Paper number 189

COMFORT METHODOLOGY AND COMFORT INDICATORS APPLIED ON HELICOPTER NOISE

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ABSTRACT

For decades now, EUROCOPTER has been deeply involved in the reduction of the cabin interior sound levels. Especially for these last ten years, sensitive progresses have been made on soundproofing and treatment technologies. In addition to these efforts on the overall cabin interior sound level reduction, EUROCOPTER is developing a new complementary approach. The latter is based on psychoacoustic indicators in order to better quantify the acoustic comfort felt by passengers inside the helicopter. This paper intends to present this additional approach based on psychoacoustic criteria. In a first part, we will introduce the dedicated problematic of helicopter environment. The second part will be dedicated to the logic followed by EUROCOPTER in order to identify the dedicated comfort law. The experimental and modelling studies performed will be introduced. For objective and subjective evaluations of comfort, tests based on headset and a 3D acoustic simulator will be presented. This methodology permits to identify the main psychoacoustic indicators involved in the helicopter comfort and to establish a comfort law based on these four criteria: loudness, dBG, sharpness, tonality. At last, the presentation of the comfort law will be the content of the third part of this paper.

Keywords: *psychoacoustics, helicopter, internal noise, acoustic comfort, annoyance, pleasantness, metrics*

I INTRODUCTION

During these last ten years, EUROCOPTER did sensitive progresses on soundproofing and treatment technologies. These progresses permit EUROCOPTER to propose to customers faster and/or more powerful helicopters, with larger windows, and having at least the same cabin interior sound level or a quieter interior acoustic. The better illustrations of these progresses are the innovations proposed and tested during the research program "DTP comfortable helicopter" on EC155. They permit to reach an average gain of ~7 dBSIL4 inside the cabin, 4 to 6 dBSIL4 on aerodynamic broadband noise, and 10 dB in average on Main Gear Box tonal components (up to 20dB on specific tones). These innovations and their results were presented during the ERF09 in Hamburg [1].

In addition to these efforts on the overall cabin interior sound level reduction, EUROCOPTER is developing a new complementary approach based on psychoacoustic indicators in order to better quantify the acoustic comfort inside the helicopter. Indeed, if the overall sound level is a key factor for the acoustic comfort, and EUROCOPTER is still working a lot to reduce it, it is not fully representative of the acoustic comfort felt by passengers. Two helicopter sounds may have the same sound pressure level, but with a very different perceived noise, meaning with different impact on the acoustic comfort felt according to their signatures. Several authors demonstrated that other criteria must be consider in addition to the sound level to be more representative of the acoustic environment felt by peoples. One of the most famous authors is Eberhard Zwicker who proposes a summary of psychoacoustic indicators relevant of the sound impact, and a specific law combining some of these indicators in order to be more representative of annoyance [2]. Among the psychoacoustic indicators, we can mention loudness, weighted dBs (dB(A), dB(B), dB(C), dB(G)…), sharpness, fluctuation strength, roughness, etc… Nevertheless, studies performed these last years seem to demonstrate that unfortunately there is no general equation allowing to be representative of the overall acoustic comfort whatever the environment is. It is thus necessary to develop a dedicated combination of indicators, depending on the acoustic environment. Meaning that the comfort equation that could be applied to a conference room will be different to the equation set for a car which will also be different from the equation set for a bus, a train, an airplane or a helicopter (Fig. 1). That is why, these last times, EUROCOPTER has launched some psychoacoustic activities dedicated to helicopter environment in order to have a more robust approach of the acoustic cabin comfort. This approach may help us to evaluate the acoustic effect of any H/C modification proposal both on the overall sound level and comfort impact.

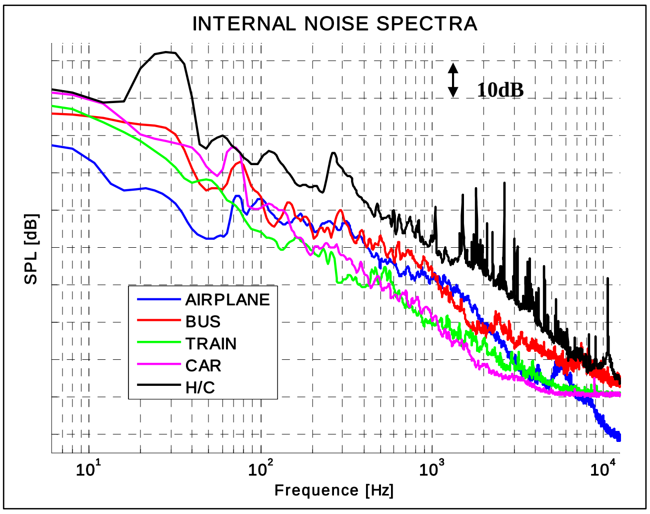

Fig. 1: Internal Noise Spectra of various transportation means, including H/C

This paper intends to present this additional approach based on psychoacoustic criteria. In a first part, we will introduce the dedicated problematic of helicopter environment. The second part will be dedicated to the presentation of psychoacoustic metrics and the logic followed by EUROCOPTER in order to identify the dedicated comfort law. The experimental and modelling studies performed will be introduced. For objective and subjective evaluations of comfort, tests based on headset and a 3D acoustic simulator will be presented. This methodology permits to identify the main psychoacoustic indicators involved in the helicopter comfort and to establish a comfort law. The presentation of the comfort law for helicopters will be the content of the third and last part of this paper.

II HELICOPTER ENVIRONMENT

The sound pressure level spectrum of a helicopter is characterised by a superimposition of several noise sources. This leads to a specific noise signature implying the need of a dedicated comfort law. The Fig. 2 illustrates the typical internal noise signature in a helicopter cabin.

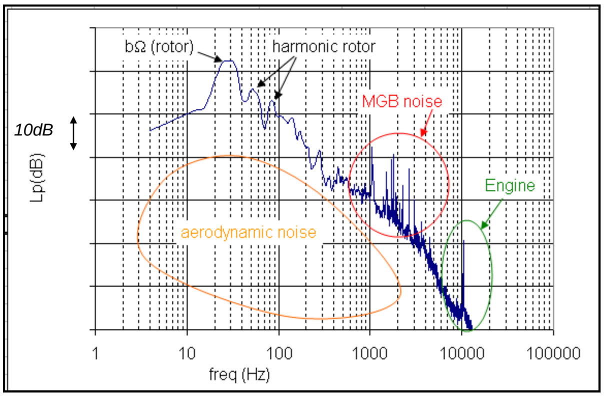

Fig. 2 : Typical sound pressure level spectrum inside helicopter

First, this signature is characterized by a broadband noise coming from aerodynamic sources. Its level is decreasing when the frequency increases and the noise felt is equivalent to a jet noise.

In addition to this aerodynamic noise, a tonal noise at low frequencies is superimposed. It corresponds to the noise generated by the rotor at the blades passing frequency (bΩ) and its first harmonics (basically harmonics 2 and 3). The noise felt is a knocking noise commonly illustrated by a “flap-flap” noise, especially on 2 blades rotors. The feeling is closer to a body sensation like vibration than a hearing noise.

At higher frequencies, from about 500Hz to 5000Hz, a tonal noise due to drive train components appears with high emergences. These frequencies correspond to the Main Gear Box (MGB) and accessories components of the drive train system. This noise is particularly impacting the feeling because of its frequency domain which corresponds to the highest sensitivity of the ears, and because of its emergence with tones higher than 10 dB above the broadband noise implying an easy detection by ears.

Last, a high frequency noise in between 6kHZ to 14kHz is added. It corresponds to the engines signature. Due to its frequency domain and the lower amplitude compared to others sources, this noise can be supposed as a second order sources, but this assumption must be verified during the comfort law identification.

Finally, we get a complex noise signature where several characteristics must be compared and weighted before defining a representative comfort law.

In the next paragraph, we will see that a lot of psychoacoustic criteria exist and each of them has a dedicate function to characterize a specific part of the sound signature which may impact the comfort. Moreover, we will see that a single criterion is not enough to be representative of the comfort but we need a combination of several of them for that.

III PSYCHOACOUSTIC METRICS AND EUROCOPTER LOGIC

During the seventies, many aeronautical companies and organisations such as the NASA led many studies in order to set up new methods and models able to quantify the annoyance generated by aircrafts flyover for regulatory purpose [3], [4], [5]. These researches showed that the metrics used up to then, such as dB(A), or even Effective Perceived Noise Level (EPNL), were not satisfying enough to quantify precisely the annoyance produced by aircraft noise in general.

Even if these studies were globally related to aircrafts external noise, their conclusions could be adapted to some extend to aircraft internal noise annoyance measurement: the need for studying and defining specific models taking into account psychoacoustics parameters.

III.1 PSYCHOACOUSTICS METRICS

Psychoacoustics can be defined as *“the scientific field which quantitatively explains the relations between sound stimuli, well defined in the physical domain, and the hearing sensations elicited by such stimuli“* (H. Fastl) [6]. Psychoacoustics tries to link physical parameters of a sound with their corresponding auditory sensations of the human hearing system.

Psychoacoustics models are based on metrics defined by empirical methods through numerous experimentations. But they are accurate enough to describe the human hearing system behaviour with its physical limitations.

One of the most important characteristic of the human hearing system is the non linearity of its loudness sensitivity over its frequency range sensitivity, going from approximately 20Hz to 20kHz. It is defined by the ISO 226:2003 norm [7] which provides the equal-loudness contour corresponding to a measure of sound pressure (dB SPL), over the frequency spectrum, for which a listener perceives a constant loudness when presented with pure steady tones (Fig. 3).

Others important ears limitations, such as temporal and frequency masking effect or pitch sensitivity and non linear distortions for example, play also an important role in the physical auditory sensation.

However, the aim of this paper is not to provide extensive details on psychoacoustics. Only the most important metrics used for annoyance and pleasantness models presented later on will be shortly explained.

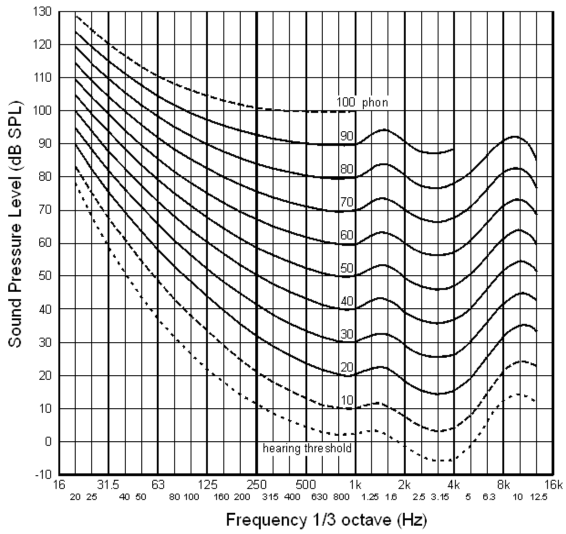

Fig. 3 : Equal-loudness contour

Loudness is the oldest and most used psychoacoustic metric, which describes the magnitude of an auditory sensation. It is defined by E. Zwicker [2] as the sum of the specific loudness of each critical band, called Bark bands Z:

$$N = \int_0^{24Bark} N' dz \quad \text{[sone]} \qquad \textit{Eq. 1}$$

N´= Specific loudness in a given Bark band.

$$N' = 0.08 \cdot \left(\frac{E_{TQ}}{E_0}\right)^{0.23} \cdot \left[\left(0.5 + 0.5 \cdot \frac{E}{E_{TQ}}\right)^{0.23} - 1\right] \frac{sone}{Bark} \qquad \textit{Eq. 2}$$

E = Total Excitation of the noise in the considered Bark band.
E_{TQ} = Excitation corresponding to the absolute hearing threshold, in the considered Bark band.
E_0 = Excitation corresponding to I0 = 10^{-12}W/m².

When a sound magnitude goes from 1 sone to 2 sone, the corresponding auditory sensation is a doubled loudness. This loudness model does not take into account the dynamic aspect of the sound. However, as the noise inside an aircraft can be considered as a stationary one, this loudness model can be used.

The loudness has generally a strong relation with the annoyance of a noise. However it is not the only parameter playing a role in the global annoyance or pleasantness of a sound.

Sharpness is related to the high frequencies content of a sound and plays a prominent role in sound quality [2]. Sharpness, among other things, can be regarded as a measure of tone colour. It is defined as following:

$$S \sim \frac{\int_0^{24Bark} N' \cdot g'(z) \cdot z \cdot dz}{\int_0^{24Bark} N' dz} \quad \text{[acum]} \qquad \textit{Eq. 3}$$

N´= Specific loudness in its Bark band.
g'(z) = weighting factor

Sharpness is often the other main parameter, playing an important role in the annoyance or pleasantness of a sound.

It has been demonstrated [6] that a good balance between low and high frequencies is linked to a pleasant auditory sensation.

Tonalness is related to tones emergence above the background noise level in each critical Bark band, taking into account frequency masking effects [2]. It can be linked to the sound ability to evoke a pitch, by the amount of tonal content and the presence of prominent tones [8]. Many different definitions of tonalness are existing, such as the Tone-to-Noise Ratio (TNR), the Prominence Ratio (PR), but also the Pure Tonalness and the Complex Tonalness [9]. To some extent the Pitch Strength and Virtual Pitch could be considered. The reason of such diversity of tonalness metrics is related to the fact that none of them are able to provide accurate tonalness results on very diverse sounds. Moreover they are more related to the physical content of the sound than the human perception of tonalness.

However, the most common model used nowadays is the TNR, according to Aures model as defined in ANSI S1.13-1995 norm for example [10]. Its calculation is complex and is using three weighting function.

Roughness is related to the sound envelope temporal variation. It is defined for amplitude or a frequency modulation going from 15Hz to 300Hz and it reaches its maximum for a 70Hz modulation [2]. It is defined by:

$$R \sim f_{mod} \cdot \int_0^{24Bark} \Delta L(z) dz \quad \text{[in asper]} \qquad \textit{Eq. 4}$$

f_{mod} = modulation frequency

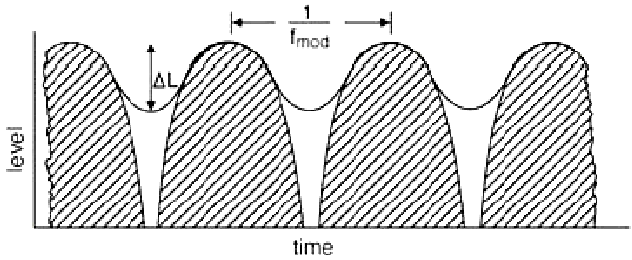

Fig. 4 : Roughness illustration

1 asper corresponds to a 1 kHz tone at 60 dB with a modulation rate of 100% at 70 Hz.

Fluctuation strength is similar to roughness, however it is defined for amplitude and frequency modulation only up to 20Hz and reaches its maximum for a 4Hz modulation [2].

$$F \sim \frac{\int_0^{24Bark} \Delta L dz}{f_{mod} / 4Hz + 4Hz / f_{mod}} \quad \text{[in vacil]} \qquad \textit{Eq. 5}$$

f_{mod} = modulation frequency

1 vacil correspond to a 1 kHz tone at 60 dB with a modulation rate of 100% at 4 Hz.

III.2 EXISTING ANNOYANCE/PLEASANTNESS EQUATIONS

The reason why a sound may be considered pleasant or not pleasant, its sensation of quality or non-quality, depends on physical parameters of the sound itself but also on the subjective relationship of the listener to this sound. These non-acoustic influences can not be anticipated because they depend on many parameters such as personal taste, emotional content of the sound, etc…

According to K. D. Kryter [11], models can be separated into two categories: The noisiness evaluation, which is related to the quality of the noise and the annoyance/pleasantness evaluation, which is related to the discomfort aspect of a noise.

• The Psychoacoustical Annoyance model (PA) proposed by E. Zwicker is a model fitted for noise evaluation. It is used sometimes in the industry as a tool for sound quality prediction [2]. It is defined by:

$$PA \approx N_5 \cdot (1 + \sqrt{w_S^2 + w_{FR}^2}) \qquad \textit{Eq. 6}$$

N_5 =loudness in sone which is exceeded for 5% of the time.

For describing the effect of a sharpness S > 1,75 acum:

$$w_S = (\frac{S}{\text{acum}} - 1.75) \cdot 0.25 \lg(\frac{N_5}{\text{sone}} + 10) \qquad \textit{Eq. 7}$$

For describing the effect of fluctuation strength and roughness F and R:

$$w_{FR} = \frac{2.18}{(N_5/\text{sone})^{0.4}}(0.4 \cdot \frac{F}{\text{vacil}} + 0.6 \cdot \frac{R}{\text{asper}}) \qquad \textit{Eq. 8}$$

• A variant of the psycho acoustical annoyance equation has been given by E.Zwicker, which is more sensitive to low level of fluctuation strength and sharpness. It is defined by:

$$UBA = d(N_{10})^{1.3} \cdot \left\{1 + 0.25(S-1) \cdot \log_{10}(N_{10}+10) + 0.3F \cdot \frac{1+N_{10}}{0.3+N_{10}}\right\} \qquad \textit{Eq. 9}$$

With d = 1
N_{10} = loudness in sone which is exceeded for 10% of the time.
S = sharpness.
F = Fluctuation strength.

• E. Zwicker and H. Fastl proposed also a sensory pleasantness model, defined by:

$$\frac{P}{P_0} = e^{-0.7R/R_0} e^{-1.08S/S_0} \left(1.24 - e^{-2.43T/T_0}\right) e^{-\left(0.023N/N_0\right)^2} \qquad \textit{Eq. 10}$$

P = Pleasantness.
R = Roughness in asper.
S = Sharpness in acum.
T = Tonalness in dB.
N = Loudness in sone.

This model takes into account the tonalness, contrary to the PA equation, but it has been proposed at a time when no model for tonalness calculation was available. Thus, this parameter had to be evaluated according to reference signals.

Thus, we can note that this model gives a relative pleasantness compared to a reference sound, of which the different psycho acoustical parameters are used as references (parameters with index 0).

The models presented previously have been used in very diverse application for evaluating different aspects of sounds [12], [13]. Even if the equations form differs, they use the same psychoacoustics metrics and intent to calculate a value representative of the preference of the listener for a specific sound characteristic.

However theses models are not always well adapted for evaluating certain sound characteristics and the correlation between listening test and model calculation is not enough significant. Therefore, other methods have been used to develop specific models.

The most common method is to use models based on a combination of psycho acoustical metrics with coefficients determined by linear or non linear regression through listening test results. Such models are rather easy to calculate and are usually well adjusted to the listening test results. However their capability to be good predictive models is somewhat limited and can be quite dependant on diverse parameters.

Many application of these models can be found nowadays in many industries such as the automotive industry for car's noise quality and comfort improvement (known as NVH) [14], [15], [16], [17], and sound quality "design" for consumer products and communication system for example [18].

In the aeronautic field, many research programs have also been carried out since the last decade, especially through European financed programs.

One of these studies focused on Artificial Neural Network model (ANN) with the aim of describing as accurately as possible the whole psycho acoustical process occurring on passengers in different types of aircrafts [19]. This method has provided a powerful tool able to cope with diverse type of noise (jet and propeller airplane, helicopters) and should be developed further in the future. However, neuronal network based models are quite complex to set up and need a lot of input data so as to ensure the best results.

III.3 COMFORT METHODOLOGY

These are the different reasons that led Eurocopter to work on the definition of a simple model able to evaluate and predict accurately the psycho acoustical comfort in a helicopter cabin.

Some preliminary work and trials has been necessary in order to understand all the aspects of the development of such model.

One important task consists in evaluating all the different parameters which play a role in the accuracy of the final model. The coefficients of the model are determined through a mathematical regression based on listening test results.

The first step consists in identifying the various possible origins of model imprecision and errors. As regression is done by using the listening test results, the listening test errors must be minimized as much as possible. These errors mainly stem from the test method, the listening method and the test conditions.

Two listening methods are possible: the use of headphones or the use of free field loudspeakers. The preliminary trials that have been carried out were realized with headphones. It's a simple to use and rather good mean for reproducing the noise with high fidelity regarding its spectral content and it allows a true binaural listening. However, with such a method, it is rather difficult to control the overall listening sound pressure levels, and to reproduce properly the feelings implied by sensitive sound pressure levels at very low frequencies.

Actually, because of the non linear relation between sound pressure level and perceived loudness [2], the best listening method should be as representative as possible of the reality, as if the comfort evaluation was done in a real helicopter. Therefore, additional tests have been carried out in a 3D simulator invested by EUROCOPTER. It is composed of four loudspeakers and a subwoofer placed inside an anechoic chamber (Fig. 5). Each speaker is connected to a RME Fireface 400 audio interface plugged to a computer. In order to ensure the best reproduction of real noise spectrum, the position of the listeners and of the loudspeakers has been optimised. In addition, a room frequency response correction and a sound spatialization software programs have been used to recreate as accurately as possible the real acoustic conditions inside a helicopter cabin. This simulator allows recreating cabin spectrum, with high fidelity with a sound level up to 105 dBA.

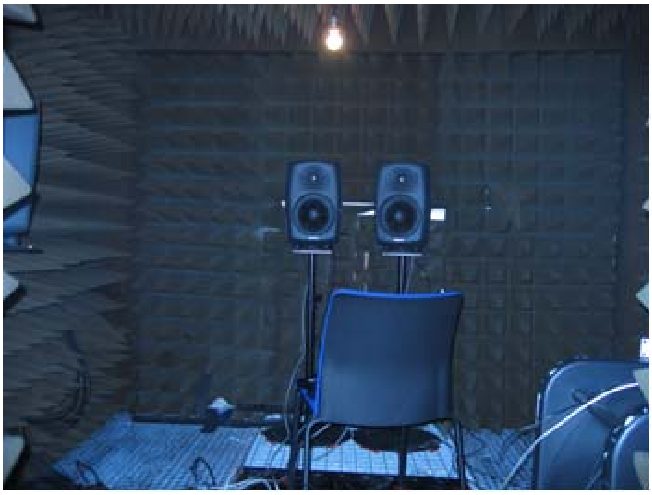

Fig. 5: Acoustic simulator in anechoic chamber

About the test methods, psychologists and psycho acousticians have developed many different ones in order to evaluate various psycho acoustical parameters [2].

Each method has its own advantages and drawbacks according to the psycho acoustical parameters to be evaluated, and also to the test set-up. Therefore, the test method has to be carefully chosen in order to ensure the best representativeness between the comfort measures and the reality, without distortion or levelling effect.

Two different methods are mainly considered in this paper:

• The Magnitude Estimation method that consists in listening one sound and evaluating the magnitude of a given parameter felt compared with reference sounds (for example difference of loudness, sharpness, comfort, etc.).

• The Interval Choice Forced method consists in listening a pair of sounds and then choosing the one that provides the highest comfort feeling, without having to determine in which proportion it is more comfortable, contrary to the magnitude estimation method.

The test method choice depends also on the particular features of the helicopter internal noise characteristics: it can be considered as being a stationary sound and its level is generally high compared to the human ear loudness sensitivity. Therefore, the test duration has to be short enough to preserve the listener of the auditive fatigue.

Another interesting aspect of the comfort would deserve to be investigated. It is based on the distinction between what could be called the "global comfort" and the "relative comfort".

The global comfort could be defined as how a noise is considered as being comfortable compared to another noise, in a global point of view. Thus, the comfort here takes into account all the psycho acoustical parameters of both sounds.

The relative comfort could be defined as the difference of comfort between two noises with their most influential psycho acoustical parameter having been "neutralized".

It has been observed that the psycho acoustical metric having the most important impact on the comfort is the loudness. To "neutralize" it, the gain of each noise should be adapted so that they both have equal loudness. By such process, the comfort difference between them would not be influenced anymore by their loudness difference, and would depend much more on others metrics such as the sharpness for example.

Such investigations are interesting for evaluating the impact of the noise signature on the global comfort and thus have a better understanding of which psychoacoustic metrics is the most adapted for the model, aside the loudness. However, the main study is not focused on this aspect of the comfort but has been nevertheless necessary for validating the final model.

In taking into account all these parameters and after many short test trial, it appeared that the interval forced choice method gives good results with equal loudness sounds for "relative comfort" estimations, whereas the magnitude estimation method gives good results for the "global comfort" estimations.

The model aims at the characterization of global comfort, but the magnitude estimation method, which should be the most adapted in our case, has been considered as being too much time consuming and complicated. As the sound will be played at the same level than in a real helicopter cabin, it has been supposed that the test results would be biased because of the auditive fatigue and the listener's lack of concentration at the end of the test. So, the test follows an interval forced choice method. The test is carried out with a software program, developed especially for the purpose, which plays all the possible combination of sounds plus a few pair repetitions. By using such test pattern it is possible to detect repetition errors and circular triads in the results. Circular triads is for example if sound n°1 is preferred to sound n°2 and sound n°2 is preferred to sound n°3 but sound n°3 is preferred to sound n°1.

At the end of the test campaign, the software program provides errors rate of each listener. This allows removing their individual results from the global comfort results if too many errors have been done.

The samples used for the test should be carefully selected. They should be representative of a wide range of helicopter noise, and also should cover a wide range of psycho acoustical metrics values. Nevertheless, the number of sounds to be tested is rather limited because of the test method. Given the sensitive noise levels measured in helicopter cabins, and the need to assess the comfort in realistic conditions, it has been estimated that the test duration should not excess 10 minutes. Based on the interval choice forced method with 3 seconds lasting sounds and a needed repetition rate of 10%, the optimal number of sound samples should be 10, corresponding to 50 sound pairs to be compared by the listener. The selection of these 10 samples is done among 54 helicopter signals, taking into account also the spectra difference between each aircrafts (Fig. 6).

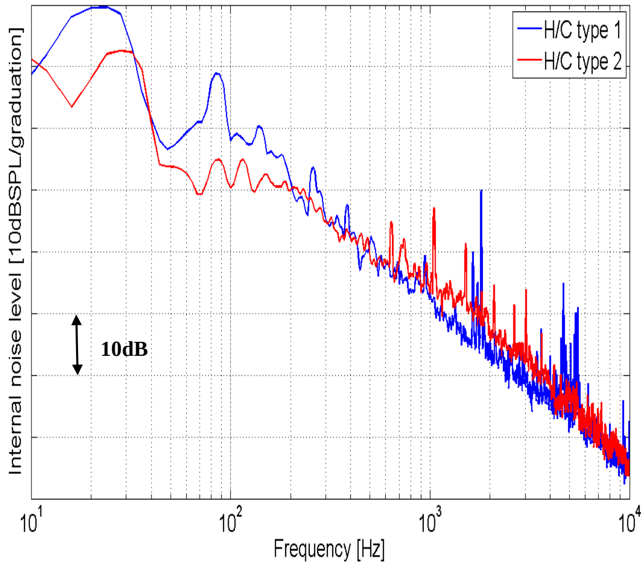

Fig. 6 : Comparison between 2 different helicopter spectra

III.4 PRELIMINARY TESTS RESULTS

As explained above, to better assess the optimal methodology and to choose appropriate tests samples, preliminary test campaigns have been carried out with a Beyerdynamic DT880 headphone. These preliminary listening tests were useful to study the comfort variations with interval forced choice and magnitude estimation test methods. In additions, many different groups of test sounds were listened, in order to determine the best test sounds selection for our case.

These experiments have led to many observations. It appeared that the magnitude estimation test results are widely influenced by the loudness variations. In the same way, tests made with equal-loudness sounds are rather difficult to evaluate because of the greater variations between listener's results. That confirms that loudness is the most prominent metric in comfort estimation. It seems that these variations in the results mainly stem from the subjective and unpredictable part of the comfort feeling of each listener, depending on its own taste, preferences, sensitivity, etc.

Many preliminary models have been calculated by linear regression through these different tests. One of critical parameter evaluated in comfort models estimation is the correlation factor R^2, known as Pearson factor. The latter mechanically increases when the number of values used in its calculation, increases. To avoid such mathematical effect, it is better to use the adjusted correlation factor R^2adj. which takes into account the number of values used for the calculation and thus gives a better idea of the real correlation between two sets of values.

As an example, one model was achieved with a preliminary selection of 10 sounds from different helicopters. It was carried out with interval forced choice method, with only two listeners of an average age of 29 years (STD = 1.4 years). Then the results have been analyzed so as to remove errors and outliers from the final data and to verify many mathematical criteria, as it will be explained later in detail in the main test campaign paragraph. The adjusted correlation factor ***R²adj*** between the test results and the calculated values from the model reaches 92.8% (Fig. 7 & Fig. 8). For comparison, the value calculated with the Zwicker PA (annoyance) equation gives only 8% of correlation (Fig. 7). This emphasize the fact that specific model need to be developed.

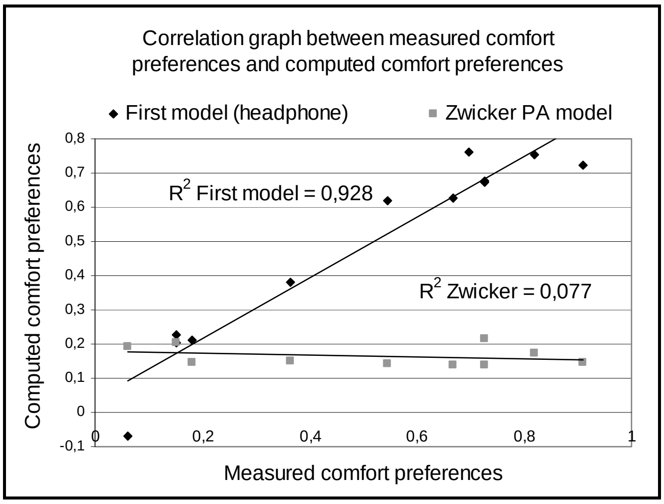

Fig. 7 : Correlation graph between test results with headphone and EC model results/ Zwicker PA results

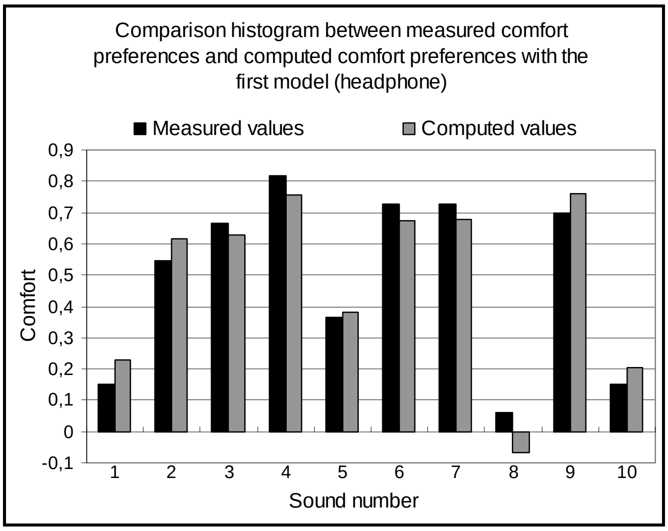

Fig. 8 : Comparison histogram between measured and calculated comfort

Additional preliminary tests were conducted in the noise simulator presented in previous sections. It was noticed that these tests could lead to rather different results than the ones obtained with headphones. It was consequently decided to lead the final listening tests using the acoustic simulator in the anechoic chamber to be as close as possible from realistic from helicopter cabin conditions.

III.5 FINAL TESTS ON NOISE SIMULATOR

In the frame of this study, a comprehensive listening campaign has finally been carried out in the 3D noise simulator with a total of 20 listeners: 2 females and 18 males, of an average age of 27 years (STD = 5.8 years) in order to try to respect some statistical criteria such as minimum sample number.

Based on the results obtained during the preliminary analysis, the final selection of test sounds contained 10 measured samples of light, medium and heavy helicopters with different sound-proofing configurations.

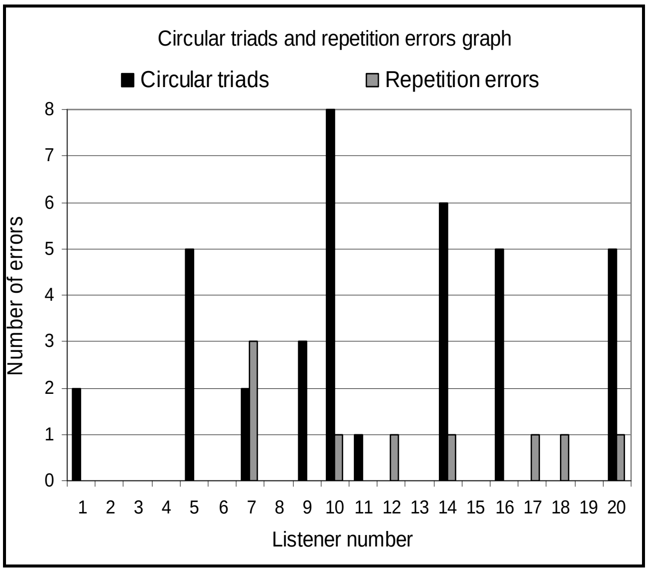

Fig. 9 : Circular triads

Each listener's results were stored by the testing software program, which contains the individual measured comfort values and the average calculated comfort value for each sound.

The first step consists in analysing the results of each listener in order to eliminate those containing too many outliers, circular triads and repetition errors (Fig. 9).

On 20 sets of results, 6 were removed (listener n°5, 7, 10, 14, 16 & 20). The average comfort value for each sound has been then calculated with only 14 individual comfort values (Fig. 10). The standard deviation intervals are also reported on the figure.

The next step is dedicated to the analysis of the impact of the different psycho acoustic metrics on the comfort measures, in order to select the relevant psycho-acoustical metrics that should be included in the model. Several internal studies based on helicopter samples have shown the relationship between comfort estimation and these different metrics**Erreur ! Source du renvoi introuvable.**.

All these studies show that loudness and sharpness are the two main metrics representative of the comfort. This will be confirmed later on in this article with the identified comfort law.

Moreover, two other metrics have been selected: the tonalness and the sound level in dB with a G weighting (dB(G)). Actually, despite the fact that their individual correlation with measured comfort can be low for some test samples, the values taken by these metrics for different helicopter signals are highly linked with physical sources contributions, meaning Rotor Noise contribution (dB(G)) and Main Gear Box noise contribution (tonalness).

At the end in the model, loudness is representative of the global noise level; sharpness is representative of the balance between low and high frequencies over all the spectrum; tonalness is linked to the tone prominence over noise level; and dB G is linked to the sound level at very low frequencies (rotor noise).

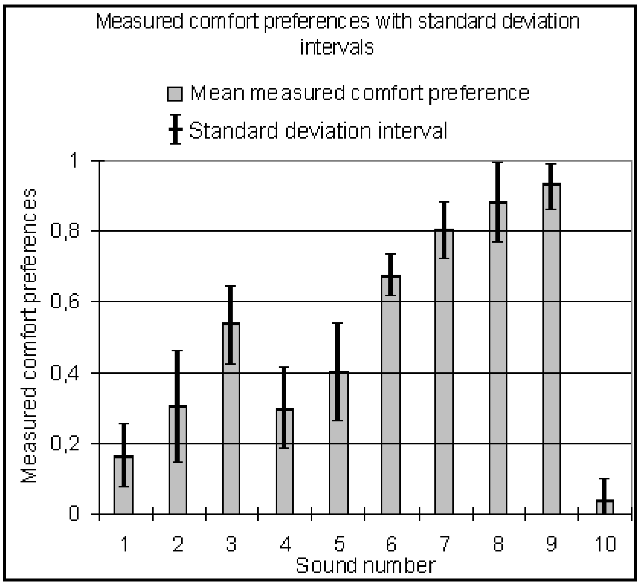

Fig. 10 : Measured values

IV HELICOPTERS COMFORT LAW

Finally, the model is composed of these four parameters plus a constant that permits to set the range of calculated comfort value in the same range as the measured comfort value [0 - 1] for a given test samples set.

Each parameter has a coefficient (a1 to a4), which is calculated through multiple linear regressions based on values of each selected metric and values of the measured comfort:

$$C.I. = a1.L + a2.S + a3.dbG + a4.T + a0 \qquad \text{Eq. 11}$$

C.I = comfort index
L = loudness in sone
S = sharpness in Acum
T = tonalness in dB
a0 = constant

It is now possible to calculate the comfort values and to compare with the measured comfort (Fig. 11). One can observe that the identified comfort law presents a very good agreement with the comfort felt by listeners.

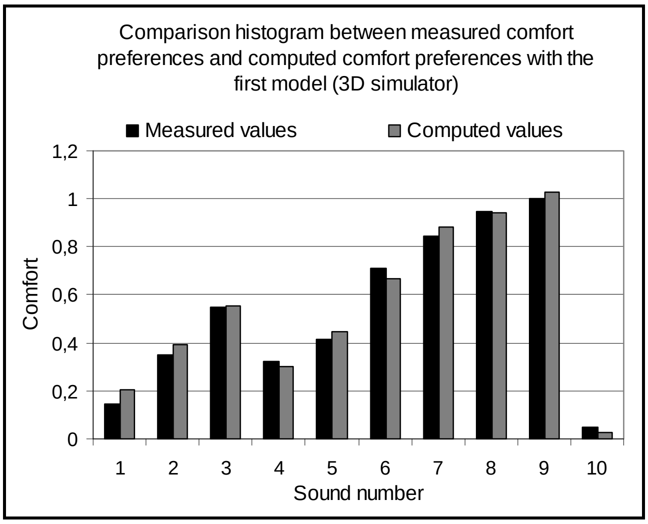

Fig. 11 : Comparison histogram between measured and calculated comfort

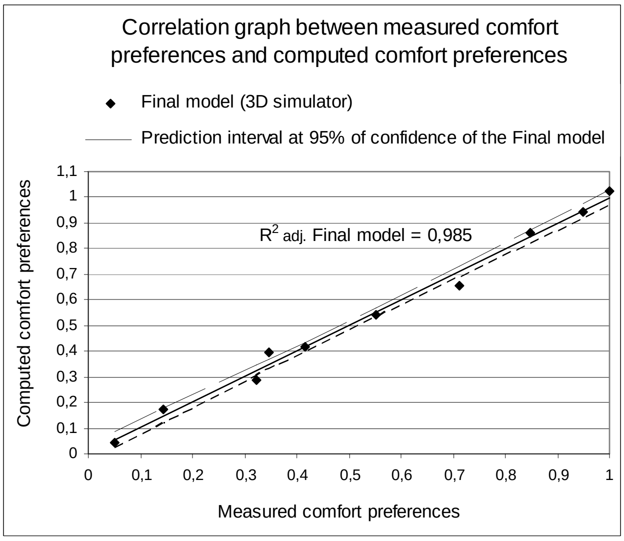

Fig. 12 : Measured comfort vs. calculated comfort

The linear regression curve shows that the adjusted correlation factor R²adj between the calculated comfort and the measured comfort reaches 98.5% (Fig. 12).

A Fisher test [20] allows determining the probability that this high correlation value is due to random values in the equation. Such probability is close to zero in our case, almost equal to 2.36E-5.

A last step is necessary to assess the quality of the model. It consists in analyzing the difference between the calculated values and the measured values, called the residual values. To ensure the model quality, it is necessary to check many parameters [20]. Fig. 13 shows that there is no autocorrelation between the residuals values together and shows a correlation between the residual values and the calculated values with a R^2 factor almost null. In addition, the mean value of the residues must be close to zero, within a 95% confidence interval.

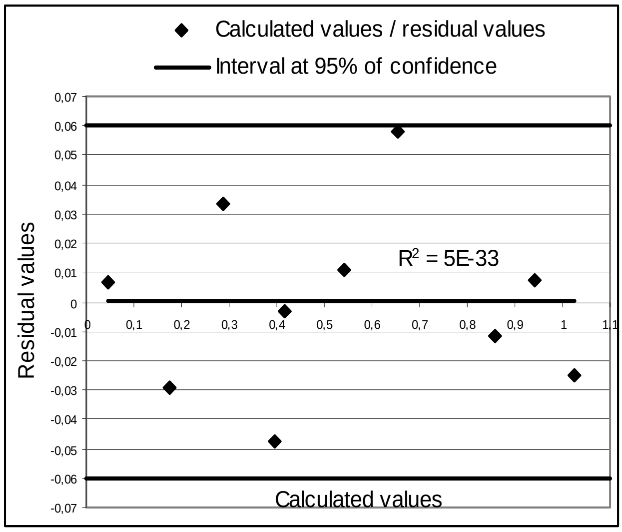

Fig. 13 : Residual values analysis

Finally, it is interesting to observe the average contribution of each metrics used in the model. The latter is plotted on Fig. 14, by a simple estimation of average contribution of each parameter on the test samples. As discussed before, the latter shows the predominance of loudness and sharpness contributions.

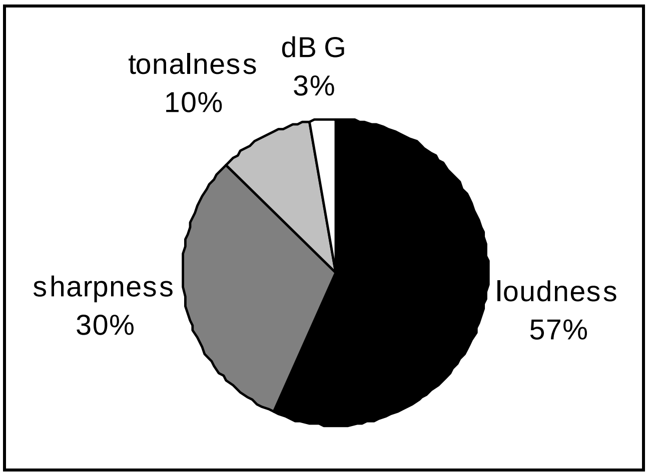

Fig. 14 : Metrics contribution

Finally, the different models presented in this paper have been tested on an extended set of helicopter signals (54 sound samples) and compared with tests performed on a limited number of listeners, in order to estimate the consistency of our model extrapolated to a wider range of samples signatures and levels. The result is shown on Fig. 15 and calculated comfort exhibits a good correlation with measured comfort.

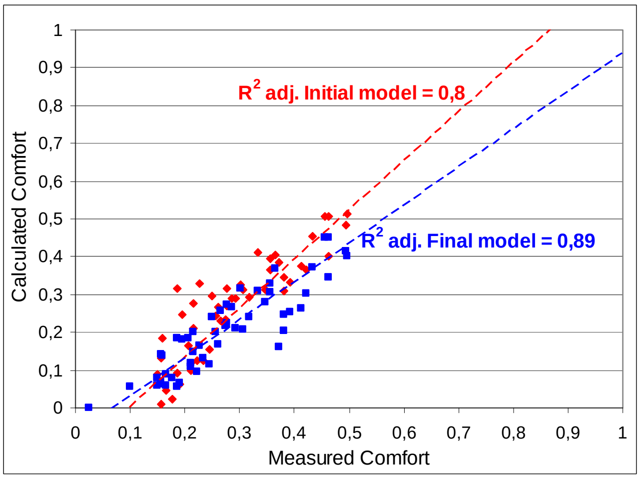

Fig. 15 : Comparison of 2 models on an extended samples set

V CONCLUSION

The aim of this study was to investigate the possible ways of improvement for comfort evaluation of helicopter noise. After a summary of approaches already existing in the literature, we were able to identify experimental processes allowing segregating the main psychoacoustic criteria to be considered in the comfort law. First round of tests was performed based on headset experiment tests. These preliminary listening tests were useful to study the comfort variations with interval forced choice and magnitude estimation test methods. In additions, many different groups of test sounds were listened, in order to determine the best test sounds selection for our case. This campaign demonstrated the need of experimental test in a more representative environment i.e. representative of helicopter sound in term of sound level and noise signature. Thus, a new experimental campaign has been performed in a 3D noise simulator invested by EUROCOPTER. This campaign provided sufficient data to identify the preponderant psychoacoustic criteria involved in the helicopter comfort. Several combinations were tested in order to identify a simple but representative comfort equation. That led us to a linear equation based on four psychoacoustic criteria: loudness, sharpness, tonalness and dBG. This equation allows reaching up to 98% of coherence with experimental test, by keeping criteria strongly linked to the noise signature. It permits to rank the helicopter noise in a relative scale.

Thus, EUROCOPTER is now considering having a first representative equation of helicopter noise comfort. This new tool will be applied on the actual fleet, and as a baseline for all the new development and/or investigations for internal noise improvement. Perspectives of this study would be to use this equation to define an internal noise label allowing ranking the noise comfort of helicopters, like it is already used for electrical appliances.

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