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Helicopter vibrations: study on the use of standard ISO 2631-1 to estimate discomfort

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Abstract

High levels of vibration exist in helicopters and manufacturers are seeking to quantify vibration discomfort. They use the ISO 2631-1 standard, proposed for all types of transport. This study aimed to verify the validity of this index in the specific case of helicopters. Perception tests were carried out in the laboratory. Volunteers assessed the discomfort of vibratory stimuli on test benches generating vertical and triaxial vibrations. Foot, seat and backrest accelerations were measured for each participant according to each stimulus. The ISO 2631-1 comfort indices were then compared with the evaluations given by the participants. The results showed that the standard provided a good estimate of discomfort. However, it lacks precision in estimating the discomfort of stimuli which include amplitude modulations, as can happen in helicopters. A new discomfort index is proposed based on ISO 2631-1 and allows better prediction of subjective assessments.

Keywords: vibrations, perception, helicopters, metric

Practitioner Summary

An improved index based on ISO 2631-1 standard is proposed to estimate helicopter vibratory discomfort. It takes into account the amplitude modulations that can appear at low frequencies in helicopters. This index could be used to estimate vibratory discomfort from accelerations measurements for all types of vehicles.

Email address: laurianne.delcor@gmail.com, etienne.parizet@insa-lyon.fr, julie.ganivet-ouzeneau@airbus.com, julien.caillet@airbus.com (Laurianne Delcor[1,2], Etienne Parizet[1], Julie Ganivet-Ouzeneau[2], Julien Caillet[2])

1. Introduction

Helicopters are complex machines that generate large amounts of noise and vibrations. Constructors actively seek to find out how to quantify vibratory discomfort in order to offer comfortable helicopters to their clients, which they do by measuring accelerations.

The existing literature includes several studies specific to aircraft. The NASA has formulated a comfort index dedicated to aircraft that includes vibrations and noise in its calculation [1]. The discomfort specific to vibrations is calculated using acceleration spectra measured at the passenger's feet along three axes of translation as well as the roll axis and the pitch axis. However, the spectral components to be taken into account in the calculation do not include all the helicopter vibration spectra.

The Aeronautical Design Standard has developed an intrusion index aimed at determining the vibration thresholds that must not be exceeded [2]. It does not provide a discomfort value, since its index only allows rejecting a machine if its vibrations are too high.

One way of obtaining a discomfort value consists in using standard ISO 2631-1 [3]. It proposes a comfort index calculated using acceleration measurements at points of contact between a person and the vibrating surfaces. Thus, it applies to all means of transport (military aircraft [4], cars [5], buses, trains and carriages [6]). Certain studies relating to helicopters have used standard ISO 2631-1 to evaluate the signals calculated following computer simulations [7] and for health requirements [8, 9, 10]. The latter use the health index which is compared to directive 2002/44/CE [11] that stipulates that the health index must not exceed 1.15 $m.s^{-2}$ over a reference period of 8h. This health index differs from the comfort index but is also calculated using acceleration measurements according to the recommendations of standard ISO2631-1.

The ISO 2631-1 standard and its foundations (weighting curves) are questioned in several studies. Marjanen's thesis [6] shows that the weighting coefficients of the standard should be adapted to each environment or each means of transport to which the standard applies. More recently, Huang and Zhang [14] showed that the weighting curves underestimated the discomfort of vertical vibrations with frequencies above 30 Hz.

However, the comparison between the comfort index ISO2631-1 and the discomfort evaluations of helicopter passengers has not been described in the literature. Also, due to the specificity of helicopter vibrations, one may wonder whether this standard is adapted to this type of machine. Indeed, the accelerations measured in helicopter cabins have a rich spectral and harmonic content with high levels. The main excitation is due to the blade passage frequency, $B\Omega$, where B is the number of blades and Ω the speed of rotation of the main rotor in Hz. Its frequency varies from 15 to 30 Hz while its amplitude ranges from 0.03 g to 0.5 g. Also found are harmonics of excitation $B\Omega$, and harmonics of Ω. Since helicopters are assemblies of several rotating parts, other non-harmonic sinusoidal excitations may occur. The aerodynamic interaction of the wake of the main rotor on the tail beam generates random excitations at low frequency, between 5 and 12 Hz. These excitations can cause vibrations in the first modes of the tail beam; this phenomenon is called "tail shake". Figure 1 shows a typical spectrum of acceleration measurements in flight, on the floor of the cabin along the vertical axis.

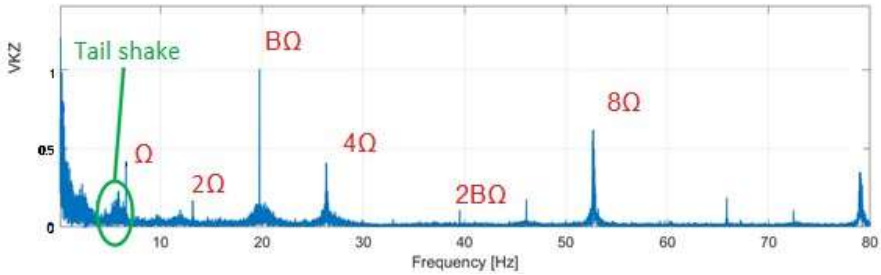

Figure 1: Spectrum representing the vertical vibrations of a three bladed helicopter at its main rotor. The amplitudes are normalized in relation to the amplitude at frequency $B\Omega$.

The objective of this study is to verify the validity of the discomfort estimations given by standard ISO 2631-1, by carrying out experiments on a jury that evaluated helicopter vibrations in laboratory conditions.

2. Experimental protocol

All the data used in this document come from the PhD thesis of the first author during which a large number of test campaigns were performed with different participants and configurations. The first experiment was carried out on a vibration test bench with 6 degrees of freedom (Cube from Team Corporation), installed in the premises of Airbus Commercial (Toulouse, France). Only the 3 translation axes, X, Y and

Z, were implemented. The objective of the test campaign on the triaxial vibrations was to understand the vibratory discomfort linked to several types of excitation representative of those of helicopters, which were synthetized and taken from measurements in flight.

The second test campaign was performed on a vertical vibration test bench, installed in the Laboratoire Vibrations et Acoustique in Lyon, France. The purpose of this study was to understand how the discomfort generated by the vibratory stimuli synthetized by the sum of two sinusoids of variable frequency and amplitude evolve. The vibrations represented the harmonic and non-harmonic phenomena found in the vibration spectra of helicopters. The vibrations capable of inducing a beat phenomenon were investigated.

The participants, the experimental equipment and the procedures of these two test campaigns are summarized in the following parts.

2.1. Participants

Experiment on triaxial vibrations.

The participants taking part in this experiment were Airbus employees. Most of them were engineers, and some were trainees. In all, 30 people participated in the experiment, 7 women and 23 men with an average age of 39.9 years old (min = 22. max = 59 years). They were of various morphologies. Their average height was 1.74 m (min = 1.60, max = 1.88 m) and their average weight was 72.3 kg (min = 50, max = 109 kg). Their average BMI (Body Mass Index) was 23.7 kg.m^{-2} (min = 18.8, max = 32.9 kg.m^{-2}).

Experiment on vertical vibrations.

The participants in this experiment were students of INSA Lyon (undergraduate and Ph.D. students). In all, 41 people participated in the experiment, 17 women and 24 men with an average age of 21.2 years old (min = 19, max = 24 years). They had varying morphologies. Their average height was 1.74 m (min = 1.53, max = 1.97 m) and their average weight was 67.5 kg (min = 47, max = 93 kg). They had an average BMI of 22.1 kg.m^{-2} (min = 17.0, max = 27.6 kg.m^{-2}).

Conditions for participating in the experiments.

For the two test campaigns, the people who participated had to attest that they were not subject to any medical contraindications and sign a form certifying this was the case. The duration of each experiment for each participant was one hour for the two test campaigns. The participants were informed of the objective of the experiments and that they could withdraw from them if they so wished. The participants of Lyon were remunerated for their participation (20 € per person), though not those participating in the experiment in Toulouse, who were employed by Airbus. The protocol of each experiment was validated by the Ethics Committees of Airbus Commercial and of INSA-Lyon.

2.2. Test resources

Experiment on triaxial vibrations.

As mentioned above, the triaxial vibration test bench was the Cube from Team Corporation (Burlington, USA). The Cube reproduces vibrations via six hydraulic cylinders, oriented by pair in each of the directions *X*, *Y* and *Z*. A control in phase of two cylinders corresponding to a direction ensures one translation, while dephasing introduces a rotation component. Each cylinder is equipped with acceleration and displacement sensors used to calibrate the Cube as a function of the setpoint excitations. This test bench permits displacements of 46 mm peak to peak on each of the axes for frequencies ranging from 0 to 250 Hz. It permits reliably reproducing signals measured at the foot of the seat of a helicopter in flight.

The seat of the helicopter in which the participants are seated is fixed to the platform of the Cube by a metal interface plate (see Figure 2). This seat is a Fischer H160 model (Landshut, Germany) and can be found in many helicopters.

This setup was then fitted with instruments to measure the accelerations required to calculate the discomfort index of ISO 2631-1. Thus, a triaxial accelerometer was placed at the feet of the seated person, directly on the interface plate between the Cube and the seat. Two pad triaxial accelerometers were placed on the seat at the seat-person interface. The first pad accelerometer was placed on the seat under the ischial bones of the participant, while the second accelerometer was placed on the back rest, where it gives greatest support to the back.

Figure 2: Picture of the Cube, in yellow, on which is mounted a helicopter seat equipped with two pad accelerometers.

Experiment on vertical vibrations.

A vibrating test bench developed previously at LVA was used. The vibration simulator is a metal structure with two parts. The upper part is linked to the low part by four springs that support its weight. A vibrator (LDS V 550, Bruel & Kjaer, Naerum, Danemark) is placed underneath and subjects the upper part to vertical vibrations. The same standard helicopter seat (H160, Fischer Seats, Landshut, Germany) was fixed to the bench (see Figure 3). The simulator was controlled by Matlab. The signals were sampled at a frequency of 1000 Hz and converted analogically by a sound card (ROGA DAQ2, Viaxys, Ferrières-en-Gâtinais, France) before being transmitted to the amplifier of the vibrator (LDS PA 1000, Bruel & Kjaer, Naerum, Danemark).

The transfer function of the bench was measured for each participant before they were subjected to the stimuli. This transfer function was defined between the output of the sound card and the vertical vibration of the upper part of the platform, measured at one of the seat fastening points. Each stimulus was then filtered to compensate the effect of this individual transfer function between 3 and 200 Hz.

The same instrumentation as that used for the experiment on the triaxial vibrations was used.

Figure 3: Picture of the test bench and helicopter seat used for the experiment on vertical vibrations.

2.3. Procedure

The objectives of the test campaign were presented to the participant. Once the explanations had been given and understood, the participants could install themselves on the seat and the experiment begin.

The two test campaigns were composed of several sub-experiments which were presented one after the other during the session. At the beginning of each sub-experiment, examples of vibratory stimuli were presented to the participant to familiarize them with the stimuli and provide them with an idea of the discomfort evaluations they could give. The examples of stimuli were taken directly from the stimuli to be evaluated and were representative of the range of variations of the different stimuli parameters of each sub-experiment. Once the examples had been given, the stimuli to be evaluated were presented one by one. The duration of a stimulus was 10 seconds for the two test campaigns (including 0.5s of fade in and fade out). At the

end of each stimulus, the participants had to give their evaluation of discomfort in the form of a numerical value between 0 and 50. These values corresponded to semantic labels placed on a scale of discomfort based on standard ISO 16832 [12] (see Figure 4).

For the test campaign on triaxial vibrations, the order of the sub-experiments and the order of the stimuli were pseudo random for technical reasons relating to the control of the test equipment, as the control software of the equipment did not permit such permutations. For the test campaign on the vertical vibrations, the order of the sub-experiments and the order of the stimuli were random.

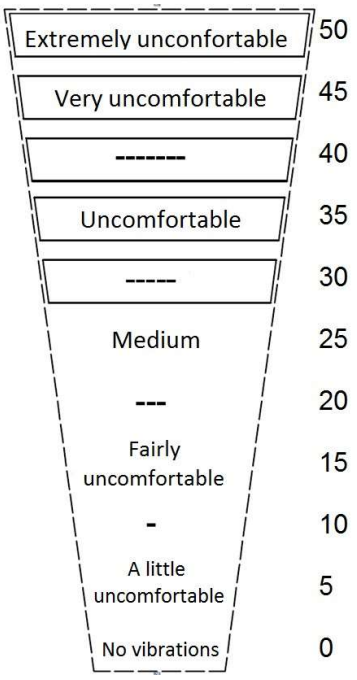

Figure 4: Semantic numerical scale used to evaluate vibratory discomfort. Based on standard ISO 16832 [12].

2.4. Stimuli

Most of the stimuli presented in the two test campaigns were synthesized by computer and divided into sub-experiments. Some of them were used to understand the sensation of discomfort for $B\Omega$ type excitations. Thus, pure sine waves of variable frequency and amplitude were played to the participants. The frequencies varied between 16 and 31.5 Hz and the amplitudes between 0.057 g and 0.18 g along axes X and Y, and between 0.1 and 0.32 g along axis *Z*. This led to about forty stimuli.

The tail shake phenomenon was also studied. It concerned 18 stimuli for which a random excitation centered on a frequency of 6 Hz was created. A bandpass 2nd order Butterworth filter was used (band-pass: 4.5 to 7.5 Hz). The amplitudes of these stimuli varied from 0.07 to 0.25 g along axis *Y*, and from 0.03 to 0.1 g along axis *Z*.

Helicopters comprise several rotating parts, and thus have a vibration spectrum with many lines, both harmonic and non-harmonic. Thus, several subexperiments were performed to understand the impact of two simultaneous sinusoidal excitations on discomfort. The amplitudes of the 128 stimuli concerned varied between 0.034g and 0,35g along axis *Z*, for frequencies ranging from 5.7 to 56.7 Hz, with a frequency delta between 0.5 and 28.3 Hz.

Lastly, twelve real stimuli were played. They came from measurements in flight made on the floor of helicopter cabins. Their frequency content was mainly situated between several Hz and about 60 Hz. Their RMS amplitude could vary between 0.05 and 0.07 g along axis *X*, between 0.03 and 0.12 g along axis *Y*, and 0.02 and 0.23 g along axis *Z*.

In all, 75 stimuli were evaluated for the triaxial vibration test campaign and 134 stimuli for the vertical vibration test campaign.

3. Results

The analysis of vibration measures performed on the test equipment during the experiments showed that, for 5 participants of the triaxial experiment and 8 participants of the vertical experiment, the signals reproduced did not conform to the targets. Therefore, the results of these 13 participants were not included in the analysis, reducing the groups of participants to 25 people for the experiment on triaxial vibrations and 33 people for the experiment on vertical vibrations.

3.1. Index of discomfort of ISO2631-1

For each stimulus and for each participant, the accelerations measured at the feet, the seat and the back rest were used to calculate the comfort indexes of ISO2631-1. Then, the average ISO indexes could be compared to the average evaluations of discomfort given by the participants for each stimulus. Figure 5 shows the average evaluations of discomfort from both vertical and triaxial experiments as a function of

the average ISO indexes expressed in dB. It shows a good correlation between these two quantities ($R^2 = 0.78$, $F(1.73) = 750$, $p < 0.0001$).

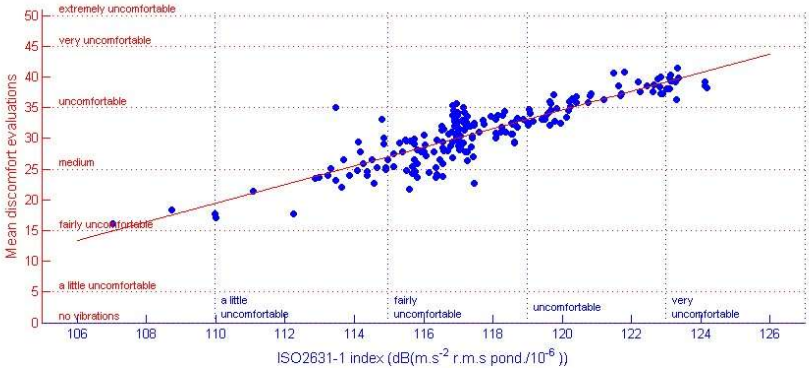

Figure 5: Relation between the average evaluation of discomfort and the average comfort indexes of ISO2631-1 expressed in dB.

However, figure 5 shows that the index does not always correctly predict the discomfort of some signals. At about 117dB, several stimuli have the same ISO value but higher average discomfort evaluations. These stimuli are composed of a sum of two sinusoids. The small difference in frequency between the two components leads to a considerable variation in amplitude of the temporal signal. This corresponds to a phenomenon frequently measured in helicopters, for example, when the excitations of the main rotor are close to those of the tail rotor.

For such signals, the discomfort predicted by the standard is significantly underestimated. Indeed, the modulations of amplitude were not taken into account in the index calculations of the standard, since only the frequency content was used. It is therefore necessary to improve the calculation of the comfort index of standard ISO 2631-1 to take into account the amplitude modulation phenomenon.

3.2. Equation of discomfort based on ISO2631-1

Since the modulated stimuli were underestimated by the comfort index of standard ISO 2631-1, a penalty on their calculation may be a solution for better correlation with the discomfort evaluations given by the participants. This penalty should depend on the amplitude modulation and have no impact on the calculation of the index for the non-modulated stimuli. One way of achieving this is to multiply the temporal accelerations

of the stimuli by (1 + a_{mod}), where a_{mod} is the amplitude of the modulation in g. Thus, if there is a large modulation, the global amplitude of the stimuli will increase and its ISO 2631-1 comfort index will be higher, indicating greater discomfort. On the contrary, if a_{mod} is null, the calculation of the index does not change.

The modulation of the amplitude was calculated using the acceleration measured at the feet, which are generally more suitable and usable than the accelerations measured at the seat or at the back rest. Moreover, a value of $a_{modX,Y,Z}$ must be calculated for each axis of vibrations. Then, the multiplication by (1 + $a_{modX,Y,Z}$) can be applied to each acceleration signal, $feet_{X,Y,Z}$, $seat_{X,Y,Z}$ and $back\ rest_{X,Y,Z}$, in relation to the axes concerned.

The amplitude modulation was calculated by detecting the envelope on the temporal signal. The signal was centered and the upper and lower envelopes, env_{inf} and env_{sub}, were searched by the peak detection method ("envelope" function of Matlab). This method is used to find the local maximums separated by at least n points. The choice of n is based on the study of Fothergill and Griffin [13] who showed that beats are no longer felt for differences in frequency between the two sinusoids that compose the signal higher than 8 Hz. The value of n should be such that only the envelopes whose frequency is lower than or equal to 8 Hz are detected. The difference between two local maximums to obtain the minimum and maximum variations of the envelope must be $\frac{T}{2} = \frac{1}{2*8H} = 0.0625\ s$. Value n is therefore deduced from this time and the sampling frequency of the signals.

Furthermore, tests were performed on the envelopes to verify whether or not there was a modulation. The first test was a simple test of correlation between the lower and upper envelopes. The second consisted in calculating the phase shift between these two envelopes. If the correlation was greater than 0.7 and the phase shift was lower than 45, the variations of the envelopes were considered as linked to the modulation of the amplitude. Otherwise, the modulation of amplitude a_{mod} was set at zero. These values were chosen arbitrarily, with a sufficiently large margin to detect modulations even when the signal was slightly noisy. Once the lower and upper envelopes, env_{inf} and env_{sup}, were calculated, the average of their absolute values was calculated to obtain a more reliable envelope env_{moy}. A peak detection was then performed on the average envelope to obtain its minimum and maximum values a_{min} and a_{max}. The latter were averaged and their difference constituted the amplitude of the modulation a_{mod} of the signal.

This penalty was applied to all the measures of stimuli in the experiments presented in this article, and the ISO2631-1 comfort indexes were recalculated on the basis of these penalized accelerations. Figure 6 shows the average evaluations of discomfort as a function of the modified ISO 2631-1 comfort indexes. They show a better correlation between these two quantities ($R^2 = 0.84$, $F(1,73) = 1.19e3$, $p < 0.00001$).

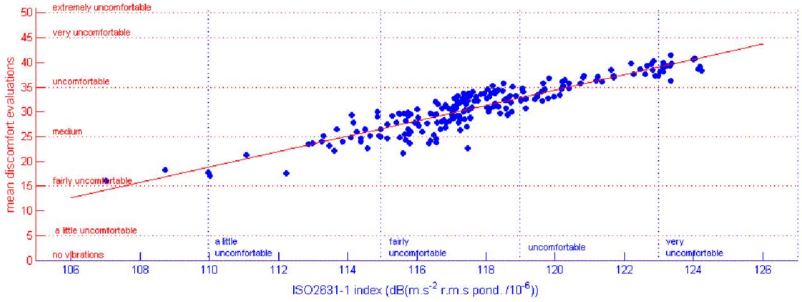

Figure 6: Linear regression between the average discomfort evaluations and the average modified ISO2631-1 comfort indexes expressed in dB.

The semantic descriptors of discomfort of the modified ISO indexes do not correspond perfectly to those indicated by the participants and the slope of the regression line shown in Figure 6 is clearly lower than 1. However, it is possible to make the semantic descriptors of discomfort correspond by a linear relation 1:

$$Vibratory\ Discomfort = a * 20 * log10\left(\frac{ISO_{modified\ index}}{10^{-6}}\right) + b \qquad (1)$$

where a and b are coefficients of the regression.

4. Discussions

The results obtained agreed with those of Fothergill and Griffin [13] who measured the discomfort equivalent to several stimuli by asking ten participants to adjust the amplitude of a sinusoidal stimulus by 10 Hz to produce the same amount of discomfort as the stimulus presented. In their study on the perception of discomfort produced by vibrations at a double frequency, the results showed that the ISO 2631-1 indexes did not allow estimating the discomfort correctly. According to their studies, the discomfort perceived for the double frequency stimuli could be estimated by the square root of the sum of the squares of the equivalent discomfort of the frequency components, or by a linear regression with as factor the estimations of discomfort of each of the frequency components. However, these indicators underestimated the discomfort for stimuli with

an amplitude modulation (in the case of a small difference between the two frequencies). This result is consistent with the application of a penalty to discomfort estimations when the stimuli have amplitude modulations.

In a recent study, Park et. al [15] showed that the discomfort of a stimulus composed of two frequencies with an amplitude ratio of 0.8 and a frequency deviation of 1 or 2 Hz was 3.8 dB higher than the vibrational discomfort of the frequency components taken alone. Our results confirm this penalty due to amplitude modulation. Using equation (1), a difference of 3 dB is obtained for stimuli similar to those proposed by Park et al. Therefore, equation (1) allows for the generalization of the results published in [15].

It should be borne in mind that these results were obtained from laboratory experiments and must be verified by tests performed in flight. Indeed, the equation of discomfort presented in this article concerns only vibrations, and the discomfort in real conditions cannot be dissociated from noise, odours and the general environment. Additional experiments specific to helicopter excitations should be performed to better understand the impact of simultaneous noise and vibration on discomfort. An interaction between the two sensory modalities has already been highlighted (see [16] for example in the case of band-pass filtered noise).

What is more, the results are based on experiments carried out on a single model of a seat and they must be repeated with different types of helicopter seat. The results should be similar to those obtained in this paper because helicopter seats are all relatively rigid.

Lastly, although this study essentially concerns passengers, it should be noted that the participants were naïve and that the results may vary for pilots and crews accustomed to flying in helicopters.

5. Conclusions

Experiments were carried out to compare discomfort evaluations made by volunteers with the comfort indexes of standard ISO 2631-1 for helicopter vibrations. The results showed that this standard provides an initial good approximation of discomfort. However, it has limitations and underestimates discomfort when the stimuli contain amplitude modulations, a situation that occurs quite regularly in helicopters. A modification of the calculation of the ISO 2631-1 index was therefore proposed. Thus, a penalty was applied to the temporal acceleration measurements with variations of

amplitude, calculated using the amplitude modulation. This modification improved the correlation between the evaluations of discomfort made by the participants and the calculated estimations of discomfort.

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