Analysis of Helicopter Sound for the Development of A New Generation Active Headset

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Abstract - Helicopters generate substantial noise levels, especially at low frequency. These noise levels are normally not harmful for the ear. However, the low frequency content masks the speech. Therefore, pilots tend to set the communication system at maximum level so that the sound levels reach severe amplitudes for the ear. These high sound levels are exposing the ear to fatigue and hearing loss. The low speech intelligibility caused by the background noise is also a safety issue since it is most important that all commands can be understood correctly.

The risk of noise induced hearing loss can normally be evaluated by sound pressure level measurements. However, in some cases, the standardized methods for these measurements do not take into account some secondary effects of the frequency distribution of the sound pressure levels. This paper addresses a noise exposure situation where the noise level itself is not harmful for hearing but is still the reason for increased risk for noise induced hearing loss. Military helicopter crews in Sweden have recently shown an increase in noise induced hearing loss.

A combined active passive technique has been chosen as a possible solution. Therefore, the dominant sound sources have to be identified and the number of harmonics for each source determined. An investigation of the coupling between the structure borne sound and the air borne sound was also performed. This analysis is the basis for the development of a new generation active headset, and is presented in this paper.

1. INTRODUCTION
Noise-induced hearing loss (NIHL) is caused by exposure of high sound pressure levels (SPLs). The risk of NIHL from high SPLs is dependent of the frequency distribution of SPL. Internationally, the standardized A-weighted function is used to express the integrated SPLs in the frequency range of hearing. In most parts of the world 85 dBA is an accepted maximum equivalent sound level for 8 hours, 5 days a week. If using sound energy to express the accepted levels for different times of exposure, 3 dB is used as the dividing factor; in other words 85dB - 8h, 88dB - 4h, 100dB - 15min.

Low-frequency noise is known to have an effective masking effect on frequencies above the masking noise. When subject s are exposed to noise with dominant frequency distribution just below or within the lower frequency-range for speech, the speech recognition and intelligibility is disturbed. There are several reasons for this. One is the relative bandwidth of the critical band (a band-pass filter in the inner ear). Another is the movements of the basilar membrane. The width of the critical band at frequencies below 400 Hz is approximately 100 Hz compared to the critical bandwidth at 1 kHz, about 160 Hz; in other words, a masking tone at low frequencies will have a masking effect of the dominant part of that frequency range while a masking tone at higher frequencies will have a relatively lower masking effect. The relative displacement of the basilar membrane is known as the excitation pattern of the membrane because of the entire membrane response to a single sound. When the ear is exposed to a low frequency sound the membrane response is largest at the apical part of the cochlea and when exposed to a high frequency sound the maximum response of the membrane occurs more basally. However, a low frequency sound affects a large part of the basilar membrane, i.e. higher frequencies [11][12].
The air force uses a helicopter, the AS332 “Super Puma,” MKII (HKP10). This helicopter generates substantial noise levels, especially at low frequency. When this was discovered in the fall 1995, a project group was formed to develop a new generation of active headsets, and to investigate the psychological effects. The partners in the research project are: The University of Karlskrona/Ronneby, Lindholmen Development, Active Control AB and Hellberg Safety AB. Financial support was provided by the Foundation for Knowledge and Competence Development. The F17 air force at Kallinge and AMI in Ronneby were selected as evaluation groups. More information about the project can be found at: http://www.hk-r.se/research_sv/headset_sv.html

Figure 1 below illustrates a typical situation when the door is open and the helicopter is in a hovering position.

2. MEASUREMENT SETUP 1

Two ordinary helicopter crews were selected for the study. All were interviewed about their experiences of high sound levels from different flying operational situations. An operational design for the investigation, which included all these situations, was developed.

The diffuse- or free-field SPL-registrations in the cabin were performed using 1/2” microphones (Bruel & Kjaer, 4165 and 4135). All other SPL-registrations were performed with miniature microphones with built-in probes (Knowles, EA 1842) in subjects’ right external auditory canal. The probe-tube opening was situated 1-3 mm from the tympanic membrane [13]. All registrations were taped on a DAT-recorder (Sony-DAT TC D-7). The analysis was performed using a 1/3-octave band analyzer (Norwegian Electronic, 830) as well as in a HP35670A signal analyzer. The analysis of the miniature microphone measurements was corrected to be comparable to free field levels [13]. Before inserting the microphone probe in the ear canals, these were inspected with the aid of an otoscope.

3. MEASUREMENT SETUP 2

Several spectral measurements were performed during the flight. In the first phase, an analysis of different frequency ranges and with different estimation methods was performed in order to establish the frequency components present. Both FFT-based narrowband analysis and third octave analysis were used in this investigation phase. On completion of this phase, several analysis bands were selected in order to gain a good understanding of the frequency content.

The transducers were positioned as illustrated in Fig. 4. One microphone was placed close to the pilot. This transducer is called “the pilot.” The other microphone was placed between the passenger seats, hanging from the ceiling. This microphone is called “the seat.” The accelerometer was mounted on the wall on the left door opening just in front of the left passenger seat. The right rear door was open during flight, as the flight was a training session for a new group of surface divers. This open door caused an increase in the low frequencies picked up by “the seat” microphone.

The photo is taken by Mr. Gösta Bolander from Air Force F17 Kallinge.
4. FREQUENCY ANALYSIS

The measurement situation in the helicopter is rather compli- cated. We do not know enough about the signal before hand to decide on the probable signal type. When analyzing the fre- quency content of a signal using, for instance, an FFT, it is most important to know if the signal is narrowband or broadband, as described and proved in the previous section. If the signal consists of a sinusoid, the amplitude scaling should be \( P_b \) (Power Spectrum). If the signal is broadband noise, the ampli- tude scaling should be \( P_c \) (Power Spectral Density). If this is not the case, severe amplitude scaling errors will result. [1] [2].

Assume we have a continuous time series \( x(t) \) that we wish to sample at equidistant times, \( \Delta t \). We will then receive a discrete time series

\[
x[n] = x(n \Delta t) \quad n=0,1,2,3,....,N-1 \tag{1}
\]

where \( N \) is the number of samples in the series. The corresponding frequency information may be achieved using an FFT, Fast Fourier Transform, which is based on the Discrete Fourier Transform, DFT. The frequency information is thus given by

\[
X(f_k) = \Delta t \sum_{n=0}^{N-1} x[n] e^{-j2\pi f_k n \Delta t} \tag{2}
\]

where \( N \) is the length of the block of data in the transform, and is of the length \( 2^N \). The DFT transform will produce frequency information at discrete frequencies given by

\[
f_k = \frac{k}{\Delta t} \quad k=0,1,2,3,....,N-1 \tag{3}
\]

where \( \Delta t \) is the sampling increment. If the signal is completely periodic with the length of the time record \( T \), the DFT transform will produce the correct frequency information at the corre- sponding \( f_k \). If this is not the case, frequency information may leak from one frequency line to another. This leakage effect can be reduced by introducing a time window. A time window \( w(n) \) will be multiplied on the time signal \( x[n] \) as

\[
x_w[n] = x[n] w[n] \quad n=0,1,2,3,....,N-1 \tag{4}
\]

and the frequency information will thus be convolved with this window, since a multiplication in time leads to a convolution in frequency,

\[
X_w(f_k) = \frac{\Delta t}{K_w} \sum_{n=0}^{N-1} x_w[n] e^{-j2\pi f_k n \Delta t} \tag{5}
\]

where \( X_w(f_k) \) denotes the windowed frequency information and \( K_w \) is the amplitude scaling necessary, due to the decrease in energy caused by the window. The scaling \( K_w \) is given by

\[
K_w = \frac{1}{N} \sum_{m=0}^{M-1} w^2[m] \quad m=0,1,2,3,....,M-1 \tag{6}
\]

where \( w[n] \) is the window used. This window will reduce leakage, but also make the analysis bandwidth larger and decrease the energy content in the time signal. There is normally a trade off between time signal energy, analysis bandwidth, picket fence effect (amplitude ripple), side lobes and spectra leakage. For the measurements acquired during the test flight, a Hanning window was used, since spectral resolution was the most important parameter in these measurements.

If the data is unknown, as in our case, it is important to measure using a number of frequency spans, and compare results. If the amplitude peaks keep their levels, we know that we have a sinusoid. If this is not the case, the signal is more broadband than narrowband and we have to be careful. The analysis of the helicopter sound has thus been split into several frequency ranges, analyzed and compared one by one. By comparing the amplitudes when changing the frequency span, it is possible to determine whether the component is narrowband or broadband.

5. DATA ANALYSIS

The sound field varies slowly during flight. It is thus very important to establish the average sound field. A Hanning window was used to reduce leakage, and maintain the frequency resolution. RMS averaging with 50% overlap was also used. This is optimal for the Hanning window as we have shown before. 10 to 50 averages were normally used.

The Super Puma helicopter has one main rotor and one tail rotor, as well as several gear boxes. There are four blades on the main rotor and five on the tail rotor. The revolution speed for each rotor is given by the equation:

\[
\text{rpm} = \text{BPF} \times \frac{60}{N_b} \tag{7}
\]

where \( N_b \) is the number of blades and the BPF is given in Hz. This gives \( N_b=4 \) for the main rotor, which gives an rpm of 17.6 x 60/4=264.
There is a 107 Hz component that is quite strong. This is the BPF of the tail rotor. The sixth order of the main rotor BPF is at almost the same frequency as the 6th order of the main rotor BPF (106.2 for the 6xBPF for the main rotor versus 106.67 for the 1xBPF for the tail rotor, calculated at 265 rpm). Since the BPF for the tail rotor is 107 Hz, this corresponds to an rpm of 1284, using equation (7). The main rotor is 16.2 meters in diameter and the tail rotor 3.15 meters.

Figure 5 below illustrates the 1/3 octave analysis of the sound at the pilots head with and without communication. There is a large increase in dBA levels when the communication system is activated.

The second peak is the first harmonic of the BPF, 35 Hz. The BPF of the main rotor creates large infra-sound levels inside the cabin. This component is not audible but affects the body. By using the built-in harmonic marker it is possible to mark the components that are harmonics of the main rotor BPF. One peak at 82 Hz is not an exact order of the main rotor BPF, as can be seen in measurement figure 2. This is the Tail Drive shaft fundamental. This component is however coupled to the BPF, but without an integer number. The main components in the 200 Hz range are, however, due to the main rotor and its first orders, and the BPF of the tail rotor. It is important to note that the low frequency components at 10 Hz and below have increased in level. This is due to the $P_{th}$ scaling, and is an analysis error. We have already verified a more correct analysis in measurement figure 6a by using higher frequency resolution. This is why it is a risk to analyze with only one frequency range.

There are no major new frequency components in the DC-400 Hz frequency range. It is interesting to note how it seems as if the low frequency content increases with each doubling of the frequency range. This is correct given a $P_{th}$ scaling, but wrong in reality. If the signal is broadband, in comparison to the analysis bandwidth there should be a 6 dB amplitude increase for each doubling, when using a $P_{th}$ scaling method.

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The following parameters have been used for the measurement analysis presented in figure 8:

**Measurement type:** Power Spectrum and Cross Spectrum
**Measurement position:** mic in seat
**Number of averages:** 10
**Hanning Window:** 50% overlap, $B_w=187.5$ mHz
**Frequency range:** DC-12.8 kHz and DC-400 Hz

In the DC-12.8 kHz range, two new frequency groups are visible, one at 8 kHz and one 10 kHz. The levels are quite high. This sound probably comes from the turbines. Note that it looks as if the low frequency components are higher in level. This is not the case. Compare with the earlier analysis, which is more correct. It is important to be aware of this common measurement error. For this kind of analysis, it is very important to measure in several frequency spans before judging the signal levels.

There is a strong correlation between the structure borne and the air borne sound in the helicopter. It is very clear in figure 8b that the BPF is coupling through the structure.
Fig. 6. Illustration of the sound levels in seat position. In the figure to the left, it is obvious that the BPF of the rotor is the main component. The BPF is $4 \times$ rotor rpm since there are four blades on the rotor. In the figure to the left the frequency range has changed a factor of two. It is interesting to note that the frequency components in the range DC-10 Hz are very close. This causes incorrect $P_T$ scaling which leads to analysis errors that make it look like this frequency component is larger than the BPF component. That is not the case.

Fig. 7. Illustration of the next analysis ranges, 200 Hz and 400 Hz. It is interesting to note that the DC-10 Hz range increases in level for every change of frequency span. This is coupled to the FFT analysis and is not describing the narrowband levels present. From these figures it is clear that the main frequency components in the DC-400 Hz are the main rotor BPF with three orders and the tail BPF that is dominating the sound level. Therefore, the active system has to treat mainly five components in this frequency range.
increase in the sound levels at 8 kHz and 12 kHz. These components are created by the turbine engines, Turbomeca MAKILA IA2, with 2109 hp each and by the gear boxes. The 768 Hz comes from the 2xBendix Shaft.

6. COMMENTS FOR AN ANC SYSTEM

The sound field in the helicopter analyzed consists of few, though large tones in the 0-400 Hz range with a good correlation. This is a good sign for an ANR system, since an X-LMS feed-forward algorithm is capable of giving a large attenuation given these circumstances. It is necessary to use a reference signal that is coupled to the rpm. The effective active attenuation is given, as a rule of thumb, by the coherence between the reference signal and the error microphone according to

\[ A_{\text{dB}} = 10 \log \left( 1 - \gamma^2 \right) \]  

where \( A_{\text{dB}} \) is the attenuation and \( \gamma \) is the coherence between the reference and the error microphone. The coherence is excellent since the active system is close to the ear and the disturbance is narrow-band.

The 17.5 Hz tone creates high infrasound levels. The wavelength at 17.5 Hz is approximately 18 meters. In a relatively small cavity like the inside of the Super Puma, this gives a good chance to suppress this component by an ANC system using loudspeakers. The silent zone around the error microphones will be approximately 2 meters in radius, which then makes it possible to receive a global reduction with few microphones. However, one paper has reported that the helicopter sound field is rather complex. If this is the case, it is much more difficult to handle the main rotor BPF by using loudspeakers. This aspect is not included in the research project “A New Generation Active Headset and its Psychological Effects.” It is therefore recommended to study a “volumetric cancellation system” using loudspeakers and microphones in a separate research project.

It should be possible to deal with the high sound levels at 1.8 kHz and around 8-10 kHz using a good classic passive attenuation in the headset.
The fundamental frequency of the main rotor is still clearly visible. The built-in harmonic marker marks the harmonics of the BPF. One peak at 82 Hz is not an order of the main rotor. We would like to thank Captain Arne Sjölund and his crew at the F17 air force base in Kallinge for all their support in making these measurements. There are many cables and much equipment that must be securely fastened. Everything went smoothly and the personnel were most supportive. We would also like to thank Mr. Asplund for supplying all the frequency/RPM information, which has been most helpful. Mr. Sven Johnsson kindly supplied a set of photos for use in the report, which was greatly appreciated.

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