 characteristics, *W(f).* This auditory filter's characteristics were determined in a series of experiments which showed that the passband of the filter is virtually symmetric when plotted on a linear frequency scale (Patterson 1974, 1976). 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:

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

The equation is an estimate of how the filter width increases with centre frequency

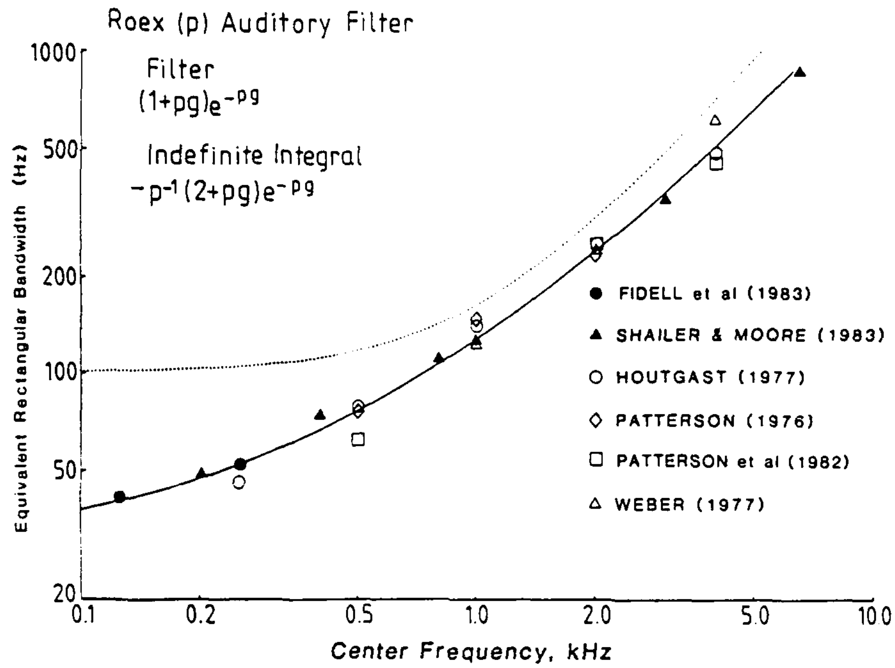


Fig. 3. Increase of ERB filter bandwidth with centre frequency

(Moore and Glasberg 1983) and the curve of the equation is shown in Fig. 3. From these 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 parameter, 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 separat .i 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 as the ROEX (p, r) filter.

This filter shape may now be substituted in the general masking equation, (1), to provide an expression for calculation of thresholds 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

$$P_S = fo \int_0^{0.8} N(g)[(1 - r)(1 + pg)e^{-pg} + r]\, dg$$

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 (1982) notes 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.

MODEL VALIDATION

The experimental work was carried out in the RAE Helicopter Noise Simulator, which accurately reproduces the noise field experienced in real flight, including the temporal and frequency variations. One advantage of such a simulator, utilised fully in this experiment, is the ability to rapidly change the noise spectrum from one helicopter to another. For this particular series of masking experiments, three helicopter noise spectra were chosen, all of which have differing spectral characteristics, the spread of which would adequately test and validate the masking model.

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-time" 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 100 Hz to 4.5 Hz. In addition, more complex "real-time" electronic warfare returns were used although the results are not included in this paper. Noise spectra from the Chinook, Sea King and Lynx helicopters were used.

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 are 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.

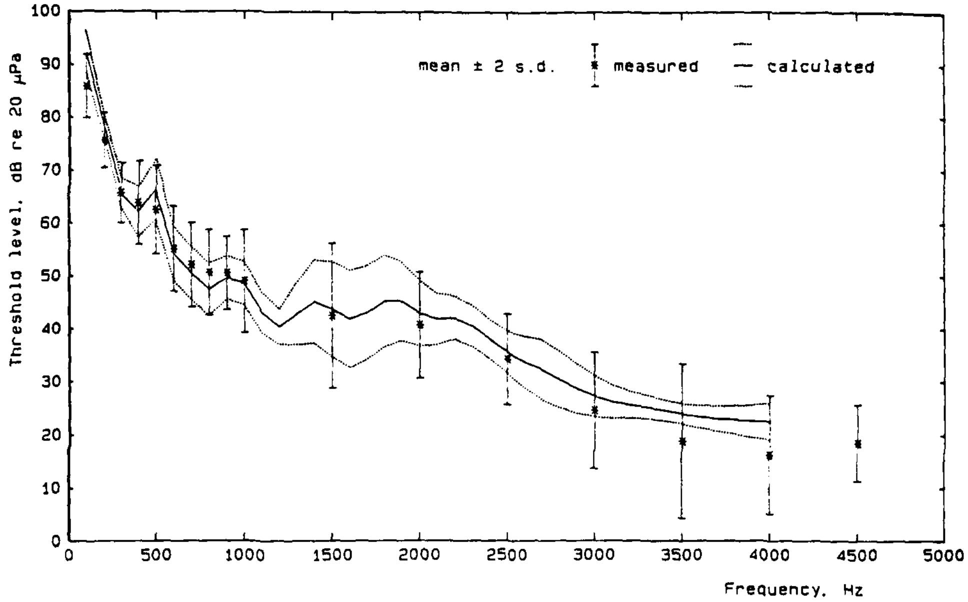
The results of the experiment are shown in Fig. 4 for Lynx cabin noise, Fig. 5 for Chinook noise and Fig. 6 for Sea King noise. Each plot shows the subjectively measured and objectively calculated threshold from the noise level measured at the ear. The solid line through the data is the average of ten predicted threshold functions. In the upper of the two plots the star shows the average of the ten listeners and the corresponding standard deviations, whilst the lower plot shows each of the ten individual points.

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 values 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. Fig. 7 shows the calculated threshold for one subject and two helicopter noise spectra indicating the variability of noise levels at each ear due predominantly to helmet fit. Fig. 8 shows one more consistent set of threshold curves again for two different helicopters. It must be strongly emphasised, however, that these differences are NOT 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 minimally 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.

Fig. 9 and Fig. 10 show plots of the difference between the calculated and measured mean threshold for the Lynx and Chinook helicopters respectively, based on the above assumption. Table 1 summarises the differences between the measured and predicted mean values of auditory threshold for all three helicopter noise spectra. The corresponding individual differences across subjects are shown for Lynx, Chinook and Sea King in Tables 2, 3 and 4 respectively in association with the corresponding standard deviations.

The measured data were 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



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

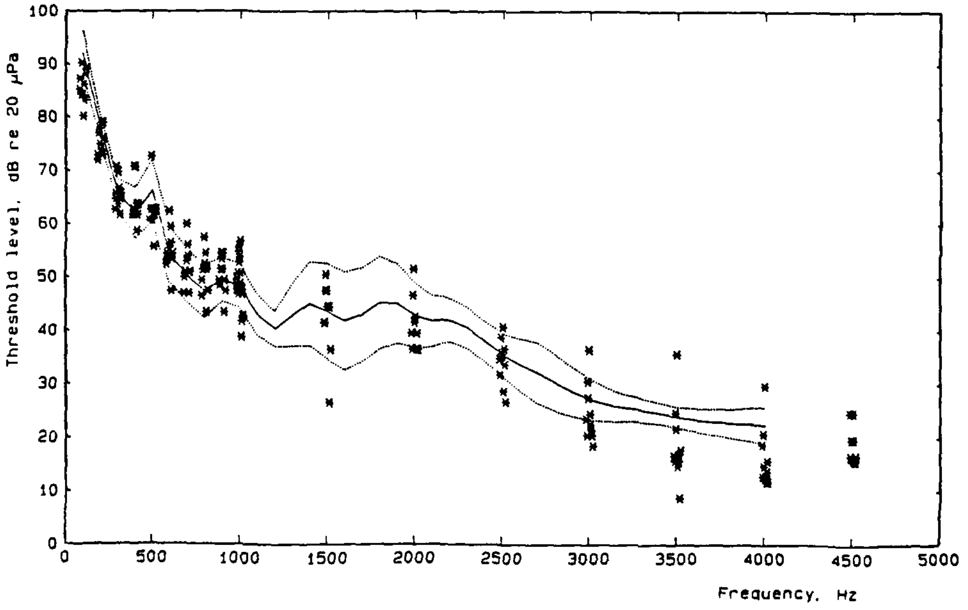
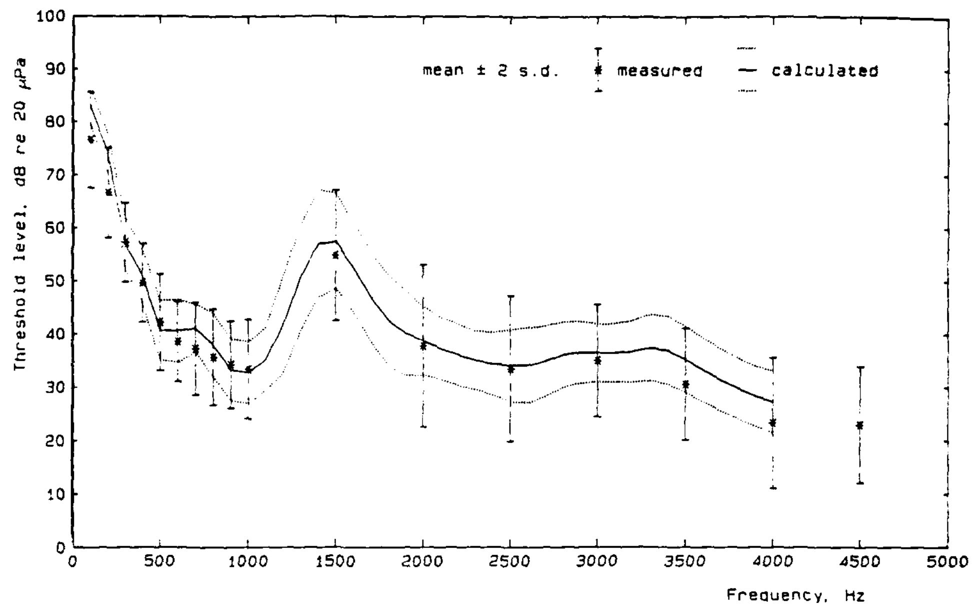


Fig. 4. A comparison of the measured and predicted auditory thresholds showing the mean data (upper figure) and the individual measured data points for 10 subjects (lower figure), both against predicted values: Lynx noise



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

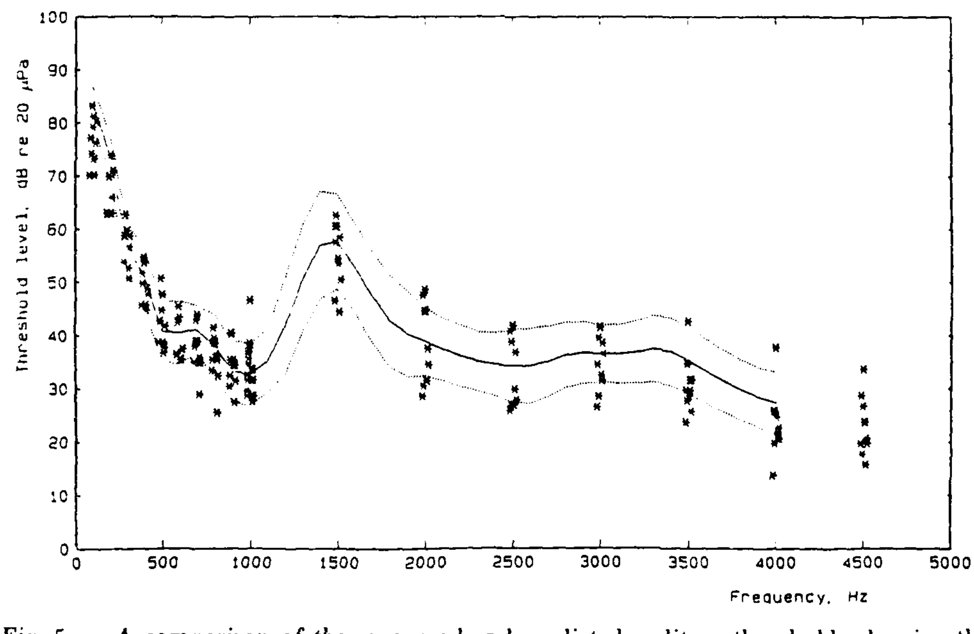
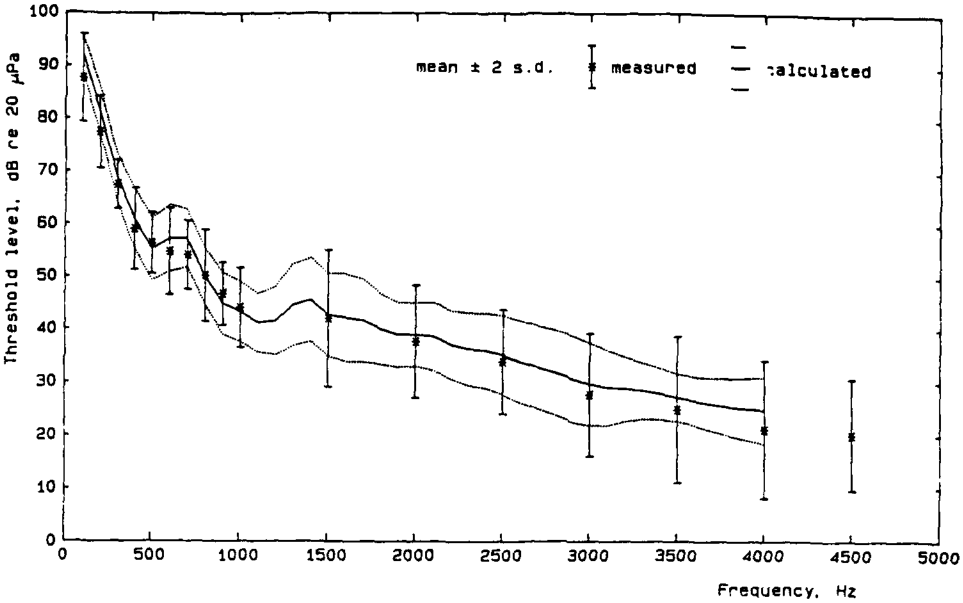


Fig. 5. A comparison of the measured and predicted auditory thresholds showing the mean measured data (upper figure) and the individual measured data points for 10 subjects (lower figure), both against predicted values: Chinook noise



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

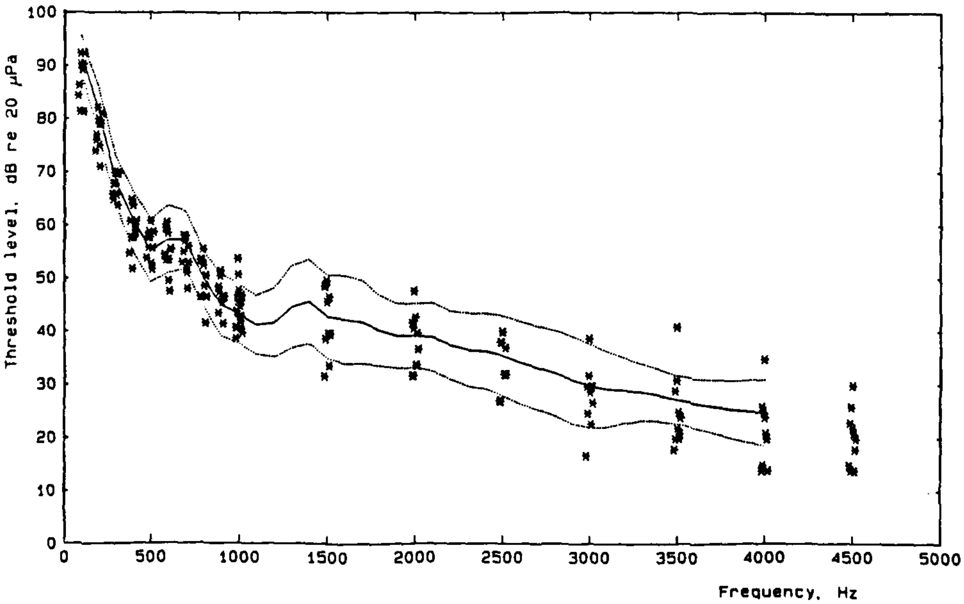
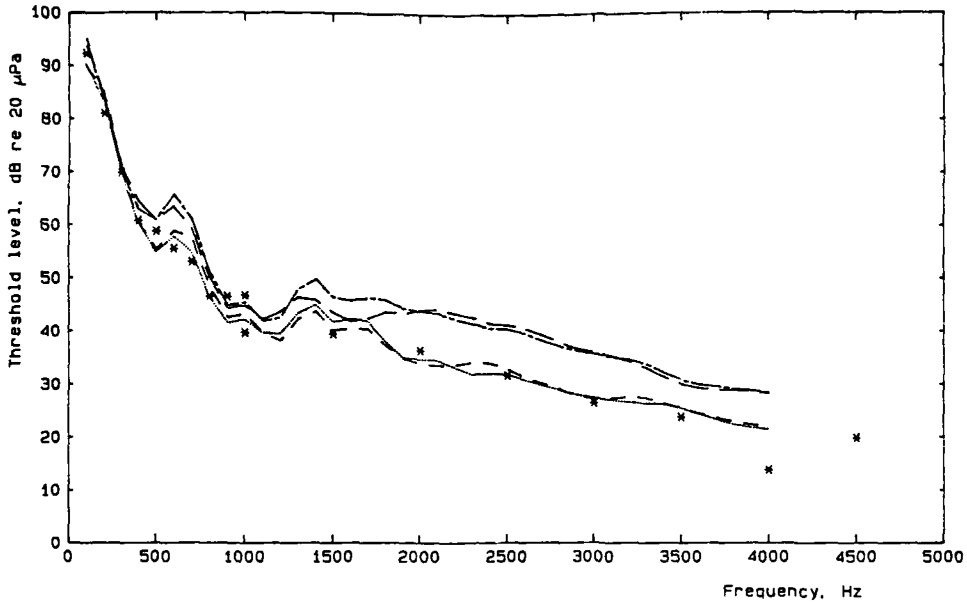


Fig. 6. A comparison of the measured and predicted auditory thresholds showing the mean measured data (upper figure) and the individual measured data points for 10 subjects (lower figure), both against predicted values: Sea King noise

GR (Artificial ear calibration) Sea King noise



GR (Artificial ear calibration) Chinook

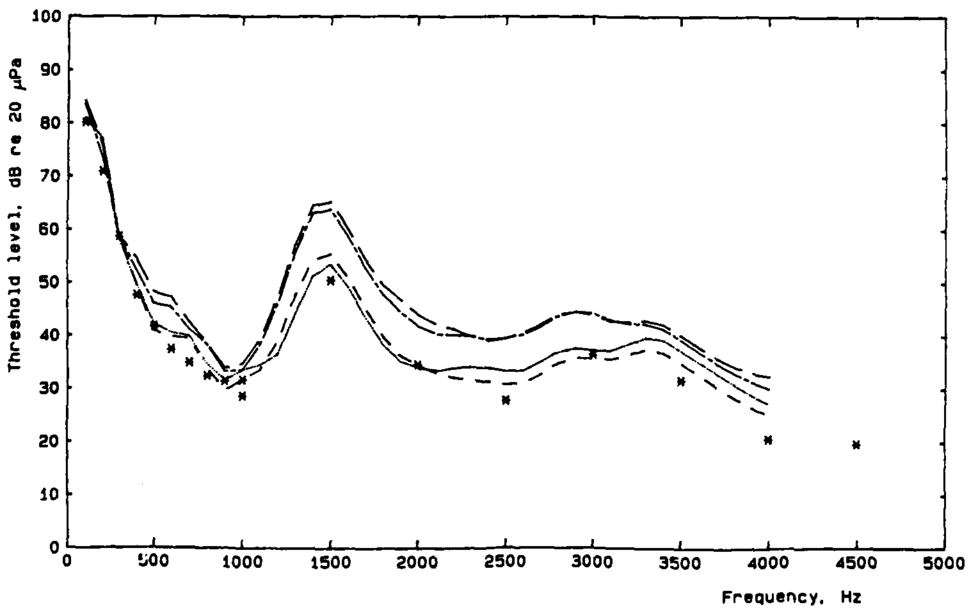
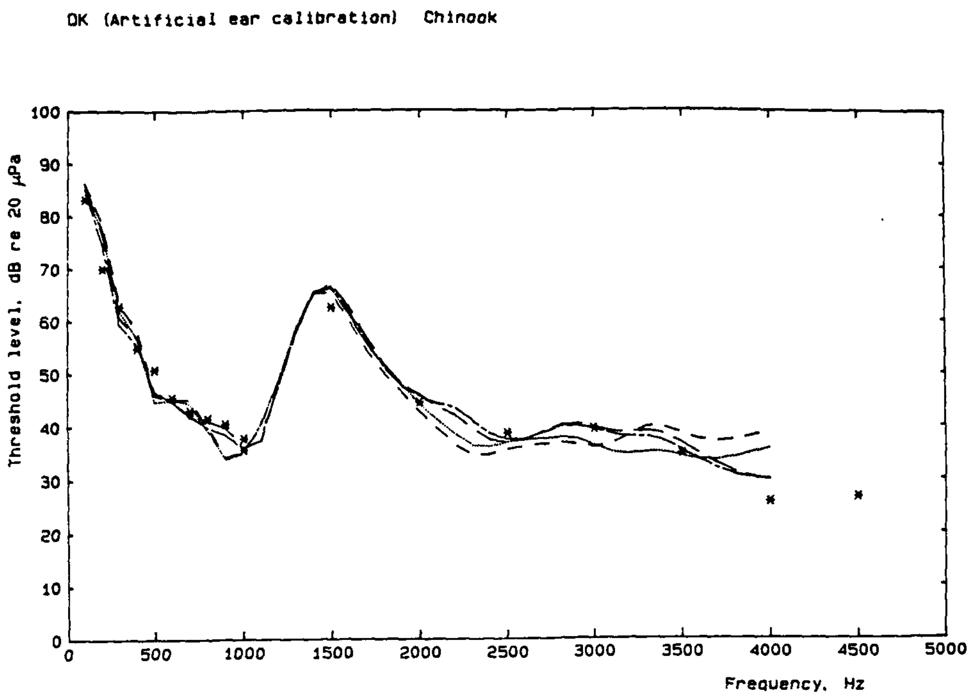


Fig. 7. A comparison of measured and predicted thresholds (left and right ears) for an individual subject. The graphs highlight the differences in helmet fit between left and right ears



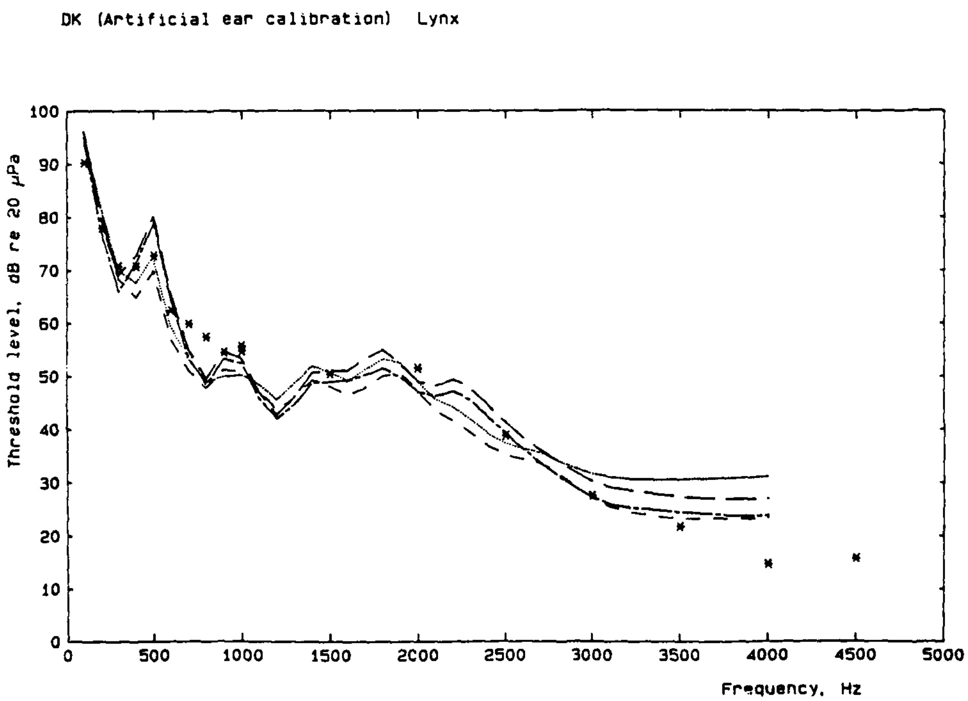


Fig. 8. A comparison of measured and predicted thresholds (left and right ears) for an individual subject with consistent helmet fit for left and right ears (compare with Fig. 7)

Table 1. A comparison of measured and predicted mean thresholds for all three helicopter noise spectra

Freq	Lynx		Chinook		Sea King	
Hz	Meas	Calc	Meas	Calc	Meas	Calc
100	85.85	92.30	76.55	83.14	87.65	92.05
200	75.60	78.33	66.60	73.89	77.40	81.57
300	65.65	65.69	57.25	57.01	59.05	60.92
400	63.75	61.96	49.65	51.05	59.05	60.92
500	62.45	66.26	42.25	40.71	56.35	55.23
600	55.00	54.21	38.60	40.53	54.80	57.34
700	52.00	50.25	37.30	41.17	54.10	57.15
800	50.60	47.31	35.70	38.01	50.20	50.03
900	50.40	49.50	34.30	33.30	46.80	44.95
1000	48.90	48.39	33.45	32.74	44.15	43.32
1500	42.50	43.59	54.90	57.60	42.10	42.74
2000	40.70	42.85	37.90	38.80	37.80	39.12
2500	34.25	35.57	33.65	34.17	34.05	35.25
3000	24.60	27.24	35.10	36.52	27.70	29.65
3500	18.85	23.91	30.65	35.28	24.85	27.09
4000	16.25	22.42	23.35	27.27	21.15	24.66

Table 2. Individual differences between measured and predicted thresholds: Sea King noise

Mean threshold of ear with lower threshold - measured threshold

Frequency	Subjects											
Hz	1	2	3	4	5	6	7	8	9	10	mean	s.d.
1000	2.9	.8	-1.4	-4.4	-8.2	-10.7	-2.6	7.6	2.2	4.4	-.93	5.71
1500	1.5	-.6	5.5	-2.7	-2.0	-3.1	.2	6.5	-5.6	6.6	.64	4.32
2000	-2.2	2.6	4.2	3.3	-3.9	-2.9	-.1	6.5	-.1	5.8	1.32	3.68
2500	.6	6.1	.8	-.7	-3.1	-3.0	-1.8	6.5	1.4	5.1	1.20	3.61
3000	.8	6.4	6.6	-4.0	4.9	-6.6	-1.6	2.0	3.5	7.3	1.95	4.75
3500	1.6	7.9	7.1	1.2	5.0	-11.1	-.7	4.7	.7	6.1	2.24	5.53
4000	7.8	5.5	4.2	1.9	.1	-5.0	5.8	7.6	-1.1	8.3	3.51	4.41
4500	thresholds not calculated											
1000	-4.1	3.8	-.4	-4.4	-3.2	-7.7	-1.6	4.6	-.8	6.4	-.73	4.49
900	-4.4	2.7	-1.1	-3.5	-2.2	-7.7	-4.3	.5	-3.3	4.9	-1.85	3.71
800	.9	3.0	5.5	.1	-2.5	-8.9	-1.0	-.8	-4.2	6.3	-.17	4.52
700	3.1	3.6	6.9	2.9	3.3	-3.8	3.2	4.5	-1.1	8.1	3.05	3.45
600	2.8	5.0	6.0	-2.3	6.5	-1.9	1.0	5.5	-2.2	5.1	2.54	3.61
500	-3.8	2.1	1.5	-3.7	-5.1	-2.7	1.6	-1.0	-3.4	3.1	-1.12	2.98
400	-.3	5.7	.4	-1.8	-1.3	9.4	1.2	1.9	-1.3	4.8	1.87	3.65
300	.4	1.3	3.4	-1.4	.6	.6	1.6	.4	1.3	2.8	1.09	1.36
200	3.0	4.8	11.0	1.9	3.3	1.8	1.1	4.2	3.2	7.4	4.17	2.99
100	-2.2	4.8	9.2	2.0	3.0	.4	2.3	9.2	6.7	8.6	4.40	3.95

Mean of 10 subjects. Lynx noise. Calculated threshold is the minimum
of the four (two left, two right) at each frequency, for each subject.

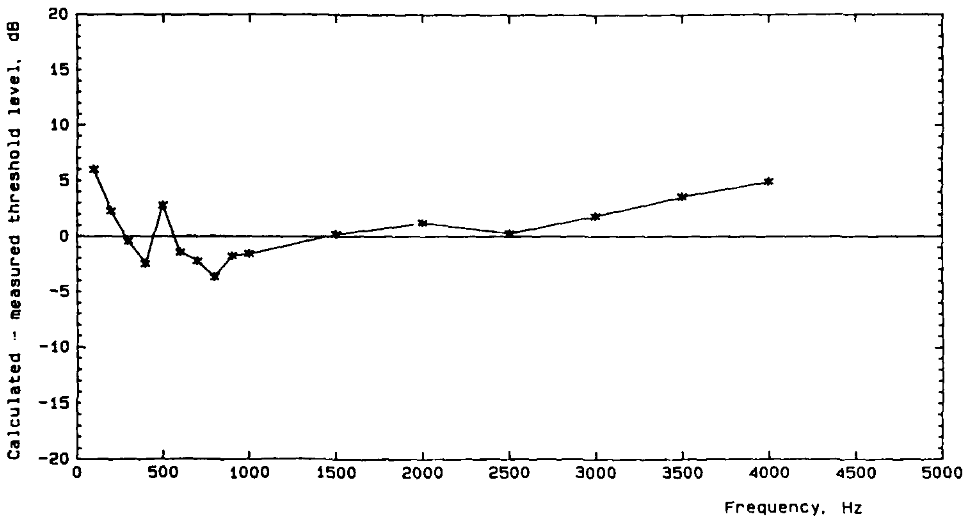


Fig. 9. A summary of the differences between calculated and measured mean auditory thresholds: Lynx noise

Table 3. Individual differences between calculated and measured auditory thresholds: Lynx noise

Mean threshold of ear with lower threshold - measured threshold

Frequency	Subjects											
Hz	1	2	3	4	5	6	7	8	9	10	mean	s.d.
1000	6.2	3.3	8.0	1.2	-7.0	-5.3	-4.2	-1.3	-5.8	-1.8	-.66	5.18
1500	5.0	4.2	14.5	-5.0	.7	-3.3	-1.0	2.0	-4.4	-1.4	1.09	5.80
2000	5.6	6.5	6.0	3.8	-2.8	-.6	-3.5	.8	3.8	1.9	2.15	3.62
2500	5.4	4.6	1.0	4.5	-5.4	-.8	-2.5	2.9	4.0	-.3	1.32	3.56
3000	6.4	9.6	7.7	1.9	2.3	-9.4	1.2	-1.4	5.4	3.1	2.65	5.37
3500	6.9	15.0	9.2	6.1	8.4	-11.9	4.1	-1.0	7.6	6.2	5.05	7.19
4000	12.9	7.2	9.5	10.6	9.4	-9.0	10.8	.8	8.6	1.1	6.18	6.67
4500	thresholds not calculated											
1000	6.2	2.3	5.0	-.8	-4.0	-5.3	-5.2	2.8	-3.8	-.8	-.36	4.22
900	2.8	1.8	5.9	-3.7	-.1	-6.5	-3.8	-.5	-2.8	-2.0	-.91	3.66
800	-2.9	.6	5.8	-8.0	-3.8	-7.6	-9.0	-6.4	-3.0	1.5	-3.29	4.76
700	-1.6	3.0	4.9	-8.5	-3.8	-5.5	-7.6	-.6	-.3	2.5	-1.75	4.56
600	.8	3.0	8.3	-7.8	-4.9	-2.3	-4.4	-.3	-1.2	.9	-.79	4.53
500	6.0	4.9	12.7	-.9	3.2	6.2	-1.5	2.4	2.3	2.8	3.82	4.02
400	-1.0	2.3	4.3	-6.3	-9.0	-.4	-4.5	-2.3	.6	-1.8	-1.80	3.95
300	-.5	2.3	3.3	-3.3	-2.8	2.9	-3.3	.2	-.5	1.8	.03	2.55
200	2.4	1.2	4.0	-1.1	4.3	4.8	.3	2.6	4.8	4.3	2.74	2.06
100	-.3	4.2	10.3	5.2	13.5	6.2	4.2	5.6	7.2	8.5	6.45	3.76

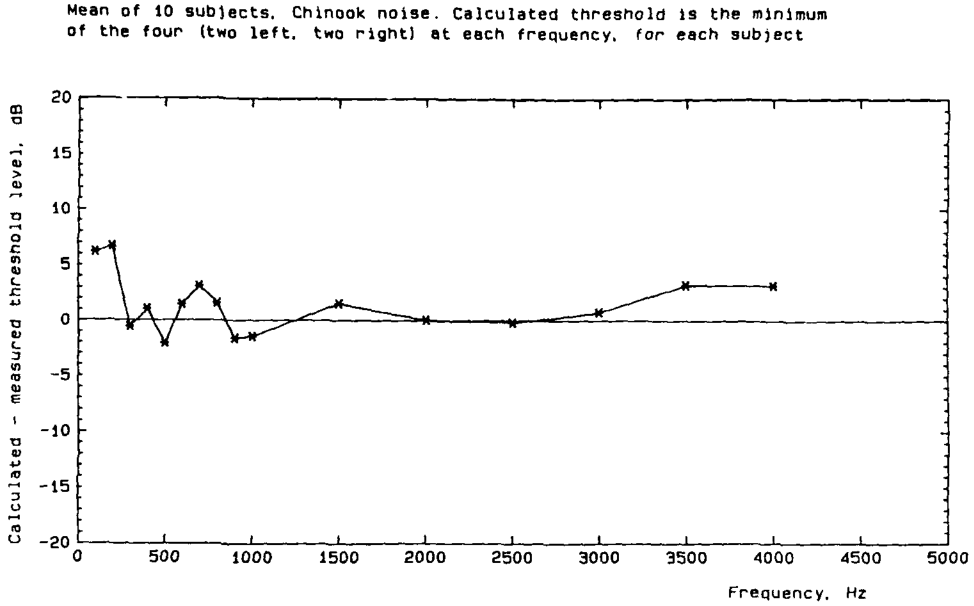


Fig. 10. A summary of the differences between calculated and measured mean auditory thresholds: Chinook noise

Table 4. Individual differences between calculated and measured auditory thresholds: Chinook noise

Mean threshold of ear with lower threshold - measured threshold

Frequency	Subjects											
Hz	1	2	3	4	5	6	7	8	9	10	mean	s.d.
1000	1.0	8.3	1.2	-5.3	-6.5	-16.0	-.3	.5	-1.5	5.6	-1.30	6.80
1500	3.9	5.0	10.4	-2.4	.3	0.0	3.2	-.5	-4.5	11.5	2.69	5.21
2000	-.5	6.1	5.8	3.3	-6.5	-7.1	-1.0	8.4	-9.5	10.0	.90	6.91
2500	4.1	3.5	2.6	2.4	-5.0	-5.5	-2.3	4.8	-4.9	5.5	.53	4.45
3000	-.1	3.8	6.5	.7	-5.5	-4.0	-3.4	7.3	2.9	5.9	1.42	4.61
3500	4.3	16.8	3.1	2.2	3.5	-4.8	1.3	6.4	5.0	8.6	4.63	5.56
4000	5.5	9.1	3.3	6.1	.1	-5.8	4.2	5.9	.9	10.1	3.94	4.66
4500	thresholds not calculated											
1000	4.0	2.3	2.2	-3.3	-2.4	-8.0	-2.3	2.5	-.5	4.6	-.10	3.96
900	-.9	3.4	1.2	-4.5	-.7	-7.5	-6.5	1.1	-.7	5.3	-1.00	4.13
800	1.7	6.6	10.0	-1.2	2.9	-2.4	-2.0	2.8	-.5	5.4	2.32	4.06
700	4.6	8.6	11.7	1.9	1.7	-3.6	-1.0	5.2	2.3	7.4	3.86	4.59
600	2.7	5.8	2.9	-1.0	3.7	-3.3	-.8	-.8	3.4	6.9	1.94	3.30
500	-.1	6.1	1.7	-3.5	-6.9	-3.3	-5.3	-2.3	-3.6	2.1	-1.54	3.92
400	2.0	5.9	4.7	1.5	-2.5	-2.5	1.3	1.9	-1.7	3.7	1.41	2.91
300	-.3	3.0	5.2	-.5	-2.1	-2.7	-2.7	-1.3	-4.0	3.1	-.23	3.00
200	3.8	10.1	10.1	7.0	.1	4.0	6.0	12.2	8.8	11.1	7.29	3.86
100	.7	9.3	9.9	9.7	2.5	2.5	2.1	8.7	6.6	14.2	6.60	4.45

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 there remained some problems of dynamic range above 3 kHz and measurements were running into the noise floor. Thus half of the Lynx data above 3 kHz are contaminated and in their 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 level 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 modifed version of the auditory model.

Both of these factors, at the high and low frequency end of the spectrum, can be seen in Fig. 11, 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 spec-

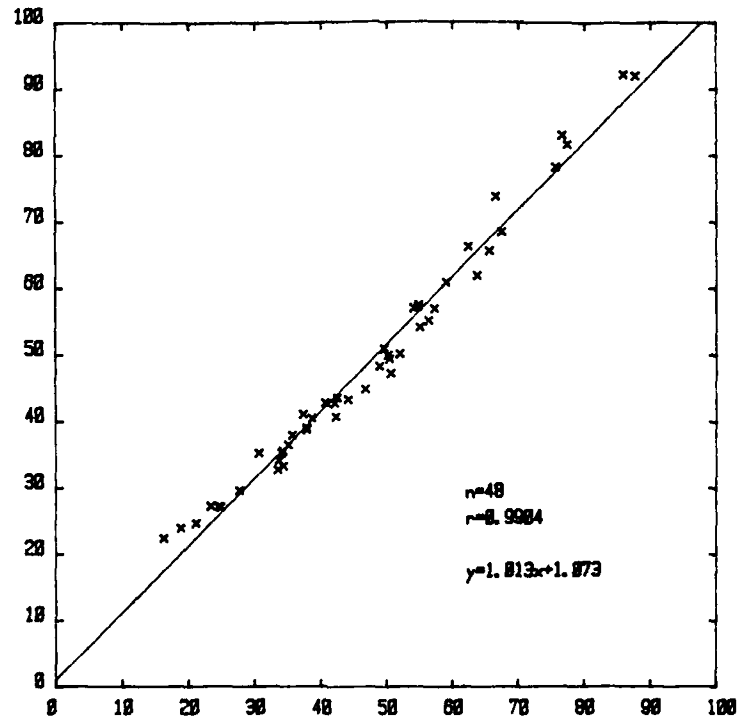


Fig. 11. Correlation of measured and predicted auditory thresholds

trum. The correlation coefficient is 0.990 ($p << 0.001$) and the equation of the regression line is $y = 1.013x + 1.073$ 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 (i.e., 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 each 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 these 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. Calculations involving more complex models indicated that, at present, no advantages are gained by using such models.

APPLICATIONS OF THE MODEL

Whilst the validation of the model has been carried out in helicopter noise levels, which provide a stringent test due to the high-level discrete frequency components present, the model will be valid for all other types of noise spectrum. Also the model is general purpose in that it may be used to predict the detectability of any type of sound (auditory warnings, auditory cues, etc.) in any noise. Currently the same scientific team are providing a set of auditory warning signals for helicopter use that are designed using the masking model, to be clearly detectable without being at such an acoustic level that startle may occur and are so aversive that the first action is to seek the cancel or mute button. Fig. 12 and Fig. 13 show such a procedure where the masked threshold is predicted, the 100% detection line drawn, a + 10 dB band added to this detection line to allow for the variations in detection levels (due to variations in cabin noise, helmet fit, individual variability, etc.) and the spectral characteristics of the auditory warning fitted to the aircraft spectra taking into account the limitations of the communications system through which the signals must be transmitted - including the headset or flying helmet.

A further current practical use is shown in Fig. 14 where the masking thresholds are plotted for a number of helicopters in order to be able to construct a single set of auditory warnings that may be used reliably across different helicopter types. In these cases it is important that the same auditory warning and its associated meaning sound subjectively the same to the aircrew in different types of helicopter with their different noise spectra. For instance, a fire warning must sound the same in all types of helicopter, irrespective of the many differences in noise spectrum.

The general conclusion from the experiments is that the auditory filter model provides a design accurate enough to be able to determine the noise masked threshold for aircrew in helicopter operations and may be used for noise fields of different spectral characteristics. A current limitation, although not yet critical in these cases, is that the model cannot yet run in real time. This would allow signal levels to be continually optimised as noise fields change, during manoeuvring flight for instance. This problem is being addressed by the same team in looking at, and producing, an auditory filter bank model which will allow not only real-time masking curves to be produced, but will allow the outputs from the cochlea and higher levels of processing to be determined and used in various models of pitch extraction, pulse streams of auditory nerve firing, etc.

Such models, as with most models of human performance, are often critical to further understanding of not only human systems themselves, but of numerous interactions between the human and the relevant machine interface.

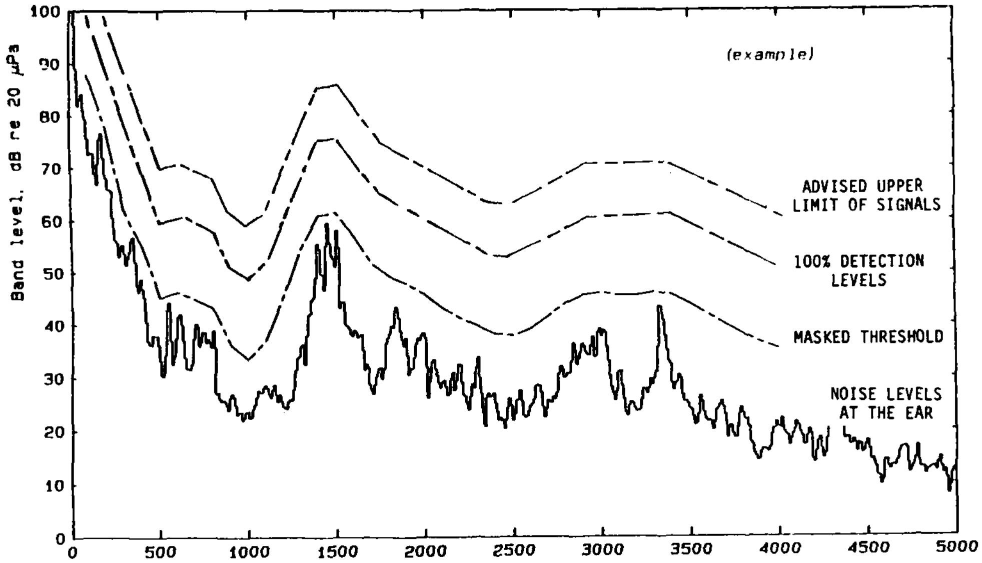


Fig. 12. An example of the use of the masked threshold prediction in setting 100% detection levels for warning signals

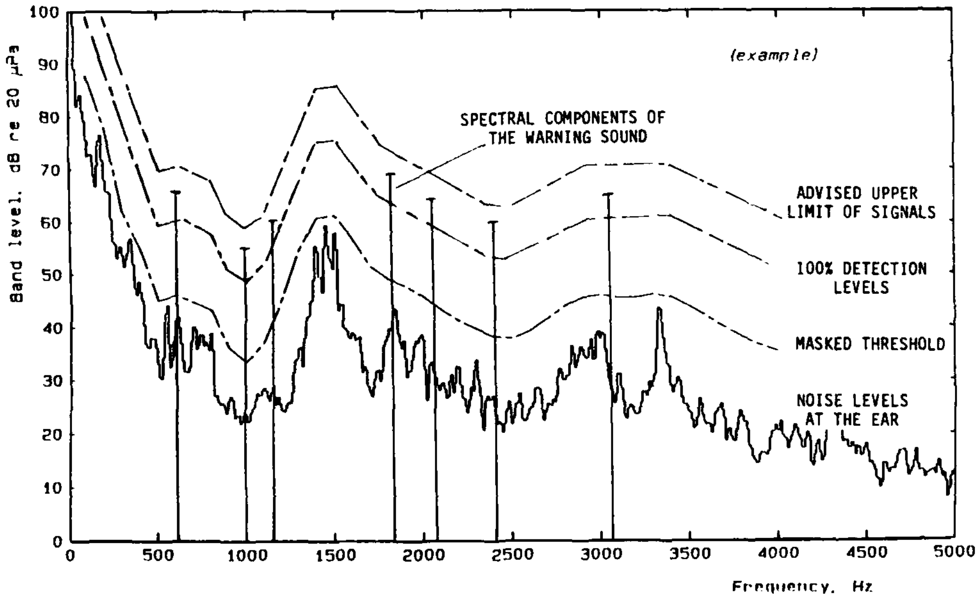


Fig. 13. Spectral content and levels of a warning sound set against 100% detection levels

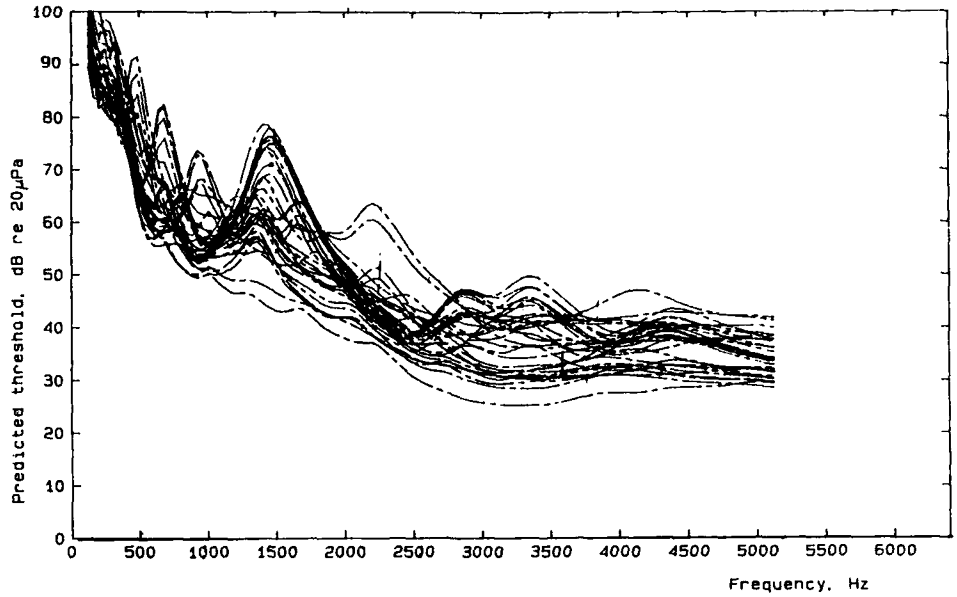


Fig. 14. Masked auditory thresholds of a number of helicopter noise spectra

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