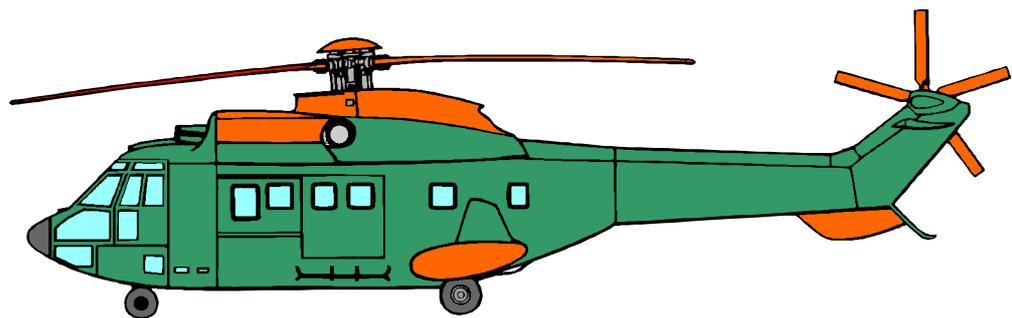


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Frequency Analysis of Helicopter Sound in the AS332 Super Puma

by

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Abstract

This technical report describes a series of measurements performed on an AS332 “Super Puma”, MKII (HKP10) helicopter. The measurements are part of a research project, “A New Generation Active Headsets and its Psychological Effects,” financed by the KKS board (Board of Knowledge and Competence). The project participants are: Lindholmen Development, Hellberg Safety, Active Control and the University of Karlskrona/Ronneby. CelsiusTech has recently joined the project as an industrial partner. The Air Force base at F17 in Kallinge and the AMI group in Ronneby are involved as evaluation groups.

There are substantial noise levels in helicopters, especially at low frequency. These noise levels are normally not harmful to the ear. However, the low frequency content masks the speech. For this reason, pilots tend to set the intercom system at maximum sound level, producing potentially damaging sound levels for the human ear. Dr. PA Hellström at Lindholmen Development has measured almost 100 dBA inside the ear canal when the intercom system is in use. This high sound level exposes the ear to fatigue and hearing loss.

The background noise is the key reason for the problem, although it is not the key source of sound damage to the ear. The frequency content in the masking background sound is of great importance. It was thus important to investigate if the sound consisted of pure tones or if it was more broadband in nature. The dominant sound sources needed to be identified and the number of harmonics for each source established. It was also important to investigate if there was a strong connection between the structure borne and the air borne sound.

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Notation

$x_c(t)$	Analog time signal
$x[n]$	Discrete time signal
Δt	Sampling increment
T	Time record length
N	Number of samples
$X_w(f_k)$	Windowed frequency spectra
B_W	FFT analysis bin bandwidth
K_r	Random signal scaling
K_s	Tonal signal scaling
$K_{w,PSD}$	Window scaling for broadband signals
$K_{w,PS}$	Window scaling for sinusoidal signals
P_{PS}	Power Spectrum
P_{PSD}	Power Spectral Density
P_{ESD}	Energy Spectral Density
A_{db}	ANR Attenuation in dB
γ^2	Coherence
$G_{xy}(f)$	Cross Power Spectrum
$G_{xx}(f)$	Auto Power Spectrum
$G_{yy}(f)$	AutoPower Spectrum
$R_{xy}(f)$	Cross correlation function
N_b	Number of blades of the rotor
BPF	Blade passage frequency
R	Main rotor rpm
T	Tail rotor rpm
rpm	Rotation per minute
LMS	Least mean square

1. Background

The air force uses a helicopter, the AS332 “Super Puma,” MKII (HKP10). This helicopter has replaced the Vertol from Boeing. There are substantial noise levels in the helicopters, especially at low frequency. These levels are not normally harmful to the ear. However, the low frequency content masks the speech. The intercom sound levels thus sometimes reach severe levels. Dr. PA Hellström at Lindholmen Development, Hearing Research Lab, has measured up to almost 100 dB levels inside the ear canal when the intercom system is in use. This high sound level exposes the ear to fatigue and hearing loss. 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 these would create. The University of Karlskrona/Ronneby was selected as Project Manager. The partners in the group 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

It is important to investigate the frequency content of the sound in order to know how many low and high frequency components are present. A series of measurements was thus performed at the F17 air force field in Kallinge.

Helicopter sound is rather complex. It was thus important to investigate if the sound consisted of pure tones or if it was more broadband in nature. The dominant sound sources were found and analyzed, and the number of harmonics present for each of them was also established. It was also important to investigate if there was a strong connection between the structure borne and the air borne sound. This is important when selecting a reference sensor for the active noise control system in the headset.

2. Measurement Setup

Helicopters are known to have high noise levels, especially at low frequency. The helicopter crew use an intercom system for communication between themselves and for communication with the tower. These headsets have a built-in passive ear protection. Damage to the hearing may be caused nonetheless. This is due to the masking effects from the low frequency background noise present in the helicopter. The helicopter analyzed in this research project was a Eurocopter, AS 332 Super Puma MKII (HKP10): see **Figure 3** below, showing the helicopter in a hovering position over the air field at F17 in Kallinge.



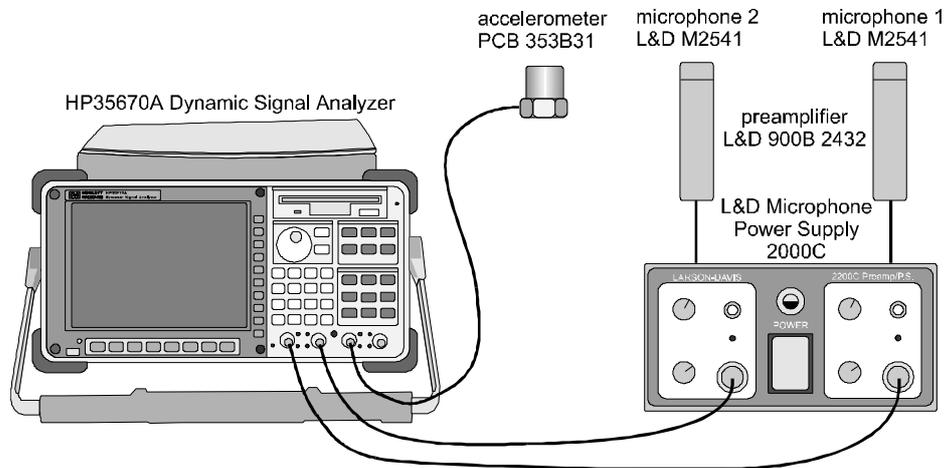
Key frequency components in the helicopter, measured in Hz.

R represents the rotation speed of the main rotor, and T represents the tail rotor. BPF represents the blade passage frequency for each rotor. BPF is 4xR for the main rotor since there are four blades.

1R, 265 rpm @ 100% load	4.42	
2R	8.88	
3R	13.25	
4R	17.67	BPF for rotor
1T	21.29	
8R	35.33	2*BPF for rotor
12R	53.00	3*BPF for rotor
16R	70.67	4*BPF for rotor
5T	106.67	BPF for tail
2*Bendix Shafts	761.34	

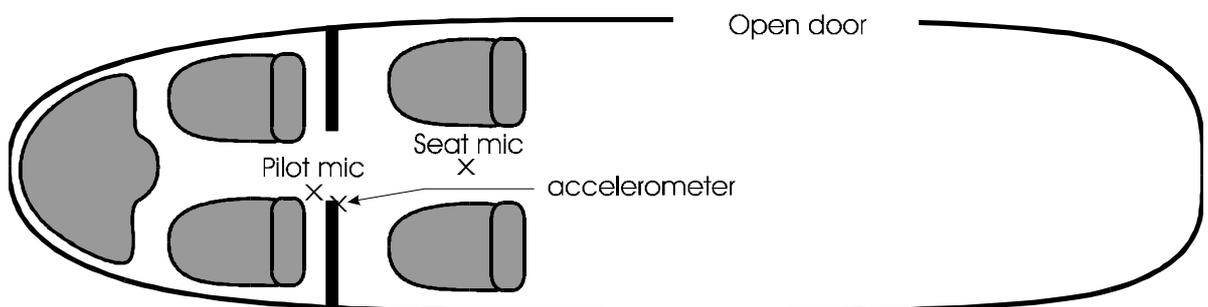
The measurement setup consists of a Hewlett-Packard HP35670A, 4-channel Dynamic Signal Analyzer. Two Larson & Davis ½" microphones model 2541 were used, along with the Larson

& Davis 900B 2432 microphone preamplifier and Larson & Davis 2200C power supply. An accelerometer, PCB 353B31, from PCB Piezotronics was connected directly to the HP35670A using the built-in ICP supply. The complete measurement setup is illustrated in **Figure 4** below.



Several 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 in **Figure 5**. One microphone was placed close to the pilot. This transducer is called “the pilot.” The other microphone was placed between the two passenger seats in the front of the helicopter, 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 gave an increased low frequency content in the seat microphone.



3. Spectrum Scaling

Measurement of spectral components in an unknown environment such as a helicopter is not an easy task. The frequency to time conversion very often assumes an a-priori knowledge of the class of signal estimated: sinusoidal or white noise. The errors that can be introduced due to this lack of a-priori knowledge are described in this chapter.

Assume we have a continuous time series $x_c(t)$ that we wish to sample with equidistant samples,

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Δt . We will then receive a discrete time series where N is the number of samples in the series. The corresponding frequency information may be achieved using an FFT, Fast Fourier Transform, which samples the Discrete Fourier Transform,

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DFT. The frequency information is thus given by where N is the length of the block of data in the transform, and is of the length 2^N . The DFT

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transform will produce frequency information at discrete frequencies given by where Δt 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 corresponding 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

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multiplied on the time signal $x[n]$ as and the frequency information will thus be convolved with this window, since a multiplication in time leads to a convolution in frequency, where $X_w(f_k)$ denotes the windowed frequency information and $K_{w, PS}$ is the amplitude scaling necessary for a sinusoid, due to the decrease in power caused by the window. The scaling $K_{w, PS}$ is given by

where $w[n]$ is the window used. The scaling for a power spectrum density is given by

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The 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 spectral leakage. There are several windows available, but the most commonly used in industrial measurements are: No Window (Rectangular), Hanning, Flat top and Exponential. It is important to note that there are several Flat top windows. The “best” flat top window is the P401 by Hewlett Packard. This window has lower side lobes than the P301, which is the “most common” Flat top window used in general measurement equipment. The coefficients for the P301 Flat top window are available, but the P401 Flat top window is Hewlett-Packard proprietary information and is not generally available. It is the P401 that is implemented in the HP35670A analyzer. For the measurements acquired during the test flight, a Hanning window was used, since spectral resolution was the most important parameter in this measurement. Different windows are presented with their key parameters in **Table 1** below. It is very clear that the spectral resolution is good with a Hanning window, and amplitude accuracy is best for the Flat top window. It was however important to be able to separate different tones in this measurement. For this reason, the Hanning window was chosen.

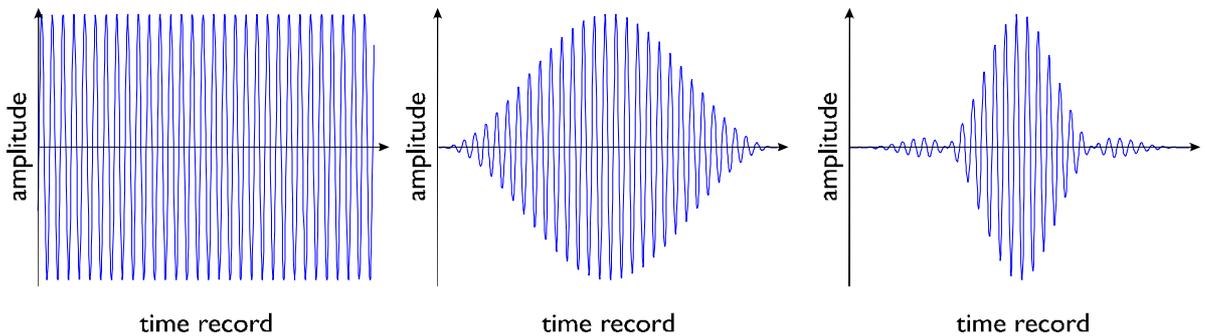
Table 1: Description of key window parameters given a frequency range from DC-3.2 kHz, 2048 samples.

Window	Amplitude error	Bandwidth, BW	First Sidelobe
Hanning	1.43 dB	6 Hz	-31.5 dB
Hamming	1.75 dB	5.5 Hz	-43.2 dB
Flat top, P301	0.01 dB	13.7 Hz	-70.4 dB
Flat top, P401	0.01 dB	15.3 Hz	-82.1 dB
Rect, no window	3.94 dB	4 Hz	-13.2 dB

In order to decrease the variance in the averaging process, given a limited measurement time, overlap data processing can be used. For a Hanning window, a common overlap processing choice is 50% and retrieves 90% of the data [1]. With a 63% overlap 100% of the data is used.

When using a window to decrease leakage some energy in the signal is lost, as described above. This energy must be compensated for according to equation (5). In **Figure 6** the effects of three common windows are presented.

In order to use the total energy in the time signal, overlap data processing should be used where the analysis system allows this. When using a Flat top window a great deal of energy is lost as can be seen in **Figure 6**. The amplitude accuracy for the Flat top window is however high, though at the price of increased variance. This overlap processing is especially important for slowly varying time-data such as the data in this helicopter measurement.



The frequency domain signal consists of a real and an imaginary part, and has negative frequencies. In most cases, a Power Spectrum with only positive frequencies is required. This is

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created by

where P_{PS} stands for the Power Spectrum. This amplitude scaling is correct assuming a periodic narrowband signal as the input signal. For white noise, a Power Spectral Density is needed, since

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this is a broadband signal. The P_{PSD} is given by

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For transient signals it is also important to scale for the time dependency. This is achieved by

In the above equations, the voltage dimension is included. There are three different scaling methods that can be used. This is a difficult situation, since it requires a-priori information about the signal before choosing the right type of scaling. Without this information it is impossible to be sure that the amplitude is correct, [7]. In [8] it is stated that P_{PS} and P_{PSD} are the same. That is a correct statement given the assumption in the book, a 1 Hz analysis bandwidth. In most practical cases the analysis bandwidth is not 1 Hz. An amplitude scaling error will thus be the

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consequence, often several 1000%. The relationship between P_{PS} and P_{PSD} is given by

Example:

Let us assume that $x[n]$ is a sinusoid with an amplitude of 1V peak and a frequency of f_0 that is

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periodic with the time record, and is measured with Power Spectrum Density. In this case, If we introduce the sampling frequency f_s and the sinusoid frequency f_0 we will achieve

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The Power Spectrum Density is given by (9) as

For the sinusoid above it then follows

and consequently for a Power Spectra scaling method

Since all the power is located in one bin (ideally), f_0 , this bin must be equal to the result. In this case, the P_{PS} is giving the correct amplitude while P_{PSD} is estimating with a bias error given by

The N/t term is the dominating error and we are thus introducing a bias that is directly related to the analysis bandwidth, or the number of bins, that is given by (for a rectangular window)

Assume that we now change to a white noise signal that is given by

Given the previous discussion it follows that the Power Spectrum Density is given by

and consequently for a Power Spectra scaling

Since the random signal is spread out over the frequency band, each frequency bin must give the correct amplitude. In this case, each bin should give A^2 not NA^2 as before, irrespective of the FFT length, since there are N bins. However, the frequency width Δf is directly coupled to the FFT length N as given by equation ?. We thus need to scale the data with this factor Δf .

In this case, there is an amplitude difference of mainly Δf . If Δf is equal to 1 Hz, there is no problem, the scaling is still one. However, in most practical cases Δf is not equal to 1 Hz. If the correct amplitude scaling method is not used, severe amplitude scaling errors will result. The correct frequency transforms in this case are given by equation (9) above. The above discussion has assumed that a rectangular window has been used for the FFT calculation. In most cases another window is used, such as a Hanning or Flattop window to decrease spectral leakage. This window must also be compensated since it decreases the energy in time domain as well as

changing the Δf term to a larger value. Table 1 illustrates the typical B_w for the most commonly used windows.

The above equations show that it is important to have a-priori information about the signal in order to evaluate any absolute amplitude levels. The method used to avoid problems when analyzing unknown signals is to use a set of measurements and observe amplitude changes for the frequency components of interest. It is not possible, in general, to find absolute amplitude levels without some information about the signal. This information can be achieved by using a set of measurements and using the information given by them as the base for further action.

The following approach is a recommendation on how to conduct measurements when absolute amplitude signal levels are of importance.

Measurement Procedure:

Start the analyzer with a Power Spectrum scaling method. Then,

1. Measure with one frequency range. Read all amplitude levels.
2. Measure the same signal again, but with a factor of two decrease in frequency span. This gives a doubled measurement time and consequently half the B_w . If some amplitude levels (peaks) change levels when compared to the previous measurement, the signal cannot be scaled correctly using P_{PS} .
3. Continue to change the frequency range until the amplitude levels are stable and do not change when the measurement settings are changed. When this happens, the amplitude values can be read, and they have the correct amplitude scaling.

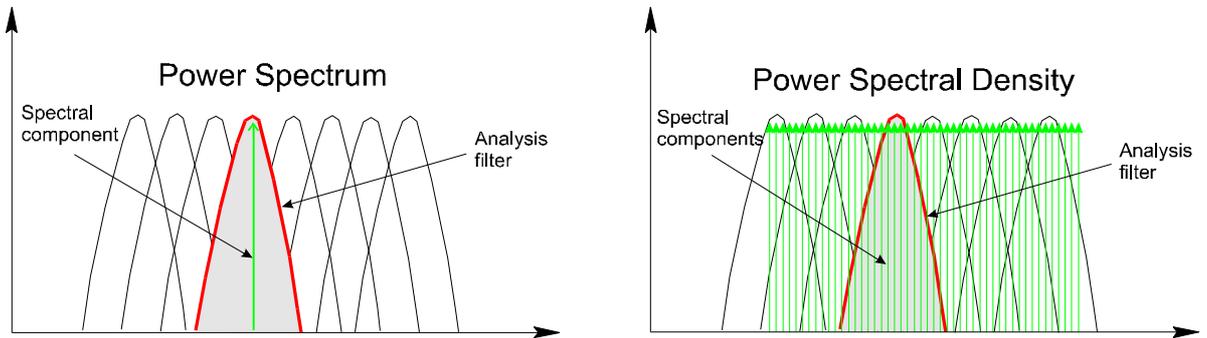
If the signal always changes for each change of frequency range, try using P_{PSD} scaling instead. If the levels do not change when using a P_{PSD} scaling, the amplitude levels are correctly scaled. Observe that there are signals where it is not possible to reach a solution for either P_{PS} or P_{PSD} . In such cases, it is difficult to rely on the amplitude values. P_{ESD} is not treated in more detail since this analysis is not part of this measurement series.

A rule of thumb when determining the amplitude scaling method is:

If the analysis bandwidth \ll the signal bandwidth: Use P_{PSD} scaling (=broadband signals).

If the analysis bandwidth \gg the signal bandwidth: Use P_{PS} scaling (=tonal components).

If the input signal is transient: Use P_{ESD} scaling (Energy Density) (=transients).



The left figure in **Figure 7** illustrates how the scaling is correct using P_{PS} , since there is no compensation for the width of the filter. If there should be more than one signal component in the left marked filter, the amplitude is wrong. The inverse is applicable for the right figure. In this case, it is necessary to compensate for the width of the filter. If no compensation is made, the amplitude will be scaled incorrectly, that is the signal would be overestimated if the analysis bandwidth B_W is larger than 1 Hz, otherwise underestimated. In Table 2 below some typical measurement settings are presented and the errors that will result from a wrong assumption about the signal.

Table 2: Complex FFT, 2048 samples (=800 effective lines), Hanning window.

Signal	Scaling	Span	B_W assuming a Hanning window	Measurement error %
Sinusoid	P_{PS}	0-12.8 kHz	48 Hz	4800
Sinusoid	P_{PS}	0-50 Hz	187 mHz	500
White noise	P_{PSD}	0-12.8 kHz	48 Hz	4800
White noise	P_{PSD}	0-50 Hz	187 mHz	500

Cross Spectrum and Coherence

A cross spectrum measurement has been performed during the helicopter measurements. This is an important measure, since the cross spectrum G_{xy} indicates the possible active reduction, where the reference signal is the reference for the Filtered X-LMS algorithm. There has to be a correlation or coherence between the two measurement points for the cross spectrum to produce “peaks” when averaging several spectra together. The averaged cross spectrum $G_{xy}(f_k)$ is given

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by

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where $G_{xy}(f_{k,m})$ are the individual estimates from reference x to response y and is given by, where $X(f_k)$ and $Y(f_k)$ is given by equation (5) respectively. It is also possible to calculate the cross

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spectrum from the cross correlation function $R_{xy}(n)$ by

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The cross correlation function $R_{xy}(n)$ is given by the convolution sum and also verifies the strong connection between the cross spectrum and the cross correlation. The cross spectrum is the Fourier transform of the cross correlation function.

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The coherence function is given by

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which is a measure of how much of the output y is caused by the input x in a linear and stationary sense. This measure is also a good indicator of how much attenuation an active feedforward LMS system is capable of suppressing. Equation (29) expresses this. It is important to note that the coherence function is always within the bounds and is always one for one measurement. This makes the coherence function “invalid” for one measurement. In the analysis described in this report the number of averages used is from 10 to 50.

4. Frequency Analysis

The measurement situation in the helicopter, is rather complicated. We do not know enough about

the signal beforehand to decide on the probable signal type. When analyzing the frequency content of a signal using, for instance, a FFT, it is most important to know if the signal is narrowband or broadband, as described in the previous section. If the signal consists of a sinusoid, the amplitude scaling should be P_{PS} (Power Spectrum). If the signal is broadband noise, the amplitude scaling should be P_{PSD} (Power Spectral Density). If this is not the case, severe amplitude scaling errors will result, [1] [2].

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 these comparisons of the amplitudes when changing the frequency span, it is possible to determine if the component is narrowband or broadband.

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 a common choice 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. This gives an rpm for each rotor

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in accordance with the following equation:

where N_b is the number of blades and the BPF is given in Hz. The main rotor has four blades and the tail rotor, five. This gives $N_b=4$ and $N_b=5$ respectively. According to the frequency analysis, the BPF (Blade Passage Frequency) is 17.6 Hz for the main rotor, which gives an rpm of $17.6 \times 60 / 4 = 264$. 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 @265 rpm, see table on page 35). Since the BPF for the tail rotor is 107 Hz, this corresponds to an rpm of 1284, using equation (28). The main rotor is 16.2 meters in diameter and the tail rotor 3.15 meters.

There are substantial noise 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, see the table on page 35 and the analysis later in the “Results of Analysis” section. There is a large component at 1.6 kHz which dominates the accelerometer signal, see measurement figure 13. This component comes from the 4xFreewheel. It is interesting to note that this component is low in the microphones, but high in the accelerometer signal.

5. Results of the Analysis

Measurement figure 1:

Measurement type: Power Spectrum

Measurement position: mic in seat

Number of averages: 10

Hanning Window: 50% overlap, $B_w=187.5$ mHz

Frequency range: DC-50 Hz

The fundamental frequency of the main rotor is clearly visible. This analysis with many frequency lines is most important in order to find out if the component is narrowband or otherwise. It is clear from this analysis that the BPF is narrowband. 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. The headset need not treat this component.

Measurement figure 2:

Measurement type: Power Spectrum

Measurement position: mic in seat

Number of averages: 10

Hanning Window: 50% overlap, $B_w=375$ mHz

Frequency range: DC-100 Hz

The fundamental frequency of the main rotor is clearly visible in the frequency plot, and we know from previous analysis that the signal is narrowband. 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 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.

Measurement figure 3:

Measurement type: Power Spectrum

Measurement position: mic in seat

Number of averages: 10

Hanning Window: 50% overlap, $B_w=750$ mHz

Frequency range: DC-200 Hz

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 BPF. This is the Tail Drive shaft fundamental. This should be the BPF of the tail rotor. 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 PS scaling, and is an analysis error. We have already verified a more correct analysis in measurement figure 1 by using more frequency resolution. This is why it is so dangerous to analyze with only one frequency range.

Measurement figure 4:

Measurement type: Power Spectrum

Measurement position: mic at pilot
Number of averages: 10
Hanning Window: 50% overlap, $B_w=750$ mHz
Frequency range: DC-200 Hz

The sound level at the pilot's seat is almost identical to the seat microphone. A decrease in the low frequency content is, however, visible. The level is not accurate in this figure, as already discussed, but is valid as a relative measurement compared to figure 3.

Measurement figure 5:

Measurement type: Power Spectrum
Measurement position: mic in seat
Number of averages: 10
Hanning Window: 50% overlap, $B_w=1.5$ Hz
Frequency range: DC-400 Hz

There are no major new frequency components in this 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_S scaling, but wrong given the 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_S scaling method.

Measurement figure 6:

Measurement type: Power Spectrum
Measurement position: mic in seat
Number of averages: 27
Hanning Window: 50% overlap, $B_w=12$ Hz
Frequency range: DC-3.2 kHz

A new component is visible. The frequency is 1.8 kHz, and the level is quite high. This is the 2nd order Meshing Tail component, according to the frequency table at page 35. This component is also clearly visible in the accelerometer signal.

Measurement figure 7:

Measurement type: Power Spectrum
Measurement position: mic in seat
Number of averages: 10
Hanning Window: 50% overlap, $B_w=48$ Hz
Frequency range: DC-12.8 kHz

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 warn about this common measurement error. For this kind of analysis, it is very important to measure in several frequency spans before judging the signal levels.

Measurement figure 8:

Measurement type: Cross Spectrum

Measurement position: acc/mic in seat

Number of averages: 10

Hanning Window: 50% overlap, $B_w=6$ Hz

Frequency range: DC-1.6 kHz

This measurement consists of a cross spectrum between the accelerometer and the microphone. If there is a correlation between the structural borne and the air borne sound there will be peaks in the spectra. It is very clear that the BPF from the main rotor is coupling through the helicopter structure. The cross spectrum verifies that the airborne sound field inside the cabin is coherent with the structural vibration levels measured by the accelerometer.

Measurement figure 9:

Measurement type: Cross Spectrum

Measurement position: acc/mic in seat

Number of averages: 10

Hanning Window: 50% overlap, $B_w=750$ mHz

Frequency range: DC-200 Hz

There is a strong correlation between the structure borne and the air borne sound in the helicopter. It is very clear that the BPF is coupling through the structure. This data indicates that it could be possible to use an accelerometer as a primary field sensor.

Measurement figure 10:

Measurement type: Power Spectrum

Measurement position: accelerometer

Number of averages: 10

Hanning Window: 50% overlap, $B_w=750$ mHz

Frequency range: DC-200 Hz

This measurement is made on the accelerometer. The BPF from the main rotor is very strong in the structure. It is interesting to note that there is not as much low frequency contribution in this signal as compared with the microphone signal. The fact that the main rotor BPF is as clear in the accelerometer is a good sign for our work. However, there is an 82 Hz component visible, that is the Tail Drive shaft fundamental. This tone is not a problem despite the fact that it is not an order of the BPF, since this component is coupled to the BPF with a rational number and not an integer.

Measurement figure 11:

Measurement type: Power Spectrum

Measurement position: accelerometer

Number of averages: 10

Hanning Window: 50% overlap, $B_w=6$ Hz

Frequency range: DC-1.6 kHz

A large frequency component is visible at 776 Hz. This is this the 4xFreewheel component. The passive part of the headset should be able to handle this component. However, it is expected that the ANR system will reduce this tone as well, given a combined attenuation.

Measurement figure 12:

Measurement type: Power Spectrum

Measurement position: accelerometer

Number of averages: 50

Hanning Window: 50% overlap, $B_w=24$ Hz

Frequency range: DC-6.4 kHz

The 787 Hz component is the strongest of them all. The analysis in the last measurement was 776 Hz. The rpm is changing slowly. This frequency component from the 4xFreewheel seems to be the key contribution in the accelerometer.

Measurement figure 13:

Measurement type: Power Spectrum

Measurement position: accelerometer

Number of averages: 10

Hanning Window: 50% overlap, $B_w=48$ Hz

Frequency range: DC-12.8 kHz

The 768 Hz component is still the strongest of them all. This component is the key contribution in the accelerometer, but is very low in the microphones. This component can thus be used as a good reference signal for the ANR system.

6. Comments regarding an ANR 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

Install Equation Editor and double-click here to view equation.

according to

where A_{db} is the attenuation and ρ 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.

There are some tones that are very sharp and have high levels, it should be possible to use them as a prediction of an rpm reference. This would have the advantage that a separate tacho signal is not needed. This technique has been successfully used in a car application for Volvo, [9]. By using this prediction algorithm the X-LMS algorithm is able to create a reference signal directly from the primary sound field.

The 17.5 Hz tone creates very high infrasound levels. The wave length 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 ANR system using loudspeakers. The silent zone around the error microphones will be approximately 2 meters in radius, which makes it possible to receive a global reduction with few microphones, [11]. This is a good situation for an ANR system. It is thus recommended to study the suppression of this component by a “volumetric cancellation system” using loudspeakers and microphones, [10]. This part is not included in the research project “A New Generation Active Headset and its Psychological Effects.”

The high levels at 1.8 kHz and around 8-10 kHz should be possible to handle by a good classical passive attenuation in the headset.

The microphone signal used for the communication system is severely contaminated with the low frequency background noise as well as the high frequency components. By using a combination of filtering techniques it is likely that a large reduction in the noise level in the microphone can be achieved. Initial tests have shown a suppression of the order of 25 dB, which is very promising. It is very important to reduce these components in the microphone since the speech intelligibility is otherwise rapidly decreased due to the noise level increase due to the microphones.

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Measurement Figures

The next 13 pages contain plots of the data, with some key comments.

MKII Super Puma HKP10 frequency table (in Hz)

1R, 265 rpm @ 100%	4.42		1
2R	8.84		2
1*2nd stage Epicyclic Sun	12.85		2.91
3R	13.25		3.90
4R	17.67	BPF for rotor 4	
1*2nd stage Planet Wheels	18.51		4.19
1T	21.29		4.82
8R	35.33	2*BPF for rotor	8
High Spot 2nd Stage Planet	37.06		9.89
High Spot 2nd Stage Annulus	39.75		9
1*1st Stage Epicyclic Sun	39.79		9.01
1*Main Bevel Rear	39.79		9.01
1*1st Stage Planet Wheels	49.16		11.13
12R	53	3*BPF for rotor	12
Port & Stbd Acc. Drive Idlers	61.74		13.98
1*Tail Rylon Drive Shaft	62.50		14.13
Prim/Sec Oil Pump	67.97		15.39
16R	70.67	4*BPF for rotor	16
High Spot 2nd Stage Sun	76.01		17.21
Port & Stbd Hydraulic Pipe	76.19		17.25
MRG Input Bevel Gear	81.44		18.44
1*Tail Drive Shaft	81.44		18.44
30R	88.33		20
High Spot 1st Stage Planet	88.36		22.27
High Spot 1st Stage Annulus	102.88		23.29
5T	106.67	BPF for tail	24.13
Port/Stbd Alt Annulus Gears	132.63		30.03
Free Wheel Drive Shafts	132.63		30.03
Oil Cooler Fan	140.27		31.78
2*Tail Drive Shaft	162.93		36.89
Port & Stbd Alternators	193.45		48.80
10T	213.10		48.25
High Spots 1st Stage Sun	215.71		48.84
2*Oil Cooler Fan	280.55		68.52
15T	319.77		72.40
1*Bendix Shafts	380.67		86.19
3*Oil Cooler Fan	420.82		95.23
2*Bendix Shafts	761.34		173.38
Meshing Tail Rotor Gearbox	937.92		213.36
Meshing Intermediate Gearbox	2688.87		603.69
M*Oil Pump 1st Stage Reduction	2788.32		631.32
M*Port & Stbd Hydraulic Pumps	3582.17		811.06
M*Port & Stbd Acc. Drive Idlers	3582.44		811.12
M*Port & Stbd Alt Annulus Gear	4643.18		1051.29
M*2nd Stage Engine Reduction	4643.32		1051.32
M*Oil Cooler Fan Gear	6173.16		1347.70
M*1st Stage Engine Reduction	11801.13		2671.96

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