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# Model of sound and vibration discomfort in helicopter cabins

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## Abstract

Noise and vibrations are major sources of discomfort in helicopter cabins and helicopter manufacturers are seeking to estimate passenger discomfort based on noise and vibration measurements. To this end, series of perceptive experiments have been conducted to link subjective assessments of discomfort to objective measurements. Firstly, it has been shown that noise discomfort is governed by perceived intensity and an acoustic comfort equation has been established based on a sound loudness metric. A second series of tests is presented in this document and aims to estimate the global discomfort due to simultaneous noise and vibrations. Discomfort indicators specific to noise and vibrations were used to create a global discomfort equation. This equation shows a similar contribution to the global discomfort from the two sources but demonstrates an interaction term which disadvantages comfort if one of the sources is dominant.

*Keywords:* noise, vibrations, perception, helicopters

## 1. Introduction

Helicopters are complex machines which generate significant levels of noise and vibrations. At the same time, comfort is more and more important for passengers. It is therefore important that manufacturers are able to quantify discomfort so that they can offer their customers comfortable helicopters. This is particularly important for machines intended for transporting people, which are the subject of this work.

The literature proposes a standard (ISO 2631-1) for the quantification of vibration comfort based on acceleration measurements [1]. However, the comfort estimations provided by this standard do not take into account the discomfort caused by vibration amplitude variations, which can sometimes be observed in helicopters. A study on vibration discomfort in helicopter cabins has proposed an improvement of this standard, making it possible to give a better estimation of discomfort using vibration measurements by considering the amplitude modulation of vibrations [2]. Vibration discomfort  $U_{vib}$  may be obtained from the ISO2631-1 index  $ISO_{mod}$  thus amended by the relation (1), which enables discomfort to be estimated between 0 “no vibrations” and 50 “extremely uncomfortable”. The indicator  $ISO_{mod}$  is calculated based on ISO 2631-1 standard but takes into account the phenomenon of amplitude modulation thanks to a penalty proportional to the modulation amplitude.

$$U_{vib} = \alpha \times 20 \times \log_{10} \left( \frac{ISO_{mod}}{10^{-6}} \right) + \beta \quad (1)$$

where  $\alpha$  and  $\beta$  are two numbers which cannot be mentioned for confidentiality reasons.

As regards noise, several studies addressed the link between discomfort and sound indicators. Various metrics have been proposed to describe noise discomfort in different vehicles and situations: loudness and sharpness in cars [3,4], sound pressure level of high frequencies in trains [5], overall sound pressure level in planes [6] are some examples. Regarding helicopters, a study conducted by NASA reported that sound level in dBA was correlated to annoyance responses of noise in helicopters, in a better way than two other noise descriptors (OASPL and SIL) [7].

All these studies agree that acoustic discomfort depends on the perceived sound intensity. However, none of them provide an acoustic discomfort equation which could be applied to modern helicopters, which have the particular feature of having a very high-level sound signature with many emerging frequencies (that are due to blade passing, engine rotation and gearbox).

Finally, regarding the discomfort related to the simultaneous presence of noise and vibrations, the literature review of [8] shows that studies devoted to the interaction between these two sensory modalities present different conclusions. These studies are based on the estimation of global discomfort from estimations of discomfort linked specifically to noise or vibrations, or from metrics which are supposed to represent these partial discomforts. In the field of ground transportation, the annoyance for residents of railroad lines (train or tramway) was modelled by a linear combination of vibration dose value and A-weighted sound energy [9] or vibration velocity and A-weighted sound pressure level [10]. No interaction was introduced in the models. Similarly, in the case of drivers of diesel car at idle [11], a model was built from a linear combination of accelerations measured at the seat track and on the steering wheel and a subjective assessment of noise, when presented in isolation.

Other studies show that a model with interactions gives better discomfort estimations. An example is given in [12], in which people in a lying position were subjected to noise and vibrations typical of what a person living near a train line might experience. It appeared that, for the highest vibration level, the influence of noise level was quite small (and vice-versa), indicating a dominant-source effect.

For airplanes application, NASA has proposed a model [13] which provides a global comfort index based on measurements of vibration and noise expressed respectively in g and dBA. These measurements make it possible to calculate an acoustic discomfort indicator and a vibration discomfort indicator to be combined to obtain the global discomfort estimation. This empirical model is very dependent on the vibration discomfort model because the calculation of the acoustic discomfort indicator depends upon it. Later, Quehl [14] conducted an experiment using a platform vibrating in the vertical direction and a stereophonic arrangement of headphones. Nine combinations of stimuli were presented to participants (noise level varied in 3-dB steps, vibration level in 4 dB steps). The experiment was replicated for stimuli recorded in turboprop or jet engines. In both cases, additive effect appeared, as noise and vibration contributed to discomfort (the contribution of noise being twice the one of vibrations). Finally, a recent study from Aggarwal et al. [15] mentioned

contradictory results: when submitted to various contributions of noise and vibration recorded in a turboprop, participants were mainly sensitive to noise level, while vibration level had a very low contribution. All in all, the existing literature presents contradictory results. Moreover, no study was devoted to discomfort in helicopters, while noise and vibration stimuli have very high levels in helicopters when compared with other transportation means.

The present study will answer two questions. Firstly, how acoustic discomfort in helicopter cabins is related to sound metrics? Secondly, how discomfort due to noise and vibrations in helicopter cabins can be estimated based on specific discomfort indicators?

To respond to these problems, two experimental campaigns have been conducted. The first concerns acoustics and aimed to estimate acoustic discomfort from measurements by linking the discomfort assessments given by a jury to sound metrics. Sound level indicators from the literature will be used, Sound Pressure Level, A- C- and G-weighted SPL, loudness level, as well as indicators usually calculated at Airbus. The second experiment is aimed to link the global assessments of discomfort given by the jury with the specific acoustic discomfort indicator from the first experiment and that of vibrations presented in the prior study of the authors [2].

## **2. Acoustic discomfort**

### *2.1. Participants*

The group of volunteers who took part in the experiment was made up of 33 people (4 women and 29 men). Their average age was 35 (min. = 21, max. = 52). They were all employed by Airbus Helicopters Marignane (engineers, sub-contractors, trainees, PhD students), and had to ensure that they had no medical contraindications and no known hearing problem before taking part in the experiment.

The participants, who enrolled for a 1-hour session, were informed of the objective of the experiment and that they could terminate it if they so wished. The experimental protocol has been validated by the Ethics Committee of Airbus Helicopters.

### *2.2. Experimental setup*

The participants listened to sound stimuli in a room in Airbus Helicopters Marignane fitted with 4 Genelec 8050A loudspeakers and 2 Genelec 7071A subwoofers (see Figure 1). Sounds were generated by a sound card (RME Fireface UC). The whole sound system was calibrated and equalized for playback. Participants were seated on a height-adjustable chair to ensure that the ears of all the participants were in the same position, in order to maximise the quality of the sound restitution and repeatability.

A measurement of all the stimuli played to participants was performed before the series of tests with a microphone in the centre head position, i.e., placed in the centre of the imaginary line between participants' ears if they are sitting on a chair. This method has been chosen rather than measuring with a dummy head

because it is representative of the noise measurements that are performed in helicopters.



*Figure 1: Photograph of the noise simulator in the sound restitution configuration for the acoustic experiment.*

### 2.3. Procedure

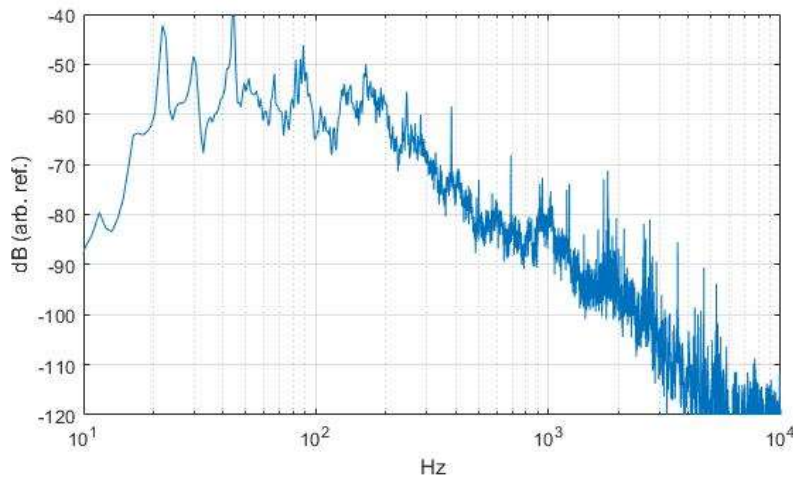
The participant was given the objectives and the instructions before starting the experiment. Then the participant was able to sit on the chair and start the experiment with several examples of stimuli. The examples were drawn from all the stimuli to be evaluated and were representative of the range of variation of the stimuli in dBA. Finally, the participants evaluated the stimuli presented one by one at their own pace.

The participants evaluated each sound stimulus on the Jury Listening Test software from Ansys, with a magnitude estimation method. They marked the sounds from 0 “no noise” (“pas de bruit” in original language) to 50 “extremely uncomfortable” (“extrêmement inconfortable” in original language) on a labelled scale based on the standard ISO 16832 [16] and similar to that used to assess the vibration discomfort in a previous study [2]. As mentioned in the introduction, the study objective is to suggest a comfort indicator for passengers in transport helicopters. This is why no specific task needs to be performed by the participants in the experiment.

### 2.4. Stimuli

The stimuli chosen for this experiment result from in-flight measurements and come from several helicopters from all Airbus offer (VIP, Oil and Gas, safety and military helicopters). The acoustic measurements in helicopters have been performed with a microphone in the centre head position, i.e., in the middle of the imaginary line between the two ears of a person sitting on a helicopter seat. The measurements are generally

performed on several seats in the cabin. These stimuli were selected from a database, with the constraint being that their sound level did not exceed 90 dBA, so as not to damage the participants' hearing. These were stimuli recorded over the entire range of Airbus helicopters during flight phases of forward travel at constant speed (varying from 100 to 143 knots). Figure 2 shows an example of noise helicopter spectrum.



*Figure 2: typical spectrum of helicopter's interior noise.*

In total, participants had to assess 45 stimuli of 5 seconds (including a 0.5 s cross-fade at the beginning and end of the signal). This choice is a compromise between playing a great number of signals and not tiring the participants with a too long experiment. The levels varied between 76.9 and 89.7 dBA. The order of the stimuli was random for each participant.

## 2.5. Results

First of all, the consensus among participants have been looked for. The correlation between two participants is always high. The average value is 0.72, the minimum one being 0.39, which still indicates a significant correlation between the answers of the two corresponding participants ( $p < 0.01$ ). So, no participant was excluded from the panel and the discomfort evaluations were averaged over the 32 participants. The approach used for analysing the results involved examining the correlations between the average discomfort assessments given by the participants and various sound indicators (see Table 1). The selection of these indicators was based on the following statements. Some of them are supposed to be related to the subjective intensity of sounds, as this was supposed to be the most important sound features, considering the large range of variation of stimuli sound levels. We use sound pressure level, A and C-weighted SPL and G-weighted SPL (G weighting consists in emphasizing very low frequencies, i.e. below 50 Hz) and loudness (computed according ISO532-1:2017). Two other indicators are commonly used by Airbus (sharpness and Tone-to-Noise Ratio). These indicators were calculated for each stimulus played by the sound simulator and measured by a

microphone as previously mentioned. The difference between the target and the measured sound levels is plus or minus 1 dB.

The best linear regression was obtained for loudness level computed according Zwicker's method [17]: coefficient of determination was  $R^2 = 0.91$  ( $F=402$ ,  $p<0.001$ ), indicating a strong relation between loudness and discomfort.

Indicators	correlations
Sound Pressure Level	0.62
A-weighted SPL	0.88
C-weighted SPL	0.63
G-weighted SPL	0.34
Loudness level (ISO532-1:2017)	0.95
Sharpness (Zwicker [18])	0.68
Tone-to-noise ratio (ANSI s1.13 [19])	0.40

Table 1: Correlations between acoustic metrics and mean discomfort evaluations.

Figure 3 presents the relation between loudness level values and discomfort evaluation of noise (mean value in their 95% confidence interval).

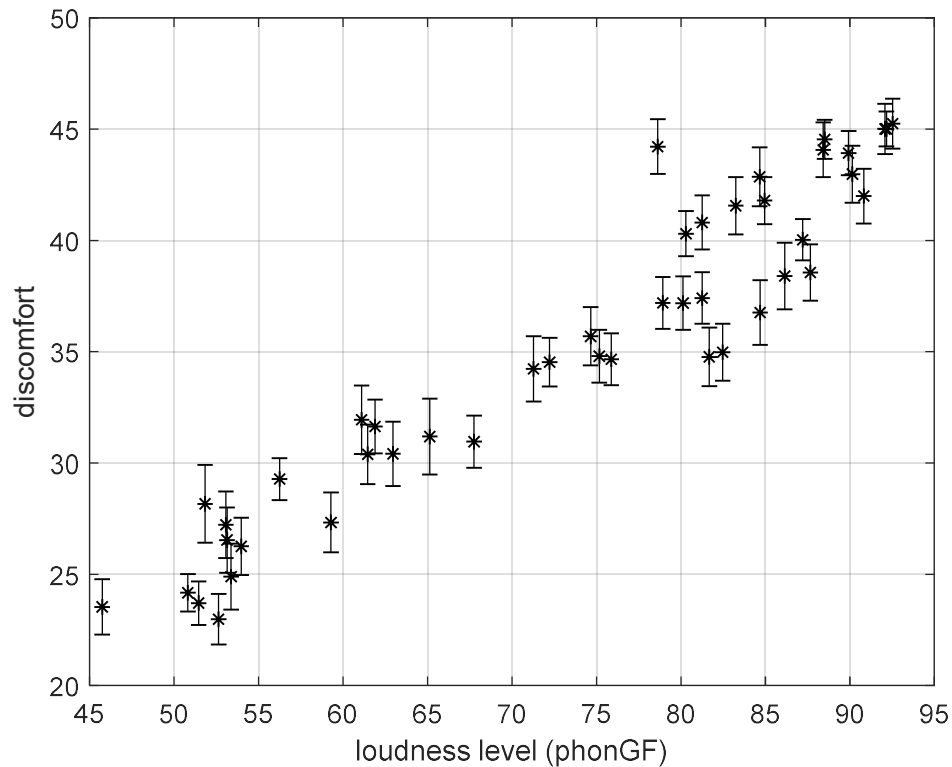


Figure 3: measured noise discomfort (mean values and 95% confidence intervals) plotted over loudness level values

This high correlation allowed to build a linear model relating discomfort to loudness:

$$U_{noise} = a \times Loudness\ level \quad (2)$$

Where  $a$  is the value of the slope which cannot be given due to confidentiality reason. An intercept did not prove to be useful, as the correlation between measured discomfort and its estimation using eq. (2) is high ( $R^2 = 0.91$ ,  $F(1,44) = 12486$ ). The maximum prediction error is around 6.5, which represents one category of the scale used by participants.

The robustness of this model was estimated by separating the data into two randomly selected subsets: 30 stimuli for which a linear model was computed, and 15 stimuli used to validate the quality of the model. This procedure was repeated 200 times. For each trial, the determination coefficient varied between 0.84 and 0.94, the slope of the model varied from 0.47 to 0.485 and the maximum prediction error (computed for the validation sub-set) varied between 2.5 and 7.

## 2.6. Discussion

The results showed that loudness is a major source of acoustic discomfort. In fact, the loudness values for these stimuli vary largely, from approximately 45 to 95 phon, which makes it a good estimator of discomfort with regard to variations in the assessments given by the participants. Similar results have been shown in the literature, particularly in the automobile sector [3,4] or for noise inside a high-speed train [5,20]. When loudness differences are large between stimuli, subjective intensity is the most important sound features, which can explain subjective evaluations on its own.

As Table 1 shows, the linear regression between discomfort and A-weighted level was also good ( $R^2 = 0.77$ ,  $F = 148$ ,  $p < 0.001$ ), which confirm results of the existing literature [7] (correlation coefficients = 0.97 when no tasks were asked to participants). On the other hand, the correlation unweighted or C-weighted level is weaker, as well as the correlation with G-weighted level. All in all, these results show that, in spite of the low frequency content of helicopter noise (see figure 1), mid and high frequencies mainly contribute to loudness. From a technical point of view, sound in that frequency range is mainly due to turbulent boundary layer, gearbox, and engine.

This model applies to listening to internal helicopter noise signals which are heard without ear protection. In fact, wearing earplugs or headphones could reduce the acoustic discomfort considerably. Furthermore, it would be necessary to have precise information about the effective attenuation brought by the protection to deduce the loudness in people's ears. Other studies are required to describe acoustic discomfort in helicopter cabins when wearing ear protection.

Finally, this model is representative of the results obtained in laboratory conditions: participants were submitted to noise only. In flight, noise cannot be dissociated from other sensory modalities, the first of which



to mention is vibrations. The above model may be less effective. The continuation of the study therefore involved assessing the discomfort of helicopter passengers subjected to noise and vibrations.

### **3. Discomfort related to simultaneous noise and vibrations**

#### **3.1. Participants**

The group of participants involved in the experiment was made up of 32 people (5 women and 27 men). Their average age was 37.1 (min. = 22, max. = 55). Their average height was 1.78 m (min. = 1.60, max. = 1.93 m). Their average weight was 75 kg (min. = 49, max. = 120 kg). The average BMI was  $23.5 \text{ kg.m}^{-2}$  (min. = 18.94, max. =  $36.23 \text{ kg.m}^{-2}$ ). The majority of them were employed by Airbus Commercial Toulouse and a minority by Airbus Helicopters. All were engineers or PhD students and had to ensure that they had no medical contraindications and no known hearing problem. The experimental protocol has been validated by the Ethics Committee of Airbus Helicopters. The two experiments presented in this paper were conducted in different locations, with different equipment and different participants, except for 4 persons who took part of both experiments.

#### **3.2. Experimental setup**

The experimental vibratory device used in this experiment was a vibrating bench on three translation axes, the Cube (Team Corporation), in Airbus Commercial Toulouse. The Cube reproduces vibrations via six hydraulic actuators oriented by pairs in each of the directions, *longitudinal, lateral and vertical*. If the phases for the two actuators for each direction are identical, then the Cube vibrates in translation, otherwise it also vibrates in rotation. Each actuator is fitted with sensors for acceleration and displacement making it possible to calibrate the Cube depending on the set-point excitations given. This test bench allows displacements of 46 mm peak to peak on each of the axes for frequencies of between 0 and 250 Hz. A standard helicopter seat (Fisher H160) was fixed to this bench via a metal interface plate. Signals were generated by the software incorporated into the Cube.

Beyerdynamic DT 990 Pro headphones and two Genelec 7071A subwoofers (with an operating frequency range of 19 to 85 Hz) were added to this bench for sound playback (see Figure 4). The stimuli were played back by a dedicated software created for Airbus, and a sound card (RME HDSP 9652) was used as the interface between the PC and the audio system.

Sound and vibrations were launched separately and 0.5 seconds fade-in and fade-out on signals ensured that participants did not feel a delay between the beginning of sound stimuli and vibratory stimuli.

Measurements of the vibrations were performed for each stimulus and each participant at their feet, by a triaxial accelerometer fixed on the platform. In addition, two seat pads were fitted on the seat and backrest of the seat. As far as noise is concerned, a measurement of each stimulus was performed before the series of tests using a dummy head (Head Acoustics HMS2) placed on the seat and an acquisition system (Head Acoustics SQuadriga).



Figure 4: Experimental set-up for the experiment on the global sound and vibration discomfort.

### 3.3. Procedure

The participants assessed the discomfort of overall situation one stimulus at a time giving them a numerical value between 0 “not at all uncomfortable” and 50 “extremely uncomfortable” using a graduated semantic scale based on ISO 16832 [16] and similar to that used in the acoustic experiment and in [2].

### 3.4. Stimuli

All the stimuli used during this series of tests come from in-flight measurements. The measurements of noise and vibrations come from the entire range of helicopters (oil and gas, military, VIP, etc.) for flight phases at constant speed of between 70 and 145 knots. Regarding noise, the sound stimuli were selected so as not to exceed 90 dBA in order not to damage participants' hearing.

The RMS acceleration levels for the vibration stimuli vary from 0.04 to 0.19 g on the  $X$  axis, from 0.03 to 0.8 g on the  $Y$  axis and from 0.05 to 0.58 g on the  $Z$  axis. For sound, the levels varied between 77 and 89 dBA.

The majority of stimuli presented to the participants were one sound and simultaneous vibrations. However, 7 stimuli only contained noise and 7 stimuli only vibrations. The aim of using such stimuli was to verify the specific indicators for acoustic discomfort presented above and vibration discomfort presented in

[2]. The participants evaluated a total of 68 stimuli, each lasting 5 seconds (including 0.5 seconds of cross-fade at the start and end of the signal), presented in a pseudo-random order due to the constraints linked to the control of the vibrating bench. Initially the order of the 68 stimuli was randomised and then these stimuli were divided into 4 series of 17 stimuli in a set order. The series were then presented to participants in a random order.

The measurements of stimuli as provided by the audio system and the vibrating bench were compared to the set-point stimuli in order to check the quality of the signal restitution. The noise measurements performed with a dummy head show that the reproduced stimuli are faithful to the stimuli: the average difference between the levels of the real stimuli and the stimuli played by the sound system is 0.8 dB. We used the measured reproduced stimuli to compute acoustic indicators. As regards vibrations, the reproduction error is between 6 and 8% when measured on the platform. Discrepancies for seat-persons vibrations can happen as participants have different body characteristics which can modify the transfer function of the seat. However, individual values of  $U_{vib}$  are very similar. So that they have been averaged in the following.

### 3.5. Results

The consensus among participants was still high, though a bit smaller than in the previous experiment. The minimum value of the correlation coefficient between two participants' answers is 0.25 ( $p < 0.05$ ). This coefficient is smaller than 0.4 ( $p < 0.001$ ) for 8 pairs of participants only (out of 496 existing pairs, corresponding to  $32.31/2$ ). This allowed to use the discomfort evaluations averaged over the whole panel. For each stimulus, the specific discomfort indicators are calculated for discomfort linked to noise ( $U_{noise}$ ) and to vibrations ( $U_{vib}$ ). One value per stimulus is obtained for acoustic discomfort according to Equation 2, from the noise measurements. For vibrations, modified ISO acceleration values  $ISO_{mod}$  were calculated for each stimulus and each participant from measurements at the feet, on the seat and on the backrest of the seat according to the procedure detailed in [2]. The indicator for vibration discomfort,  $U_{vib}$ , is computed for each participant according to Eq. 1 and finally averaged over participants..

The validity of the specific discomfort indicators is verified initially from stimuli that only contain noise and those that only contain vibrations. The determination coefficient from linear regression between the average discomfort evaluations and the average vibration discomfort indicators for stimuli only containing vibrations is  $R^2 = 0.97$  ( $F(6,1) = 193$ ,  $p < 0.001$ ) see Figure 5. This validates the vibration discomfort indicator developed in [2]. For stimuli only containing noise, the determination coefficient from linear regression between the discomfort evaluations and the acoustic discomfort indicators is  $R^2 = 0.84$  ( $F(6,1) = 25.3$ ,  $p < 0.001$ ) see Figure 6. This correlation is not as good as the correlation coefficient developed from the listening test in experiment 1 and may be explained by a difference in listening method between this experiment and the experiment performed for noise alone in the first part of this paper. In fact, in the coupling experiment, the sound is presented by headphones coupled to subwoofers, whereas in the experiment on noise alone the playback was carried out by loudspeakers coupled to subwoofers. Nevertheless, considering the robustness of

the previous models (see Figure 5 and Figure 6), we have used them for the following estimation of global discomfort.

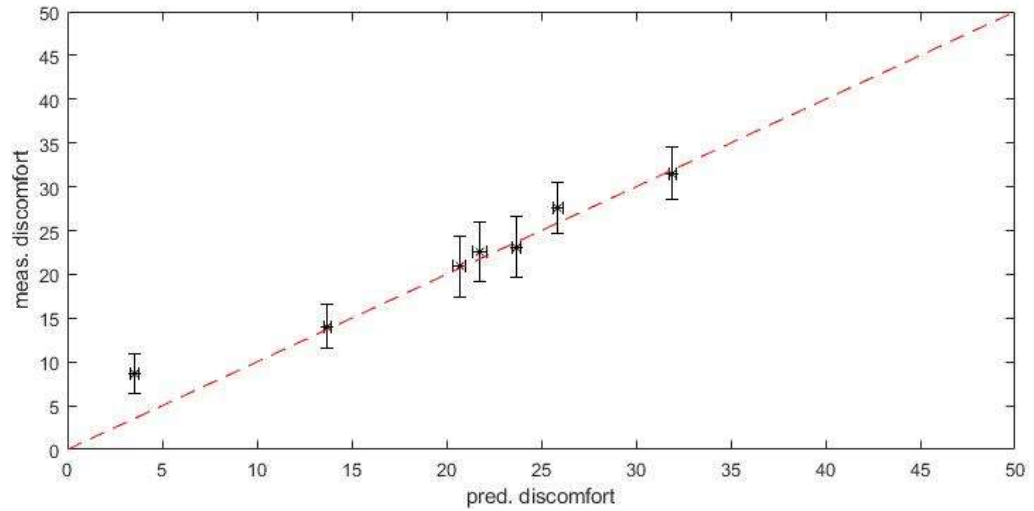


Figure 5: Measured overall discomfort (mean value in their 95% confidence interval) plotted over  $U_{vib}$  for stimuli containing only vibratory content

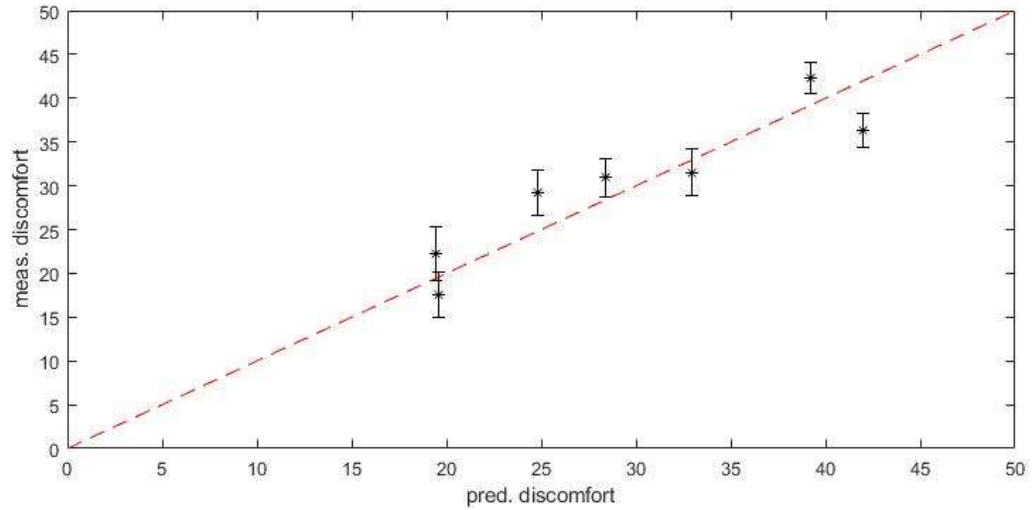


Figure 6: Measured overall discomfort (mean value in their 95% confidence interval) plotted over  $U_{noise}$  for stimuli containing only acoustic content

Models relating specific annoyance of noise and vibration (estimated as explained earlier) and overall annoyance have been looked for. A simple model consists in a linear regression involving  $U_{vib}$  and  $U_{noise}$ ; a model with no intercept has been looked for, as one can expected that an absence of noise and vibration leads to no annoyance. The best-fit model is expressed by Equation 3:

$$U_{vib+noise} = 0.56 \times U_{vib} + 0.77 \times U_{noise} \quad (3)$$

Figure 7 shows the average discomfort assessments depending on the global discomfort indicator calculated from Equation 3. The determination coefficient from linear regression between observed and predicted values is high:  $R^2 = 0.76$ ,  $R_{adj}^2 = 0.76$  ( $F(66,2)=212$ ,  $p<0.001$ ).

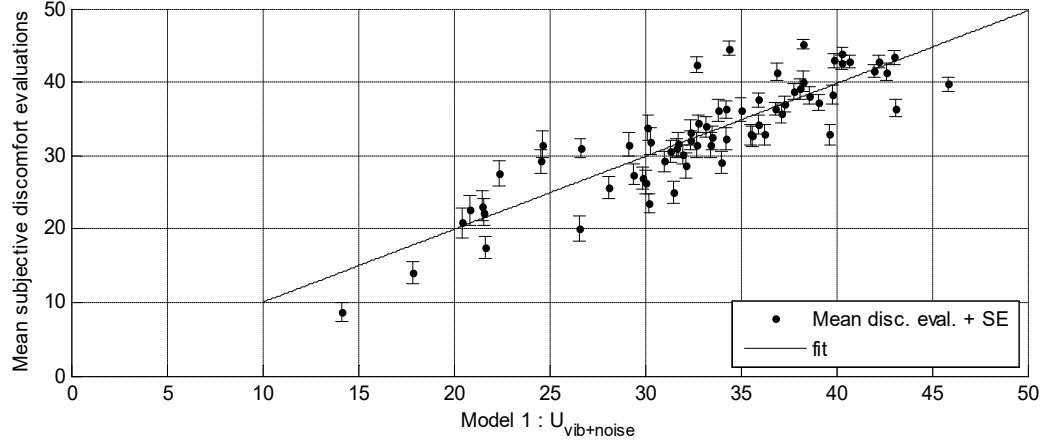


Figure 7: Measured overall discomfort (mean value in their 95% confidence interval) plotted over model of Equation 3

The addition of an interaction coefficient to the model could improve the quality of the global discomfort estimation. The literature has shown that mixed models made up of a linear regression with specific discomfort indices as factors and an interaction coefficient modelled by the discomfort difference between sources give promising results, especially the studies [21, 22] which concern multiple acoustic discomfort sources in the environment (traffic noise or industrial noise). A mixed perceptual model is calculated from acoustic and vibration discomfort indicators as shown by Equation 4.

$$U_{vib+noise} = 0.64 \times U_{vib} + 0.56 \times U_{noise} + 0.40 \times |U_{vib} - U_{noise}| \quad (4)$$

The coupling coefficient chosen here makes it possible to penalise the global discomfort if one of the two sources is dominant.

The coefficients associated with the vibration discomfort indicator and the acoustic discomfort indicator are close (though the coefficient of  $U_{vib}$  is higher than the one of  $U_{noise}$ ). As these two indicators vary over the same range of values (from 0 to 50), it must be concluded that the model gives approximately the same weight to each source of discomfort. The difference between the discomfort indicators relating to noise and vibrations has a lower weight in the calculation of the estimation of global discomfort. This seems to show that the interaction plays a less important role in global discomfort than the discomfort associated with each of the sources.

The determination coefficient for this model is very good ( $R^2 = 0.87$  and  $R_{adj}^2 = 0.87$ ,  $F(65,3)=448$ ,  $p<0.001$ ). Figure 8 shows the average discomfort assessments given by participants depending on the estimated global discomfort indicators calculated from Equation 4.

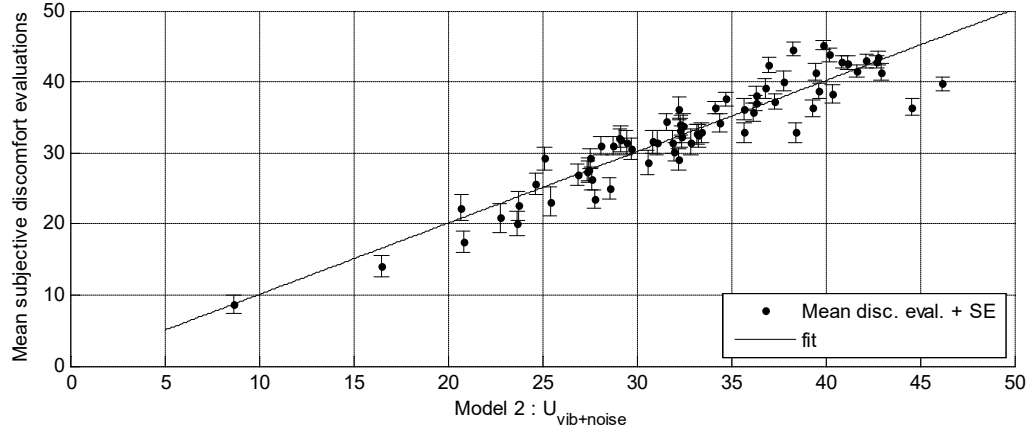


Figure 8: Measured overall discomfort (mean value in their 95% confidence interval) plotted over model of Equation 4.

### 3.6. Discussion

The results of the experiment coupling noise and vibrations showed that a linear combination associated with a coupling coefficient makes it possible to estimate the discomfort very accurately using the specific discomfort indicators in terms of noise and vibrations. The introduction of this difference-based factor significantly improved the accuracy of the model, as  $R_{adj}^2$  increased from 0.76 to 0.87. The maximum difference between a measured annoyance and its corresponding prediction is less than 10. For 63 stimuli (over 68), this difference is smaller than 5. In the existing literature in which this mixed model has been proposed [21, 22], the improvement allowed by this absolute difference of specific annoyances was much smaller in [21], which studied total annoyance from road and tramway noise. On the other hand, it was important in the case of total annoyance due to industrial and road traffic noises [22]. The present study represents a third case (total discomfort due to noise and vibrations) for which the introduction of this interaction term seems to be useful. It should be noted that this model is slightly better than a model including a multiplicative interaction between  $U_{vib}$  and  $U_{noise}$ ,  $U_{vib+noise} = XX \times U_{vib} \times U_{noise}$ , for which  $R_{adj}^2 = 0.82$ ,  $F?$  pvalue ?.

Similarly, this model can hardly be compared to models of the existing literature regarding aircrafts [13, 14, 15]. In our study, stimuli levels are higher, especially regarding vibration levels (maximum values close to 4 m/s<sup>2</sup>, to be compared to 0.6 m/s<sup>2</sup> in [14] and 1m/s<sup>2</sup> in [15]. Indeed, helicopters represent a very specific example of transportation means.

As each specific discomfort indicator may itself be estimated accurately from the stimuli (acoustic or vibration), it is therefore possible to assess the global discomfort from measurements in the aircraft.

Equation 4 makes it possible to plot a set of iso-discomfort curves, using  $U_{vib}$  and  $U_{noise}$  as input values (Figure 9). Theoretically, this model allows discomfort values above 50. However, these levels should not be reached in the normal operation of a helicopter.

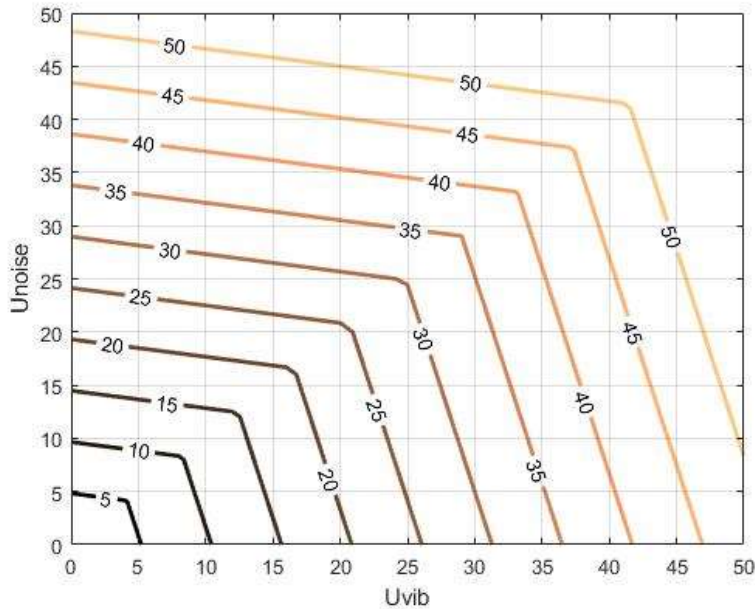


Figure 9: Iso-discomfort curves computed from  $U_{vib}$  and  $U_{noise}$  according to Equation (4)

However, as mentioned in the experiment on acoustic discomfort, this equation is only valid for stimuli heard without ear protection. The aircraft concerned are those transporting passengers and in which the cabin acoustic treatment already makes it possible to obtain sufficiently low levels. Furthermore, the vibration discomfort equation on which the results are based has been devised from perceptual experiments conducted with a single helicopter seat. It would be wise to check the validity of this equation for several helicopter seats.

Finally, these two experiments are the result of laboratory work and should be validated in real conditions during in-flight tests.

#### 4. Conclusions

The series of tests on acoustic discomfort has shown that the use of loudness alone offers high correlation with the evaluations of discomfort given by participants. The acoustic discomfort model resulting from this study is a linear function, providing a discomfort value of between 0 and 50 depending on loudness ( $R^2 = 0.91$ ).

Secondly a linear model based on this acoustic discomfort indicator and a vibration discomfort indicator proposed in a previous study [2] provided an initial correct approximation of global discomfort ( $R^2 = 0.76$ ,  $R_{adj}^2 = 0.76$ ). However, it does not take account of the interaction between noise and vibrations. The difference

between the contributions of noise and vibrations to global discomfort was then added to a linear regression to create a mixed model. Thus, the model adds a penalty if one source is dominant. This mixed model gives very good results ( $R^2 = 0.87$  and  $R_{adj}^2 = 0.87$ ) taking the acoustic and vibration discomfort indicators as factors. It can be used to estimate the global discomfort linked to noise and vibrations for helicopter passengers.

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