



**HAL**  
open science

## Model of sound and vibration discomfort in helicopter cabins

Laurianne Delcor, Etienne Parizet, Julie Ganivet-Ouzeneau, Julien Caillet

► **To cite this version:**

Laurianne Delcor, Etienne Parizet, Julie Ganivet-Ouzeneau, Julien Caillet. Model of sound and vibration discomfort in helicopter cabins. *Applied Acoustics*, 2022, 195, pp.108847. 10.1016/j.apacoust.2022.108847 . hal-03753953

**HAL Id: hal-03753953**

**<https://hal.science/hal-03753953>**

Submitted on 22 Aug 2022

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# Model of sound and vibration discomfort in helicopter cabins

Laurianne Delcor<sup>1,2</sup>, Etienne Parizet<sup>1</sup>, Julie Ganivet-Ouzeneau<sup>2</sup>, Julien Caillet<sup>2</sup>

<sup>1</sup> Univ. Lyon, Institut National de Sciences Appliquées de Lyon, Laboratoire Vibrations Acoustique (LVA), 25 bis avenue Jean Capelle F-69621 Villeurbanne, France

<sup>2</sup> Airbus, Aéroport International Marseille Provence, 13700 Marignane, France

## 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.

34 
$$U_{vib} = \alpha \times 20 \times \log_{10} \left( \frac{ISO_{mod}}{10^{-6}} \right) + \beta \quad (1)$$

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

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

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

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

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

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

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

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

78 To respond to these problems, two experimental campaigns have been conducted. The first concerns  
79 acoustics and aimed to estimate acoustic discomfort from measurements by linking the discomfort assessments  
80 given by a jury to sound metrics. Sound level indicators from the literature will be used, Sound Pressure Level,  
81 A- C- and G-weighted SPL, loudness level, as well as indicators usually calculated at Airbus. The second  
82 experiment is aimed to link the global assessments of discomfort given by the jury with the specific acoustic  
83 discomfort indicator from the first experiment and that of vibrations presented in the prior study of the authors  
84 [2].

## 85 **2. Acoustic discomfort**

### 86 *2.1. Participants*

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

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

### 94 *2.2. Experimental setup*

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

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

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



104

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

106

107

### 108 2.3. Procedure

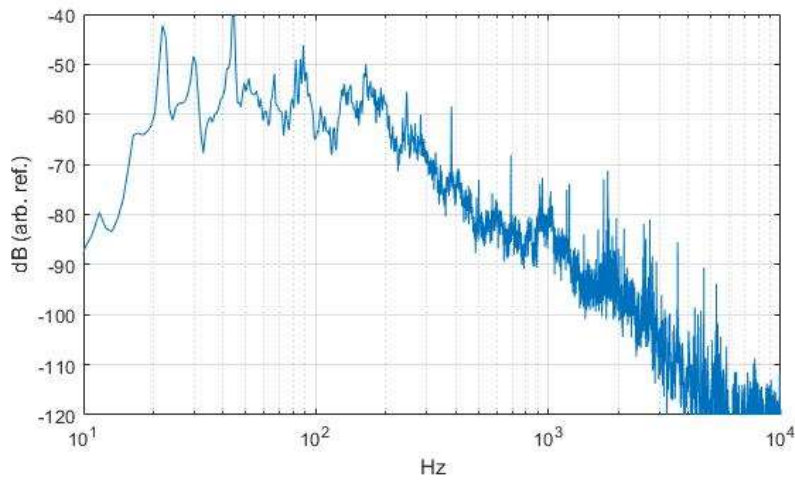
109 The participant was given the objectives and the instructions before starting the experiment. Then the  
110 participant was able to sit on the chair and start the experiment with several examples of stimuli. The examples  
111 were drawn from all the stimuli to be evaluated and were representative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

113 The participants evaluated each sound stimulus on the Jury Listening Test software from Ansys, with a  
114 magnitude estimation method. They marked the sounds from 0 “no noise” (“pas de bruit” in original language)  
115 to 50 “extremely uncomfortable” (“extrêmement inconfortable” in original language) on a labelled scale based  
116 on the standard ISO 16832 [16] and similar to that used to assess the vibration discomfort in a previous study  
117 [2]. As mentioned in the introduction, the study objective is to suggest a comfort indicator for passengers in  
118 transport helicopters. This is why no specific task needs to be performed by the participants in the experiment.  
119

### 120 2.4. Stimuli

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

125 performed on several seats in the cabin. These stimuli were selected from a database, with the constraint being  
126 that their sound level did not exceed 90 dBA, so as not to damage the participants' hearing. These were stimuli  
127 recorded over the entire range of Airbus helicopters during flight phases of forward travel at constant speed  
128 (varying from 100 to 143 knots). Figure 2 shows an example of noise helicopter spectrum.  
129



130  
131 *Figure 2: typical spectrum of helicopter's interior noise.*  
132 In total, participants had to assess 45 stimuli of 5 seconds (including a 0.5 s cross-fade at the beginning  
133 and end of the signal). This choice is a compromise between playing a great number of signals and not tiring the  
134 participants with a too long experiment. The levels varied between 76.9 and 89.7 dBA. The order of the stimuli  
135 was random for each participant.

## 136 2.5. Results

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

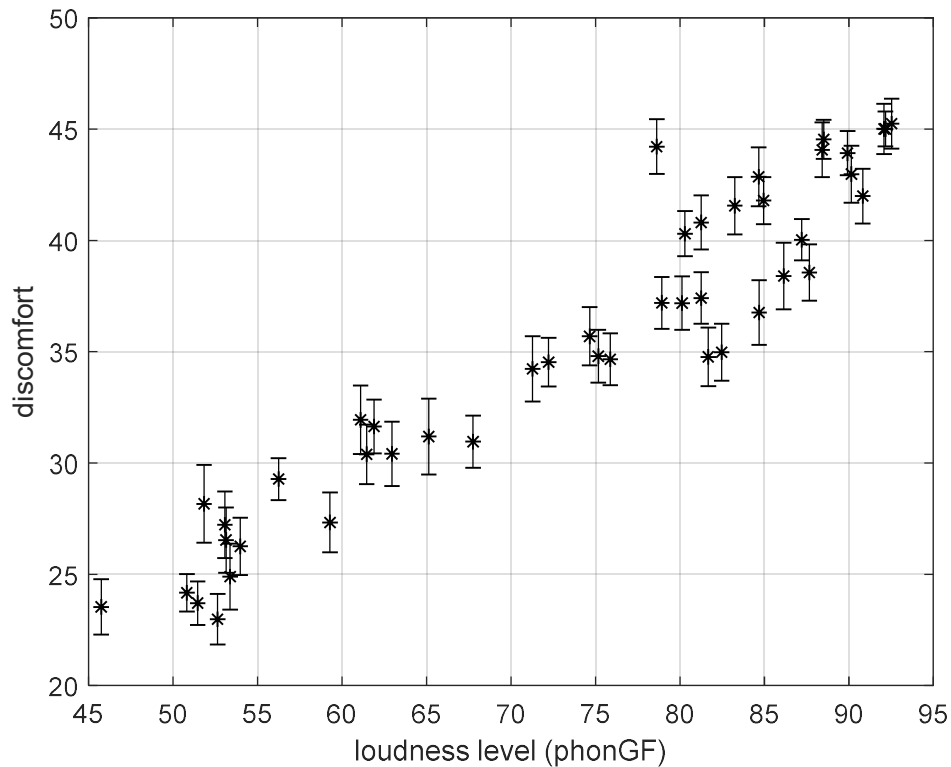
149 microphone as previously mentioned. The difference between the target and the measured sound levels is plus  
 150 or minus 1 dB.

151 The best linear regression was obtained for loudness level computed according Zwicker's method [17]:  
 152 coefficient of determination was  $R^2 = 0.91$  ( $F=402$ ,  $p<0.001$ ), indicating a strong relation between loudness  
 153 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

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

155  
 156 Figure 3 presents the relation between loudness level values and discomfort evaluation of noise (mean  
 157 value in their 95% confidence interval).



158

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

160  
161 This high correlation allowed to build a linear model relating discomfort to loudness:  
162 
$$U_{noise} = a \times Loudness\ level \quad (2)$$
  
163 Where  $a$  is the value of the slope which cannot be given due to confidentiality reason. An intercept did not prove  
164 to be useful, as the correlation between measured discomfort and its estimation using eq. (2) is high ( $R^2 = 0.91$ ,  
165  $F(1,44) = 12486$ ). The maximum prediction error is around 6.5, which represents one category of the scale used  
166 by participants.  
167 The robustness of this model was estimated by separating the data into two randomly selected subsets: 30  
168 stimuli for which a linear model was computed, and 15 stimuli used to validate the quality of the model. This  
169 procedure was repeated 200 times. For each trial, the determination coefficient varied between 0.84 and 0.94,  
170 the slope of the model varied from 0.47 to 0.485 and the maximum prediction error (computed for the  
171 validation sub-set) varied between 2.5 and 7.

## 172 2.6. Discussion

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

179 As Table 1 shows, the linear regression between discomfort and A-weighted level was also good ( $R^2 =$   
180  $0.77, F = 148, p < 0.001$ ), which confirm results of the existing literature [7] (correlation coefficients = 0.97  
181 when no tasks were asked to participants). On the other hand, the correlation unweighted or C-weighted level  
182 is weaker, as well as the correlation with G-weighted level. All in all, these results show that, in spite of the low  
183 frequency content of helicopter noise (see figure 1), mid and high frequencies mainly contribute to loudness.  
184 From a technical point of view, sound in that frequency range is mainly due to turbulent boundary layer,  
185 gearbox, and engine.

186  
187 This model applies to listening to internal helicopter noise signals which are heard without ear  
188 protection. In fact, wearing earplugs or headphones could reduce the acoustic discomfort considerably.  
189 Furthermore, it would be necessary to have precise information about the effective attenuation brought by the  
190 protection to deduce the loudness in people's ears. Other studies are required to describe acoustic discomfort  
191 in helicopter cabins when wearing ear protection.

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



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

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

#### 197 *3.1. Participants*

198 The group of participants involved in the experiment was made up of 32 people (5 women and 27 men).  
199 Their average age was 37.1 (min. = 22, max. = 55). Their average height was 1.78 m (min. = 1.60, max. = 1.93  
200 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,  
201 max. =  $36.23 \text{ kg.m}^{-2}$ ). The majority of them were employed by Airbus Commercial Toulouse and a minority by  
202 Airbus Helicopters. All were engineers or PhD students and had to ensure that they had no medical  
203 contraindications and no known hearing problem. The experimental protocol has been validated by the Ethics  
204 Committee of Airbus Helicopters. The two experiments presented in this paper were conducted in different  
205 locations, with different equipment and different participants, except for 4 persons who took part of both  
206 experiments.

#### 207 *3.2. Experimental setup*

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

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

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

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



228

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

230

### 231 3.3. Procedure

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

235

### 236 3.4. Stimuli

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

241 The RMS acceleration levels for the vibration stimuli vary from 0.04 to 0.19 g on the *X* axis, from 0.03 to  
242 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.

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

246 [2]. The participants evaluated a total of 68 stimuli, each lasting 5 seconds (including 0.5 seconds of cross-fade  
247 at the start and end of the signal), presented in a pseudo-random order due to the constraints linked to the  
248 control of the vibrating bench. Initially the order of the 68 stimuli was randomised and then these stimuli were  
249 divided into 4 series of 17 stimuli in a set order. The series were then presented to participants in a random  
250 order.

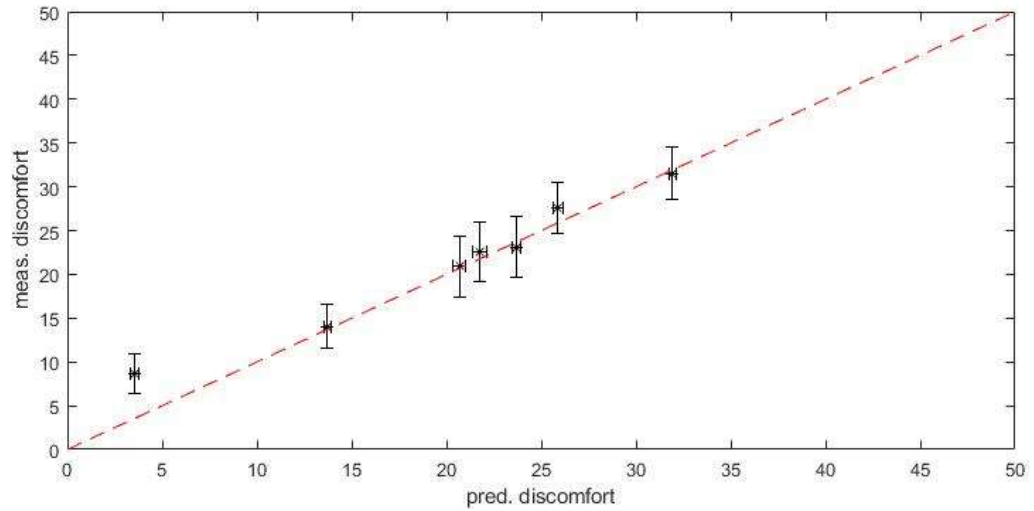
251 The measurements of stimuli as provided by the audio system and the vibrating bench were compared to  
252 the set-point stimuli in order to check the quality of the signal restitution. The noise measurements performed  
253 with a dummy head show that the reproduced stimuli are faithful to the stimuli: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

### 259 3.5. Results

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

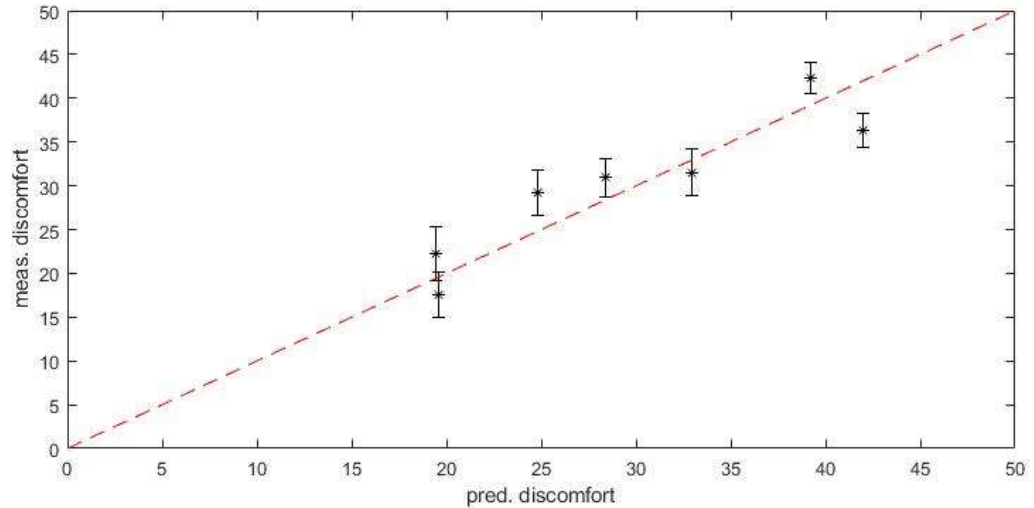
270 The validity of the specific discomfort indicators is verified initially from stimuli that only contain noise  
271 and those that only contain vibrations. The determination coefficient from linear regression between the  
272 average discomfort evaluations and the average vibration discomfort indicators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

281 the previous models (see Figure 5 and Figure 6), we have used them for the following estimation of global  
282 discomfort.  
283



284

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



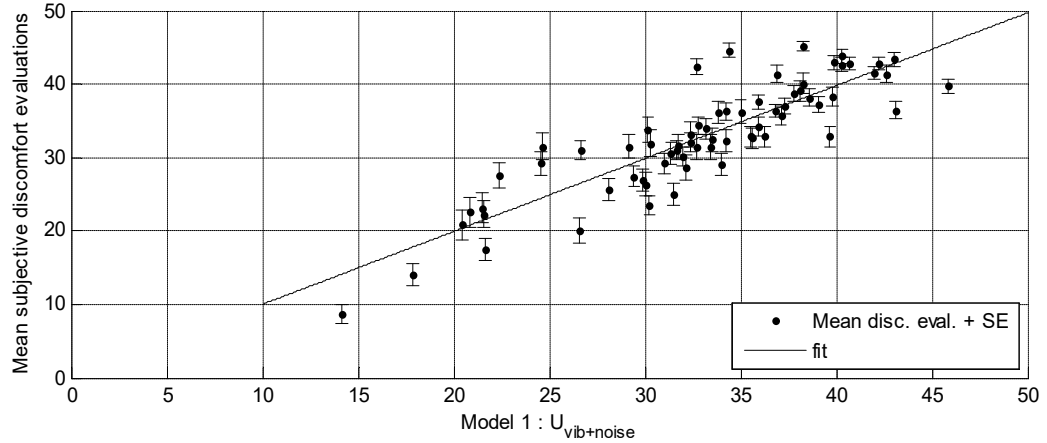
287

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

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

294 
$$U_{vib+noise} = 0.56 \times U_{vib} + 0.77 \times U_{noise} \quad (3)$$

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



298

299 *Figure 7: Measured overall discomfort (mean value in their 95% confidence interval) plotted over model of Equation*  
 300 *3*

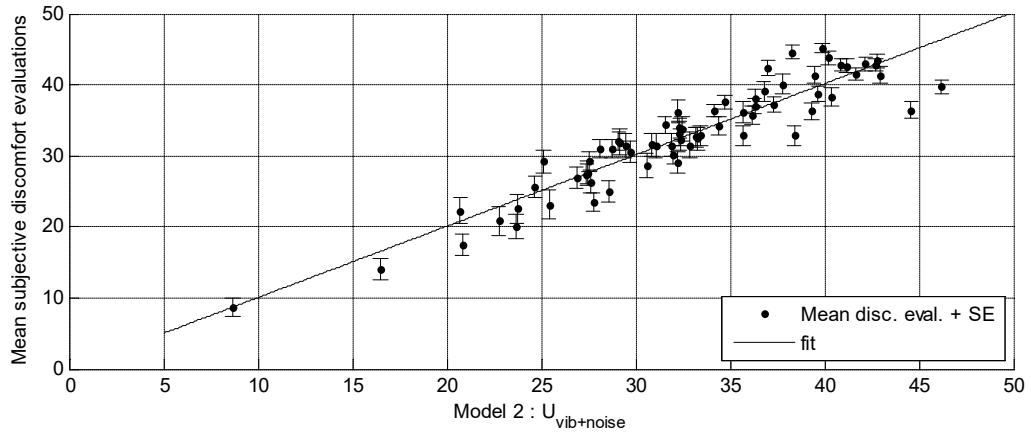
301  
 302 The addition of an interaction coefficient to the model could improve the quality of the global discomfort  
 303 estimation. The literature has shown that mixed models made up of a linear regression with specific discomfort  
 304 indices as factors and an interaction coefficient modelled by the discomfort difference between sources give  
 305 promising results, especially the studies [21, 22] which concern multiple acoustic discomfort sources in the  
 306 environment (traffic noise or industrial noise). A mixed perceptual model is calculated from acoustic and  
 307 vibration discomfort indicators as shown by Equation 4.

308 
$$U_{vib+noise} = 0.64 \times U_{vib} + 0.56 \times U_{noise} + 0.40 \times |U_{vib} - U_{noise}| \quad (4)$$

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

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

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



321

322 *Figure 8: Measured overall discomfort (mean value in their 95% confidence interval) plotted over model of Equation*  
 323 *4.*

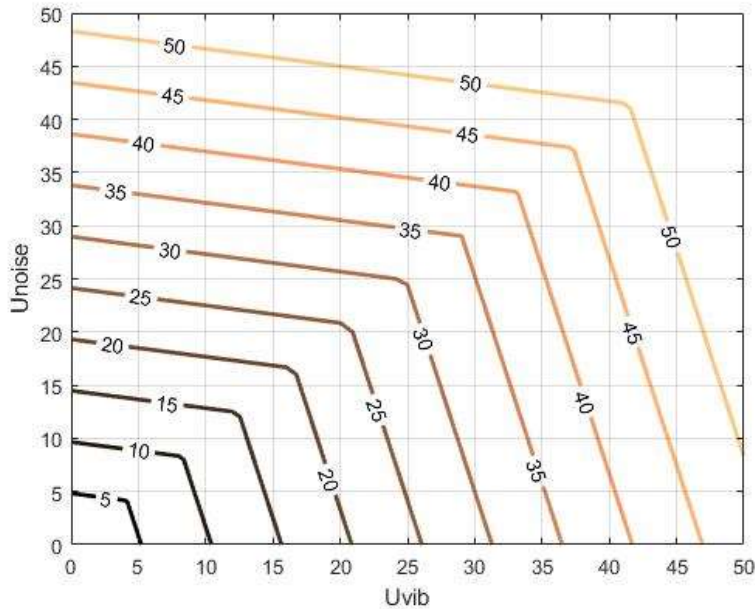
324 **3.6. Discussion**

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

337 Similarly, this model can hardly be compared to models of the existing literature regarding aircrafts [13,  
 338 14, 15]. In our study, stimuli levels are higher, especially regarding vibration levels (maximum values close to 4  
 339 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  
 340 example of transportation means.

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

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



346

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

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

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

#### 355 4. Conclusions

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

360 Secondly a linear model based on this acoustic discomfort indicator and a vibration discomfort indicator  
361 proposed in a previous study [2] provided an initial correct approximation of global discomfort ( $R^2 = 0.76$ ,  $R_{adj}^2$   
362  $= 0.76$ ). However, it does not take account of the interaction between noise and vibrations. The difference

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

367

### 368 **Funding**

369 The PhD of the first author was partially funded by ANRT (Association Nationale de la Recherche et de la  
370 Technologie), who granted a CIFRE. (Industrial Agreement for Training through Research). This work was  
371 supported by the LABEX CeLyA (ANR-10-LABX-0060) of Université de Lyon, operated by the French National  
372 Research Agency (ANR).

373

### 374 **References**

375 [1] ISO 2631-1, Mechanical vibration and shock — evaluation of human exposure to whole-body  
376 vibration — Part 1: General requirements, Standard, ISO (1997).

377 [2] L. Delcor, E. Parizet, J. Ganivet-Ouzeneau, J. Caillet. Assessment of helicopter passengers'  
378 vibration discomfort: proposal for an improvement of the ISO 2631-1 standard. *Ergonomics*, (2021)

379 [3] R. M. Van Auken, J. W. Zellner, D. Kunkel, Correlation of Zwicker's loudness and other noise  
380 metrics with drivers' over-the-road transient noise discomfort, Tech. rep., SAE Technical Paper (1998).

381 [4] D. Li, Y. Huang, The discomfort model of the micro commercial vehicles interior noise based on  
382 the sound quality analyses, *Applied Acoustics* 132 (2018) 223–231.

383 [5] J. Y. Hong, Y. Cha, J. Y. Jeon, Noise in the passenger cars of high-speed trains, *The Journal of the*  
384 *Acoustical Society of America* 138 (6) (2015) 3513–3521.

385 [6] S. Pennig, J. Quehl, V. Rolny, Effects of aircraft cabin noise on passenger comfort, *Ergonomics*  
386 55 (10) (2012) 1252–1265.

387 [7] D. G. Stephens, J. D. Leatherwood, Physical and subjective studies of aircraft interior noise and  
388 vibration. *Symp. on Internal Noise in Helicopters* (Southampton, 1979). Available on <https://ntrs.nasa.gov>

389 [8] M. Amari, Etude du confort vibro-acoustique automobile en simulateur, (Study of automobile  
390 vibro-acoustic comfort in the simulator), Ph.D. thesis, Ecole doctorale MEGA (2009),  
391 <http://theses.fr/2009ISAL0079>

392 [9] H. Howarth, M. Griffin, Subjective response to combined noise and vibration: summation and  
393 interaction effects, *Journal of Sound and Vibration* 143 (1990) 443–454.

394 [10] R. Paulsen, J. Kastka, Effects of combined noise and vibration on annoyance, *Journal of Sound*  
395 *and Vibration* 181 (1995) 295–314.

396 [11] E. Parizet, J. Brocard, B. Piquet, Influence of noise and vibration on comfort in diesel engine  
397 cars running at idle, *Acta Acustica united with Acustica* 90 (2004) 987–993.



398 [12] D. Aubrée, J. Roland, Détermination en laboratoire du seuil de détectabilité d'un signal  
399 vibratoire en présence d'un signal sonore sur plusieurs sujets, Cstb report ref GSH/89-030 DA.CB (1989).

400 [13] J. D. Leatherwood, T. K. Dempsey, S. A. Clevenson, A design tool for estimating passenger ride  
401 discomfort within complex ride environment, Human Factors (22(3)) (1980) 291–312.

402 [14] J. Quehl. Comfort studies on aircraft interior sound and vibration, Ph. D. dissertation, Carl von  
403 Ossietzky Univ. Oldenburg (2001) - <https://oops.uni-oldenburg.de/340/2/quecom01.pdf>

404 [15] G. Aggarwal; N. Mansfield, F. Vanheusden, S. Faulkner. Human discomfort in aircraft cabins:  
405 effect of noise level and vibration magnitude. Proc. Comfort Congress 2021 -  
406 <https://comfort.ergonomics.org.uk/programme/#proceedings>

407 [16] International Organization for Standardization ISO 16832:2006, Acoustics — loudness scaling  
408 by means of categories.

409 [17] International Organization for Standardization ISO 532-1:2017, Acoustics - Methods for  
410 calculating loudness – Part 1 : Zwicker method.

411 [18] H. Fastl, E. Zwicker, Psychoacoustics: facts and models, Springer, 1990.

412 [19] American National Standard Institute ANSI S1.13-2005, Measurement of sound pressure levels  
413 in air.

414 [20] E. Parizet, N. Hamzaoui, J. Jacquemoud, Noise assessment in a high-speed train. Applied  
415 Acoustics 63 (2002), 1109-1124

416 [21] A. Klein, C. Marquis-Favre, P. Champelovier, Assessment of annoyance due to urban road traffic  
417 noise combined with tramway noise, The Journal of the Acoustical Society of America 141 (1) (2017) 231–242.

418 [22] M. Pierrette, C. Marquis-Favre, J. Morel, L. Rioux, M. Vallet, S. Viollon, A. Moch, Noise annoyance  
419 from industrial and road traffic combined noises: A survey and a total annoyance model comparison, Journal of  
420 environmental psychology 32 (2) (2012) 178–186.