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Abstract

Vibrations contribute to helicopter's ride comfort. This study aimed to determine the relationship between main rotor vertical excitations and discomfort. Fifty-three participants, seated on a helicopter seat fixed to a vibration test bench, evaluated the discomfort of vertical sinusoidal vibrations using a magnitude estimation procedure. Stimuli had a frequency between 15 and 30 Hz and a level between 0.32 and 3.16 m/s². The average discomfort was shown related to vibration velocity using Steven's power law, without any frequency dependence. The exponent depended on velocity and was 1.18 for higher velocities (approx. above 0.008 m/s) and 0.65 for velocities below that limit.

Keywords

Perception, vibrations, helicopters

Introduction

In a helicopter, noise and vibration levels are very high compared to other vehicles (planes, trains or cars). This contributes significantly to the overall discomfort of passengers. As a result, manufacturers are making constant efforts to reduce these levels in order to provide comfortable equipment to their customers.

In addition, helicopters have a specific vibration signature since the main excitation comes from periodic aerodynamic loading on the main rotor blades. These forces are transferred into the cabin and create vibrations. The helicopter's structure is such that some frequencies are filtered and the most important excitation occurs at the blade passing frequency (BPF). The BPF is defined as:

$$BPF = B \times rev \quad (1)$$

where B is the number of blades and rev is the rotation speed of the main motor (expressed in Hz).

Depending on the helicopter model, BPF varies between 15 and 30 Hz. This induces vibrations, mainly in the vertical direction. The amplitude of vibrations varies between 0.3 and 5 m/s².

In literature, only a few studies have addressed the discomfort caused by helicopter vibrations^{1–3}. But the signals used by these studies do not allow their results to be applied to the evaluation of BPF vibrations. Currently, there is no helicopter-specific method for assessing the discomfort caused by vibration measurements, and ISO 2631-1⁴ is used. However, this standard is generic for all modes of transport and may be inaccurate for

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helicopter applications. This is why Airbus is developing research in the field in order to improve models for predicting vibration discomfort in its helicopters.

Subjective intensity of vibrations can be related to their amplitudes using Steven's power law⁵:

$$\psi = a \times \varphi^b \quad (2)$$

where ψ denotes the perceived intensity of the stimulus and φ its physical intensity. The exponent b depends on the considered sensory modality and a varies according to the experiment.

Previous studies addressed the relationship between vibration levels and comfort or subjective intensity for seated persons. Leatherwood and Dempsey⁶ showed that Steven's law exponents are similar whether comfort or subjective intensity is considered, which makes it possible to consider the whole set of studies.

A review of these studies is provided in Griffin⁷ and shows a great discrepancy between them: in the frequency range corresponding to blade passing (15–31.5 Hz), proposed exponents vary between 0.46 and 1.47 (mean: 1.0 and standard deviation: 0.22). These studies were realized either in real conditions (in hovercraft, helicopter or train) or in laboratory, using aircraft seat or aluminium table with or without a cushion. In a more recent study, Morioka and Griffin⁸ proposed values between 0.7 and 0.8 in that frequency range, participants being seated on a rigid wooden seat. In 2012, Basri and Griffin⁹ replicated the experiment with subjects seated on a seat with a backrest that could be reclined at different angles. In the 15–25 Hz frequency range, they suggested exponents varying from 0.63 to 0.79 (for a vertical backrest) and from 0.71 to 0.79 (for a 30° inclination). Finally, in 2019, Huang and Zhang¹⁰ proposed exponent values from 0.38 to 0.64 between frequencies ranging from 15 to 31.5 Hz for a rigid seat without backrest.

Given the variability of the published results, the aim of this study was to determine the relationship between vibration amplitude and perceived discomfort in the specific case of blade-passing helicopter excitations. As the seat could be one of the reasons for the variability of published results, it was also decided to use a real helicopter seat.

Experiment

Participants

Fifty-three persons were participated in this experiment: 51 students of INSA Lyon et 2 Airbus engineers (21 women and 32 men). Their average age was 21.3 years old (min: 19 years old and max: 39 years old). Their average weight was 65.4 kg (min: 49 kg and max: 95 kg), height was 1.74 m (min: 1.59 m and max: 1.92 m) and the average BMI was 21.3 kg/m² (min: 17.8 kg/m², max: 28.4 kg/m²). Only six subjects had ever flown in a helicopter before (or used a helicopter flight simulator).

Setup

A bench previously developed in the laboratory was used. The simulator was a two-part metallic structure. The upper part of the simulator was connected to the lower part through four springs which supported the weight of the upper part of the simulator. A shaker (V 550, LDS, Bruel & Kjaer, Naerum, Denmark) was placed underneath and could move the upper part vertically. A standard helicopter seat (H160, Fischer Seats, Landshut, Germany) was fixed to the upper part. Figure 1 shows a picture of that bench.

The simulator was controlled via Matlab. Signals were generated by a sound card (ROGA D, Viaxys, Ferrières-en-Gâtinais, France) and went through a band pass filter whose cut-off frequencies were 10 and 40 Hz before being sent to the shaker amplifier (PA 1000, LDS, Bruel & Kjaer, Naerum, Denmark).

Before presenting stimuli to each participant, the transfer function of the bench was measured. 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 attachment points. The level of each stimulus was then modified to take into account this transfer function and to make sure that the vibration level of the upper part was equal to the target value.

As the simulator was noisy under some conditions, a masking noise was added using two speakers (Tapco S8, Loud Audio, Woodinville, USA) facing the participant in a stereophonic configuration. A lowpass-filtered white noise was used (cut-off frequency = 500 Hz, overall level 85 dB SPL).



Figure 1. Picture of the bench and the helicopter seat used for this experiment.

Table 1. Amplitudes values of the vibratory stimuli.

	Amplitudes for each stimulus (m/s^2)											
15 Hz	0.32	0.40	0.50	0.63	0.79	1.00	1.26	1.58				
20, 25 and 30 Hz	0.32	0.40	0.50	0.63	0.79	1.00	1.26	1.58	2.00	2.51	3.16	

Procedure

The simulated vibrations intended to represent the amplitudes and frequencies of the commonly measured BPF, which means sinusoidal vibrations from 15 to 30 Hz with accelerations from 0.3 to $5 m/s^2$. Four frequencies were selected: 15, 20, 25 and 30 Hz. However, preliminary experiences have shown that the highest levels were really too uncomfortable to be presented to the participants. This was especially true for the lowest frequency. As a result, the maximum level was reduced to $1.58 m/s^2$ for the 15 Hz frequency and to $3.16 m/s^2$ for the other frequencies. In all cases, lowest levels were set to $0.32 m/s^2$.

Reducing the maximum level to $1.58 m/s^2$ for 15 Hz stimuli was accepted because the majority of helicopters have more than three blades. Hence, such a low blade-passing frequency is not often encountered. Moreover, levels higher than $2 m/s^2$ are very rarely noted in such helicopters.

Table 1 gives a detail of the levels of the 41 stimuli used in the experiment.

For each frequency, 4-s long stimuli were synthesized using a 2 dB step between the minimum and maximum levels, giving a number of eight samples for 15 Hz and 11 for the other frequencies. This 2 dB step is a little bit higher to the usually accepted discrimination level for vertical whole body vibrations (around 1.5 dB⁷).

Each stimulus was presented three times to each participant in a pseudo-random order. This order has been arranged so that two successive stimuli do not have an acceleration difference greater than 6 dB. The motivation is to prevent participants to successively rate two very different stimuli, which would create an evaluation bias¹¹.

For each subject, four subsets of experiments were used (one for each frequency). The order of these subsets was randomly selected for each participant. The assessment of discomfort was made by a magnitude estimation without reference. After the presentation of each stimulus, participants were asked to give a number proportional to their discomfort. They could score from 0, which means ‘no vibration at all’, to values as high as they wanted, so as not to limit their rating scale. They were allowed to use decimals.

Before each set of stimuli, a few examples were presented to give participants an indication of the range of stimuli they would have to evaluate. The examples were set for all participants and contained medium, then high and then low acceleration stimuli.

The total duration of the experiment was around 40 min, including explanations and installation of the participant on the seat. Throughout the experiment, participants were instructed to remain seated normally with their legs uncrossed and their backs resting normally against the seat back. A seat belt was fastened at their waist for the duration of the experiment. The procedure has been approved by the ethical committee of INSA-Lyon.

Results

Subjective data processing

The raw discomfort ratings show that the participants use very different scales. The majority of participants felt that discomfort increased with the level of vibration.

The minimum ratings given by participants ranged from 0.05 to 30 and the maximum ratings from 6 to 210. Ratios between maximum and minimum individual data varied between 7 and more than 100. This shows that participants used very different scales to assess discomfort.

Therefore, an average of the three rehearsal ratings followed by a normalization had to be done. This was achieved using the average deviation procedure described by Han et al.¹².

Let X_{ijk} be the raw discomfort assessment given by the subject i for the presentation k of the stimulus j . The normalized value of the i th participant for the j th stimulus SV_{ij} is defined as follows:

$$SV_{ij} = M_{ij} - MD_i \quad (3)$$

where M_{ij} is the average of the logarithm of the three ratings for the i th participant and the j th stimulus:

$$M_{ij} = \frac{\sum_{k=1}^3 \log_{10}(X_{ijk})}{3} \quad (4)$$

and MD_i is the difference between the average of the participants' i th odds and the general average GM :

$$MD_i = M_i - GM \quad (5)$$

where M_i is the average of the score of the i th participant (computed over the 41 stimuli) and GM is the average of all scores of the 53 participants:

$$M_i = \frac{\sum_{j=1}^{41} M_{ij}}{41} \quad (6)$$

$$GM = \frac{\sum_{i=1}^{53} M_i}{53} \quad (7)$$

Subjective discomfort

Figure 2 shows the averages of the normalized values of each stimulus with their 95% confidence intervals¹³. For low accelerations, the lowest frequency stimuli are evaluated with the highest discomfort values, which is in accordance with the ISO 2631-1 frequency-weighting curve W_k for Z axis. These evaluation differences tend to decrease at the highest levels.

Steven's law constants were calculated for each of the four vibration series of 15, 20, 25 and 30 Hz from the average of the normalized values of all participants. According to the logarithm of the equation (2), a simple linear regression gives the power constants of Steven's a and b of accelerations x (m/s^2) and the discomfort ratings $\psi = SV_{ij}$:

$$\psi = a \times \varphi^b \rightarrow \log(\psi) = \log(a) + b \times \log(\varphi) \quad (8)$$

Hence, there is a linear relationship between excitation levels expressed in dB and the logarithm of sensation.

The results give the constants of Stevens $a = 1.09$ and $b = 0.89$ ($R^2 = 0.98$) for 15 Hz, $a = 0.94$ and $b = 0.92$ ($R^2 = 0.98$) for 20 Hz, $a = 0.87$ and $b = 0.98$ ($R^2 = 0.98$) for 25 Hz and $a = 0.80$ and $b = 1.03$ ($R^2 = 0.99$) for 30 Hz. The higher the frequency, the higher the exponent of Steven's law. There is a difference of 0.14 between the b values for 15 and 30 Hz vibrations.

Historically, helicopter crews used to talk about uncomfortable vibrations using the inch per second unit of measurement. This means that they express the amplitude of vibrations as velocities rather than accelerations as is often the case in the literature.

The discomfort ratings normalized as a function of vibration velocity are shown in Figure 3. The figure shows a good overlap of data. This means that the discomfort depended only on vibrational velocity.

In addition, a closer look at the Figure 3 shows that Steven's power law could be calculated separately for low and high velocities. For levels below approximately 0.008 m/s (138 dB reference 10^{-9} m/s), the measured data could be represented by the relationship $\Phi = 3352 \times v^{1.18}$ ($R^2 = 0.99$). Above this limit, a similar relationship was found but with a lower exponent: $\Phi = 245 \times v^{0.65}$ ($R^2 = 0.97$).

Discussion

The values of the exponent obtained in this study are within the range of variation of those given by the literature, not far from the average exponent mentioned earlier (mean = 1.0 and std = 0.22). They are close to values related by Leatherwood and Dempsey⁶ but significantly greater than the exponents proposed by Morioka and Griffin⁸ or Basri and Griffin^{13,14} in some of the last papers related to that topic. There are some differences in the experimental procedures used in these studies (shorter stimuli duration, larger level range, use of a reference, different backrest inclinations). But it is unlikely that such differences can explain the differences between exponents obtained in both studies. On the other hand, 12 people only participated in the experiment described in

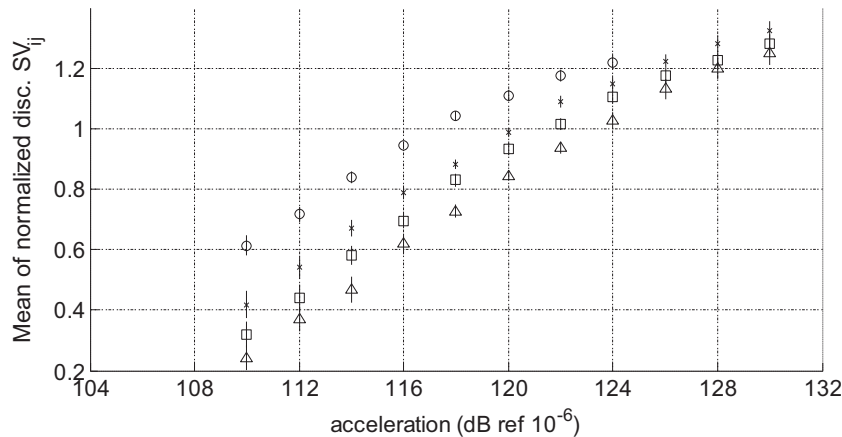


Figure 2. Mean normalized discomfort ratings SV_{ij} for each frequency and their confidence intervals (15 Hz in circles, 20 Hz in crosses, 25 Hz in squares and 30 Hz in triangles) as a function of accelerations in dB reference 10^{-6} m/s^2 .¹³

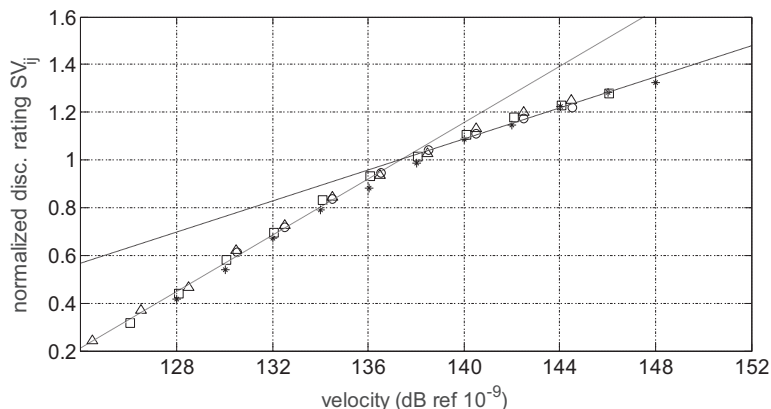


Figure 3. Vibratory discomfort Stevens' law represented for normalized mean discomfort scores as a function of vibrations velocity for all frequencies (15 Hz in circles, 20 Hz in crosses, 25 Hz in squares and 30 Hz in triangles).

Morioka and Griffin⁸, Basri and Griffin^{9,14} and no normalization was applied. As the interindividual variability is great (as mentioned above), the small size of the sample may have led to inaccurate results.

When comparing signals with different frequencies, our results show that the vibration velocity is a better descriptor than acceleration. This has already been mentioned by Miwa¹⁵. By measuring equal sensation contours for vertical vibrations, Miwa¹⁵ showed that the velocity was an adequate descriptor between 5 and 40 Hz. This is also in agreement with the weighting curve used in the ISO 2631-1 standard. In the case of whole body vertical vibration, the slope of this weighting curve (W_k) is inversely proportional to the frequency between 15 and 30 Hz.

Finally, the different exponents obtained for low and high levels (as shown in Figure 3) had also been noted by Miwa¹⁵. The cut-off level was 0.01 m/s, which is close to the 0.08 m/s proposed in the current study. However, the two exponents proposed by Miwa¹⁵ were also smaller than the ones appearing in Figure 3 (in the low level range: 0.6 instead of 1.18; in the high level range: 0.46 instead of 0.65).

The helicopter seat used in that study was very rigid. Its transfer function in the vertical direction (between the seat attachment points and the seat-person interface) was close to 1 in the considered frequency range. Thus, it can be considered that participants were submitted to the vibration levels shown in Table 1. This would not be true if a softer seat had been used, as the ones used in cars.

Conclusions

For vertical single-frequency vibrations between 15 and 30 Hz, discomfort seems to be related to the vibration velocity. The associated psychophysical relationship can be represented by Steven's law, with two different exponents (1.18 at levels below 0.008 m/s and 0.65 above this value). Nevertheless, it can be noted that the discomfort ratings were obtained in the laboratory. These ratings may be different in real flight conditions, where passengers are submitted not only to vertical vibratory stimuli but also to horizontal vibrations, sound and visual stimuli from the cabin.

From an industrial point of view, the results of this experiment give the variation of discomfort according to the vibrations BPF, but cannot give a discomfort value that can be related to a semantic label (for example, saying that a rate of 1 is the equivalent of 'very uncomfortable'). In addition, to assess the complete vibratory discomfort in the helicopter cabin, further experiments must be performed. They must include multiaxial vibrations and aerodynamic excitations.

Declaration of conflicting interests

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