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ACOUSTIC FEATURES IN VEHICLE INTERIOR NOISE QUALITY

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1. INTRODUCTION

It has long been recognised that simple physical measures, such as A-weighted sound level, provide only a relatively poor correlation with subjective response to vehicle interior noise. In addition, simple measures do not provide sufficient information about the character of the sound to determine the most effective means of noise control. On the other hand, the human listener generally concentrates on an evaluation of the separate sources contributing to the total sound, and might well find certain low level components much more annoying than other components which dominate the physical spectrum.

This propensity of the human listener has been recognised in the acoustic feature approach to sound quality assessment [1], where the main emphasis is on assessing the relative significance of individual components or features within the overall sound rather than on the overall sound per se. This paper describes an application of the acoustic feature approach to the assessment of helicopter interior sound quality, where the Weighted Sensation Level Function (WSLF) is shown to give much higher correlations with subjective response than conventional measures.

2. OVERALL APPROACH

The main function of subjective sound quality assessment is to determine priorities for future noise control action. The most direct method of achieving this objective is to test the effect of alternative engineering modifications by carrying out listening tests, and comparing the results against physical measurements of the sound. Such listening tests can be carried out; with real sounds in the vehicle concerned; with artificially manipulated recordings of real sounds; and with completely synthesised simulations of the real sounds. All three methods have a role, but the complete synthesis method was adopted for this work because it offers the maximum degree of both flexibility and experimental control. On the other hand, there are always limits to the representativeness of any particular simulation as compared to the real thing and these limits must be kept in mind.

3. METHOD

The first step was to construct a realistic simulation of the helicopter interior noise as referenced against recordings made in a real helicopter. Binaural recording techniques are often used in this application, but there are a number of uncertainties regarding; the accuracy of spatial reproduction, with particular reference to head movement effects; frequency response equalisation; and the appropriate transforms to obtain true measures of the in-situ listener head position spectrum. Sound field simulation using loudspeakers is not subject to these uncertainties and was therefore the method of choice. The sound field was presented without directional information as it was based on in-flight recordings made with omni-directional instrument microphones. Such directional information can be considered less relevant at low frequencies in any confined semi-reverberant enclosure such as a small aircraft cabin.

Spatially averaged time varying frequency spectra were obtained from in-flight recordings which were kindly supplied by (Dr) Andy Rossall of Westland Helicopters Ltd. The recordings represent a fully-fitted out example of a medium sized passenger helicopter. The main application of the work was to determine the relative degree of subjective benefit to be obtained by parametric variation in the separate contributions made to the overall sound field from a number of separate generic noise sources on the aircraft. These generic sources (main rotor harmonics, gear box frequencies, and environmental control system sounds) were represented by low, mid, and high frequency groups of appropriately modulated pure tone components, as determined by careful comparison of both short term and long term averaged narrow band frequency spectra against vibration order sheets for the particular aircraft.

Each group of pure tone components was then generated digitally and mixed together in varying proportions to represent both the fully-fitted out reference condition and a number of artificial conditions where each of the modulated tone groups were reproduced at higher and lower relative levels than for the reference condition. These artificial conditions represent more or less effective noise control action applied to each generic source separately.

The main rotor blade passage frequency of 17.5 Hz was reproduced separately using a specially made bandpass tuned loudspeaker system. When presented in isolation, the 17.5 Hz very low frequency tone was not detectable to the ear, but could still be sensed as a very low frequency vibration in different parts of the body, depending on proximity to the loudspeaker. The complete series of ten test conditions (reference - all tone groups at 0 dB - plus each of the modulated tone groups at +5 dB, -5 dB, and - 10 dB relative to the reference) was repeated both with and without the 17.5 Hz very low frequency tone to determine the effect of this component. The reference condition was critically evaluated for subjective realism by Westland flight test engineers and some minor adjustments were made before proceeding further with the listening tests.

The listening tests comprised two sections; the tone group masked threshold tests and the overall sound quality rating tests. The masked threshold tests were carried out to be able to determine the sensation level of each tone group separately for each of the test conditions. Sensation level is the amount (in decibels) by which the actual level of any single feature exceeds its masked threshold level. Listeners were asked to vary the level of each tone group separately against the reference condition (but excluding that particular tone group) using a multi-turn potentiometer to find the approximate masked threshold level, which was then investigated more precisely using an audiometric technique with 2 dB steps.

The sound quality rating tests used relative 'noisiness' and 'acceptability' questionnaire items. 'Noisiness' was defined as being an intrinsic property of the sound (as perceived by the listener) and 'acceptability' was defined in terms of the context in which the sound was heard (again, as in the personal opinion of the listener). All test conditions were presented according to a balanced experimental design based on Latin Squares to control for order effects.

There were 10 male and 10 female listeners between the ages of 20 and 35 years. All listeners were confirmed as possessing better than 20 dB hearing levels (normal hearing) by a screening audiometric test before taking part in the listening tests.

4. RESULTS

The mean noisiness and acceptability ratings for each test condition were compared against the corresponding ratings for the reference conditions with and without the 17.5 Hz very low frequency tone separately. The effect of increasing the level of the low and mid frequency tone groups by 5 dB was statistically significant in each case, but the effect of reducing the level of the same tone groups by - 5 dB and -10 dB was statistically significant in some cases but not in others. The effect of changing the level of the high frequency tone group was only statistically significant for the + 5 dB acceptability rating with 17.5 Hz present and was not statistically significant for any other test condition.

Figure 1 below illustrates the effect of changing the relative level of the low frequency tones above and below the reference condition. Similar patterns of results were observed for the other test conditions, although not all differences were statistically significant as discussed above.

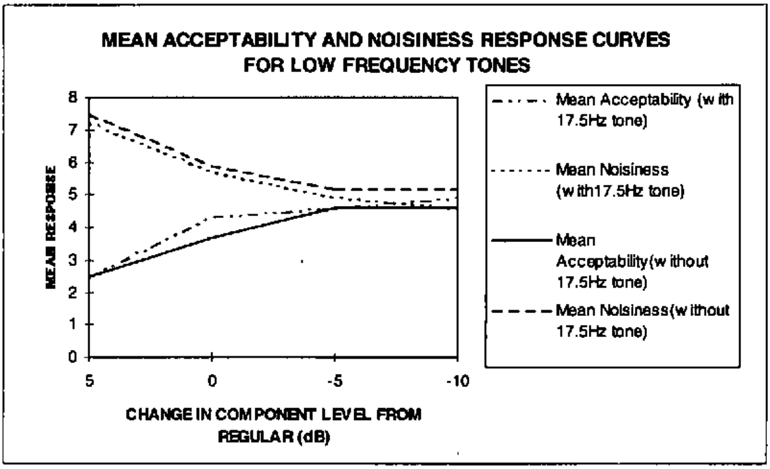

Figure 1.0 Test results for one set of tones, similar results were found for MF and HF tones.

The general pattern of results show that acceptability increases as noisiness decreases and vice versa. In addition, further reductions in separate component levels below - 5 dB relative to the reference condition have no effect on the ratings because the separate component is then generally below its masked threshold level (negative sensation level). An interesting result was that the acceptability ratings increased and the noisiness ratings reduced when the 17.5 Hz very low frequency tone was introduced, in this case leading to slightly higher C and significantly higher Lin weighted overall sound levels.

5. DISCUSSION

The first step of the data analysis was to compare the different correlations obtained between the mean subjective ratings for acceptability and noisiness and the different overall physical measures in common use. Each physical measure was determined from 1/3rd octave band frequency spectra as measured at the listener's head position with the listener absent. The resulting correlation matrix is given at Table 1 below;

Table 1

Correlation Matrix									
	Acceptability	Noisiness	dBA	dBB	dBC	dBD	dBLin	Zwicker
Acceptability		-0.9442	-0.4967	-0.8457	-0.8404	-0.648	-0.4968	-0.7893
Noisiness	-0.9442		0.475	0.8402	0.8831	0.6352	0.5747	0.8213

The correlation matrix shows that acceptability and noisiness are quite highly correlated (negatively). dBA gives the weakest correlations with mean subjective ratings and dBC gives the highest correlations. This is presumably because of the significant low frequency content and because the absolute sound levels used in the simulation were quite high. The A-weighting was originally intended for low level sounds and significantly downweights low frequency content. The correlation for dBLin is intermediate between dBC and dBA. Although dBLin is similar to dBC in some respects it would naturally take greater account of the very low frequency 17.5 Hz frequency components when present. Zwicker loudness [2] did not perform as well as dBC, indicating that the significant additional complication involved in calculating this measure would not be justified for this type of sound.

The next step in the analysis was to calculate a value of Weighted Sensation Level Function (WSLF - see above) for each test condition separately. The general pattern of the data indicates that relative acceptability decreases and relative noisiness increases where the sensation level of each component increases separately above the reference condition, but that relative acceptability does not increase as much and relative noisiness does not decrease as much where the sensation level of each component decreases separately below the reference condition. This is presumably due to the effect of the remaining components where any one component reduces, and could be described as a 'worse case' effect, i.e. that the overall noisiness is determined by the noisiest separate component present.

The WSLF models this effect by taking a weighted sum of the amounts by which each component sensation level separately exceeds a defined effective threshold. This means that separate component sensation levels below the effective threshold do not count. The defined effective threshold represents the amount by which the sensation level of a separate component has to exceed zero before it actually becomes significant in terms of noisiness or acceptability, and would normally be in the range of 0 to 10 dB. The weighting multiplier represents the relative importance of each of the separate components to the overall noisiness and acceptability in the particular context being tested.

The effective thresholds and weighting multipliers for each component were adjusted iteratively to obtain the maximum values of correlation coefficient between the WSLF values and the corresponding relative acceptability and noisiness values. This process was carried out manually and the various coefficients are unlikely to have been fully optimised by this technique. However, the overall correlation obtained in this way (0.8938 for acceptability and 0.9599 for noisiness) is significantly higher than for any of the conventional noise metrics investigated (0.8404 for acceptability and dBC and 0.8831 for noisiness and dBC). This suggests that the separate component sensation level approach has considerable potential.

Note that an important implication of these results is that further reductions in the separate contribution made by individual components or features in the overall sound field below the effective sensation level threshold for that component will not give corresponding improvements in perceived sound quality. On the other hand, even small increases above the effective threshold might give significant reductions in perceived sound quality. Neither of these effects is likely to be properly represented by any composite or overall measure which does not take the individual contributions made by each component or feature into account separately.

There is a limitation to the work as currently described, in that there is no objective measure at present in existence which can reliably determine the sensation level of any arbitrarily defined feature in any arbitrarily defined masking noise in the general case. Universal application of the WSLF approach depends on the future development of such measures, to avoid the necessity for the empirical determination of the separate component masked threshold levels as was required for this work.

6. CONCLUSIONS

Statistical analysis of subjective ratings of the relative acceptability and noisiness of a range of simulated helicopter interior sound fields showed that the Weighted Sensation Level Function as based on the previously described acoustic feature approach to sound quality assessments gave significantly higher correlations between objective and subjective measures than conventional physical measures such as dBA, dBC or Zwicker phons.

7. REFERENCES

1. **N. D. Porter, I. H. Flindell & B. F. Berry** 1993 *An Acoustic Feature Model for the Assessment of Environmental Noise.* Acoustics Bulletin (November)
2. **International Standards Organisation** 1975 ISO 532-1975 (E) *Acoustics - Method for Calculating Loudness Level*