Paper 201

COMFORT METHODOLOGY AND INDICATORS APPLIED ON HELICOPTER VIBRATIONS

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ABSTRACT

In general helicopters are generating vibrations during flight. The human body is sensitive to those vibrations and can affect his performance, comfort feeling and health. Eurocopter improves the vibration levels of its helicopters continuously. The helicopter designs have been optimised and various anti-vibration devices permitting to efficiently decrease the cabin and cockpit vibration levels have been developed, taking into account the human body natural sensitivity to vibrations. For instance the most preponderant axes and frequencies are considered.

Eurocopter is optimising the design process for improving comfort and limiting impact on health for helicopter users. Up to now the vibration levels were quantified in general by using accelerometers located on the floor of the cabin. Recent tests showed that this approach must not be fully representative for the vibratory level suffered by a crew member or passenger. The impact of the seat dynamics cannot be neglected in any case.

The paper briefly describes the sources of cabin vibrations and the applied methods of vibration reduction. The impact of specific vibrations on the human body is reviewed in detail based on ISO 2631-1. The applied flight test method as well as test results are shown.

Introduction

The main rotor of a helicopter is the most important source for the vibrations in the airframe during flight. Even an ideal rotor will generate vibratory loads at its centre with a frequency of N/rev (N is the blade number).

Several concepts for the reduction of these vibrations have been developed through out the helicopter community. Besides an optimized tuning of the rotor blades, active and passive means are applicable for preventing the cabin and the occupants from annoying accelerations. The location can be at the rotor, between rotor and cabin, or in the cabin itself.

The sitting humans are exposed to the vibrations which finally reach the seats. The exposition to vibration has been explored in detail. The impact on the occupants depends strongly on the frequencies and the orientation of the vibrations. Now these results and the recommendations [3] are applied to the helicopter. The residual accelerations with the N/rev frequency play the most important role especially in the vertical direction.

Flight test by use of special accelerometers helped to evaluate the status of current products following the requirements on whole-body vibration. After post processing of the data, the resulting equivalent vibration levels according ISO 2631-1 are available. Due to the fact that helicopter vibrations depend on the flight condition, the individual mission spectrum is of importance for the daily vibration exposition dose.

Eurocopter intends to further optimise the vibration comfort of all its products by application of the described methods. It will help for a significantly better consideration of the human body sensitivity.

Vibration chain of a helicopter

To fulfil this ambition, it is necessary to keep in mind the origin of those whole body vibrations *(see Figure 1).*

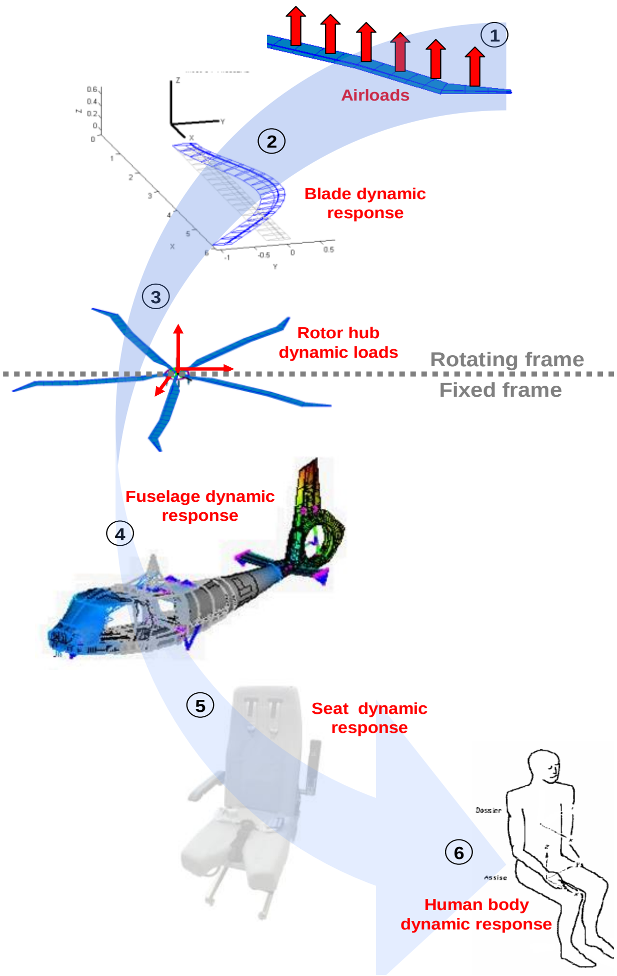

Figure 1: Vibration path

The crew and passengers are mainly exposed to vibrations at main rotor harmonic frequencies. As shown on the picture, air loads (1) excite the blades which have a dynamic response (2). The blade dynamic deflection involves dynamic loads at the rotor hub centre (3) which are transmitted to the fuselage (4) at main rotor harmonic frequencies (N/rev, 2.N/rev, …n. N/rev where N is the number of blades). The vibrations in the fuselage are the result of the fuselage dynamic response to the rotor excitation. In the same way, the seats dynamic response (5) transforms the vibrations at cabin and cockpit floor level in vibrations directly undergone by the passenger. And finally, the impact of vibrations on the whole human body comfort/health is dependant of the human body dynamic behaviour (6).

The vibration path demonstrates that to improve the helicopter user's vibratory environment, several key factors must be optimised:

- The blade dynamic response
- The transmission between rotor and fuselage
- The fuselage dynamic response
- The seat dynamic response

Helicopter vibration reduction means

In the past EUROCOPTER developed different concepts of anti-vibration devices aiming to act on each relevant part:

- Main rotor:
  - Modern 5-bladed main rotors in BMR and Spheriflex technologies
  - Blade pendulum, rotor hub resonator (passive systems)
  - Blade active flaps (active system)
  - Higher Harmonic Control through swashplate actuators,
  - Individual Blade Control through actuators in rotating frame
- Transmission rotor/fuselage:
  - SARIB, ARIS systems
  - Main Gear Box elastomeric insulation system
- Fuselage:
  - Cabin resonators (passive system)
  - Active Vibration Control System
- Seat:
  - Vertical insulation system
  - Lateral absorber

Human body dynamics: impact of vibrations on comfort and health

Theory takes into account the posture in which people are submitted to vibrations. It has an influence on where the accelerometers will be hold. In the helicopter, the users are in a seated posture. Therefore, the vibration levels have to be recorded at the very place where they are introduced in the body that is to say under the buttocks, behind the back and on the floor near the feet.

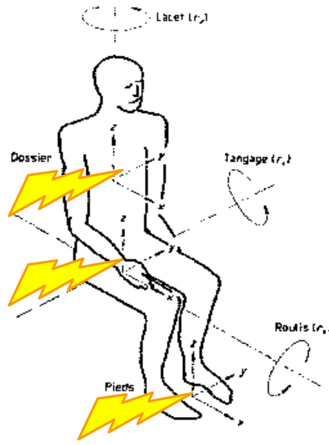

Figure 2: Axes and measurement spots on a seated person

Vibrations have impact on two different aspects which is the comfort and the health. Measurements are the basis of these evaluations. All three orthogonal axes (X, Y, Z) are relevant considering human reaction, therefore 3-axis accelerometers are the best means to equip a seat. *(Figure 2).*

For the evaluation of the comfort aspects three measurement spots and all three axes are necessary. In case of health considerations vibrations at the feet are not of importance and the backside is represented only by the X axis.

Besides location and axis the applied frequency is of importance for quantifying vibration effects. The human body appears to be sensitive to frequencies between 0.5 to 80 Hz. This sensitivity has been proven to be higher between 3 and 12 Hz for vertical and between 0.5 and 3 Hz for lateral vibrations. This range squares with the maximum transmissibility frequencies of spine, head and all human body. The effect of vibrations is known to decrease with raising frequencies (see *Figure 3*, what two of the main current standards propose on the subject [2])

The graphs of *Figure 3* represent the maximum vibrations level allowed by the criterions of both BS 6841 and ISO 2631 standards, as a function of frequency, for a time of exposure given. It is relevant to notice that the global trend is the same and confirm biodynamic data explained above. Indeed, in lateral axis for instance, the allowed maximum levels are lower under 3 Hz than above. It means that the body would receive the same damage with a low level at 1 Hz and with a high level at 10 Hz, which proves that at low frequency, human body is far more sensitive to vibrations. Helicopters with high main rotor harmonic frequencies (high rotor rotation speed and high number of blades) will be less impacting.

Therefore to increase the contribution of the most impacting frequencies, each recording needs a frequency weighting.

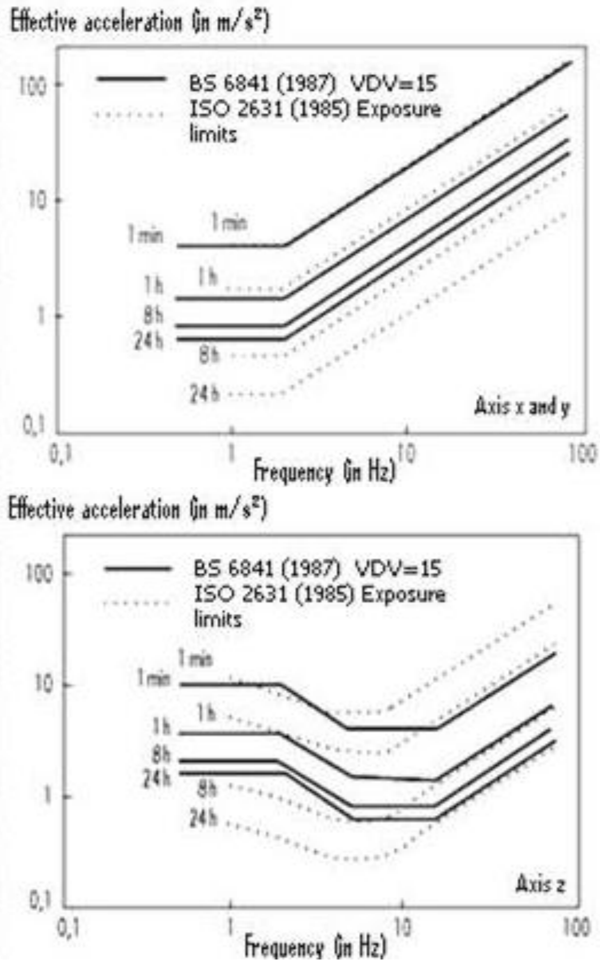

Figure 3: Frequency dependency in BS 6841 and ISO 2631

Then, a second weighting is made according to the axis and the recording spots. This is the expression of the difference between horizontal and vertical vibrations, but also of where vibrations are the most important. For instance, a very high vibration level at one's feet will certainly not put one's vital organs in jeopardy as much as if it was located under one's buttocks. That is because legs dissipate a significant part of the vibration energy.

Therefore, performing recordings at the most relevant locations and using consistent weighting factors according to the frequency, axis and locations of measurement will have a more reliable image of the whole human body reaction.

Eurocopter’s evaluation method according ISO2631 coefficients

The ISO2631 gives a methodology to calculate coefficients representing the vibration impacts of comfort and health defined in [3] as the comfort and health coefficients: $a_{comfort}$ & a_{health}

To perform the complete evaluation of such coefficients on a helicopter, it is necessary to deal with both flight measurements and data processing.

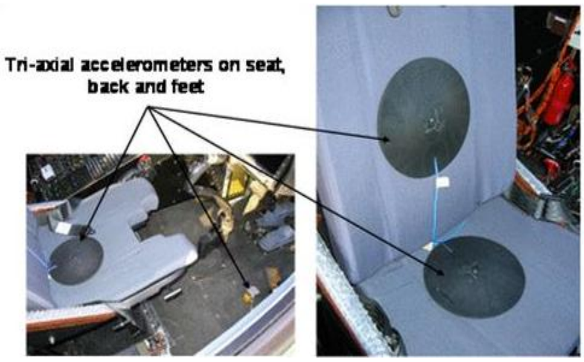

Figure 4: An equipped seat

The flight instrumentation has to be adapted to seat measurements. The 3-axes sensors are the most appropriated because of the need to record X, Y, and Z axis to have a clear idea of the vibrations. Therefore, three accelerometers are enough to equip a seat (feet, buttocks and back, *Figure 4)*. Two flat accelerometers should be placed at the main contact point between the back and the backside. The other one should be placed under the buttocks of the crew member, at the end of the spine. The third accelerometer can be a usual one and takes place on the floor in the vicinity of the feet. This way the device records exactly what the crew member or the passenger is submitted at because the sensors are at the interface between the seat and the body. Calculation of the seat impendence is made possible (vibrations before they go through the seat and after). It witnesses to the seat capability to absorb vibrations and gives a good mean to classify them.

Considering a frequency range from 0.5 Hz to 80 Hz appears to be enough to highlight hazards for human body since it decreases consequently beyond these limits. Recording duration can be limited to 20 to 30 seconds if the flight phase is kept the same during the recording. A helicopter vibrates differently during a hover phase and when it’s cruising at 140 knots for instance. That is why measurements must be done for all possible steady flight conditions.

The helicopter evaluation has to be performed in conditions as near as possible from costumer usages. That means the usual loading (“average user configuration”) of the helicopter should be respected, as well as the centre of gravity position and a person should be on each measurement equipped seat. Moreover, each mission generates its own vibratory profile. For the evaluation a helicopter vibration level the daily mission is important.

To take the mission into account means to know how the helicopter flies carrying out the mission. The usual flight phases and finally how long each flight phase lasts, all these pieces of information are necessary to establish the flight spectrum and therefore the vibration level. These data are generally the same for a same daily use. This is where the aspect of “type mission” appears, like for example Off-shore, VIP, Search And Rescue missions.

When flight data are extracted, it should be processed before any interpretation. Each recording needs a frequency weighting to increase the contribution of the most impacting frequencies for human body as explained in the previous paragraph. The frequency weighting factors used are extracted from the regulation ISO2631 [3].

The weighted acceleration is calculated as follow:

$$a_W = \left[\frac{1}{T} \int_0^T a_w^{\,2}(t).dt \right]^{\frac{1}{2}}$$

a_W (t): the weighted acceleration as a function of time in m/s²
T: the measurement duration in s

Or with a spectral method as:

$$a_W = \left[\sum_i (W_i . a_i)^2 \right]^{\frac{1}{2}}$$

$a_{W:}$ the weighted acceleration
Wi :the frequency weighted factor for the ith frequency band
ai=the RMS acceleration for the ith frequency band

The weighted acceleration must be calculated for all measurement spots. The frequency weighting factors are different according the location and axis of measurement as they are adapted to the body parts where the vibrations are recorded (Table 1).

	Buttock			Back			Feet		
	x	y	z	x	y	z	x	y	z
Comfort	Wd	Wd	Wk	Wc	Wd	Wd	Wk	Wk	Wk
Health	Wd	Wd	Wk	Wc	-	-	-	-	-

Table 1: Frequency weighting factors W

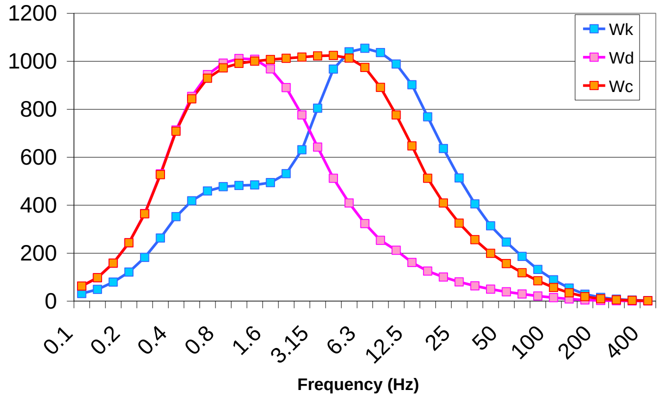

Figure 5: Frequency weighting factors x1000

Then <u>the axis weighting</u> is performed in order to take into account the human body sensitivity. According to calculated coefficients and the axis, weighting factors are not the same (Table 2).

	Buttock			Back			Feet		
	x	y	z	x	y	z	x	y	z
Comfort	1	1	1	0,8	0,5	0,4	0,25	0,25	0,4
Health	1,4	1,4	1	0,8	0	0	0	0	0

Table 2: Axis weighting factors K

Thus the comfort and health coefficients are calculated for each recorded flight phase as follow:

$$a_{comfort} = \begin{pmatrix} awx_{buttock}^{\ 2} + awy_{buttock}^{\ 2} + awz_{buttock}^{\ 2} \\ + (0{,}8.awx_{back})^2 + (0{,}5.awy_{back})^2 + (0{,}4.awz_{back})^2 \\ + (0{,}25.awx_{feet})^2 + (0{,}25.awy_{feet})^2 + (0{,}4.awz_{feet})^2 \end{pmatrix}^{1/2}$$

$$a_{health} = \begin{pmatrix} (1{,}4.awx_{buttock})^2 + (1{,}4.awy_{buttock})^2 + awz_{buttock}^{\ 2} \\ + (0{,}8.awx_{back})^2 \end{pmatrix}^{1/2}$$

This is when the mission flight spectrum has to be taken into account. During its usual mission, a helicopter meets several flight phases, and for a variable occurrence according to the phase. Therefore, to qualify the mission, the flight phases and the time slices related are needed. That is why the third weighting integrates this time-dependency, giving more importance to lasting phases. Among both ISO 2631 proposals [3], Eurocopter uses the quadratic dependency one:

$$a_{eq} = \sqrt{\frac{\sum a_{wi}^{\ 2}.T_i}{\sum T_i}}$$

a_{eq} the global coefficients
a_{wi} the coefficients (health and comfort) corresponding to flight phase i
T_i the time spent in flight phase i

This method permits to calculate the health and comfort coefficients for any kind of flight spectrum as these coefficients were previously calculated for various elementary flight phases. Therefore the health and comfort coefficients could be calculated for usual type missions (Offshore, VIP, SAR, …) or for more specific missions if the costumer provides his own flight spectrum.

Nevertheless the flight could have lasted 30 minutes or 5 hours, the result would have been the same, as time is normalised in this calculation, only the spectrum has an influence.

Currently the comfort time dependency has never been proved. Therefore, the global coefficient comfort $a_{comfort}$ could be directly used. The comfort coefficient can be compared to a scale dedicated to comfort (see table 2) which is a semantic one that runs from “comfortable” to “extremely uncomfortable”.

Applied to helicopter, this scale extracted from [3] associates a comfort label and might be a criterion for the customer. This scale is not only dedicated to Helicopters; it is consistent for all transport devices.

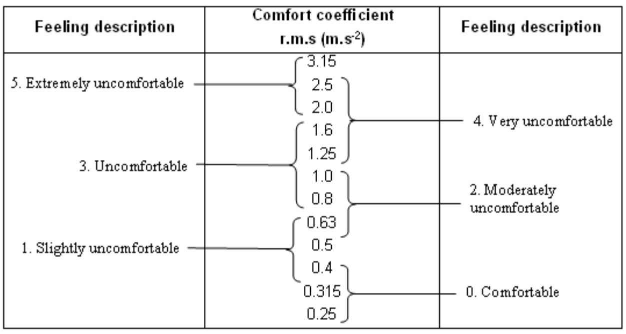

Table 3: Comfort scale

The a_{health} coefficient calculated above is not directly linked to the exposure time, it is only linked to the helicopter and the flight spectrum. However, the impact of vibrations on health is linked to the exposure time, and so to the flight time duration. To express time dependency it is useful to calculate the vibration dose from the health coefficient with an associated time exposure which must be the flight duration:

$$VD = \left[(1.4.a_{health})^{4}.T \right]^{1/4}$$

with T: time exposure in s

Therefore, this value represents the vibration dose cumulated by a crew or a passenger after the flight.

For comparing the obtained data, the application of a standard exposition duration is useful. The ISO 2631 [3] defines as time reference an 8 hours working day, which is a good choice to measure the impact on workers. Criterions on acceleration have to be chosen for this standard exposure time.

Health coefficient from measurement of 8 hours would be compared straightaway. If not, the data will need a conversion into an "8 hours equivalent" value by this formula:

$$a_{health-8eq} = a_{health} \cdot \left(\frac{T_{flight}}{8} \right)^{1/4}$$

$A_{health\text{-}8eq}$ the "8 hours equivalent value"
A_{health} the health coefficient calculated an exposure different from 8 hours
T_{flight} the real duration of the flight in hours

The health dedicated scale needs more accuracy because it is supposed to limit the flight time of the crew. Experience shows that below 0.5 m/s² during 8 hours (or a "Daily Vibration Dose"=9,1m/s^{1,75}), there is no impact for health. Until 1.15 m/s² (or a DVD=21m/s^{1,75}), impact is possible but not demonstrated. So precautions should be taken in order to limit the vibration level. Beyond this value, a too long exposure can have consequences on health.

These coefficients are a more reliable image of the impact of vibration on comfort and heath as they take into account the human body sensitivity and thus are relevant drivers for our developments from the rotor to the seat.

Basically *Figure 6* shows the frequency effect on the maximum tolerable vibration level on the seat (see frequency weighting factors of *Figure 5*). For simplicity all directions have the same acceleration level. The target is to have no possible impact on health during a 8 hour exposition time. The blade tip speed is kept constant at 220 m/s.

A higher rotor diameter or a reduced blade number reduces the frequency and therefore lowers the allowable accelerations. This is a common approach and has nothing to do with a specific helicopter *(Figure 6).*

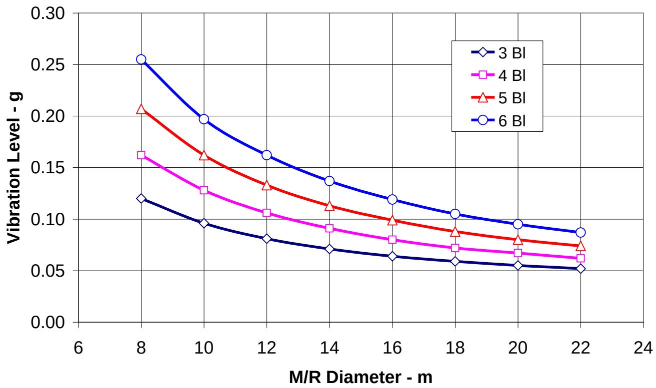

Figure 6: Maximum tolerable accelerations as a function of rotor diameter

Tests and results analysis on the EC155, seat dynamic behaviour

Tests were done on one EC155, at cabin and cockpit level. The EC155 has a Spheriflex 5-bladed rotor, a MTOW of 5 tons, and has only a one axis isolation system between the gearbox and the upper deck. The simplified spectrum hereafter will be used to interpret these results (*Table 4*).

Flight phase	Occurrence (in %)
Hover	10
100 kts	20
Maximal speed	70

Table 4: Simplified spectrum

The evaluation method was applied to the crew seats and 4 passenger seats as is indicated in *Figure 7*.

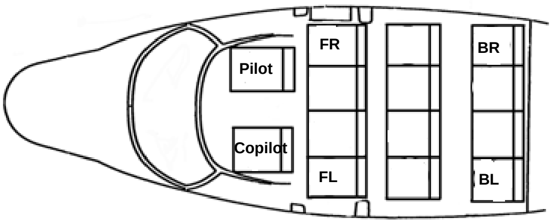

Figure 7: EC155 seats assessed

The comfort analysis of the 6 seats is depicted in *Figure 8*. It shows that the vibration levels are different on every seat. The right side is less submitted to vibration than the left side in the cabin.

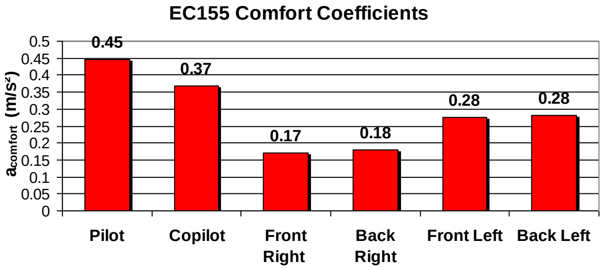

Figure 8: Comfort coefficients

On the comfort scale defined previously (Table 2), all the levels in cabin are considered "comfortable" so the passengers can fly in a very comfortable vibratory environment. According the experience, such results can be considered as excellent for an H/C. In the cockpit, they stay widely acceptable since the copilot seat is considered as "comfortable". Only the pilot seat is described as "slightly uncomfortable" on scale usable on any transport means.

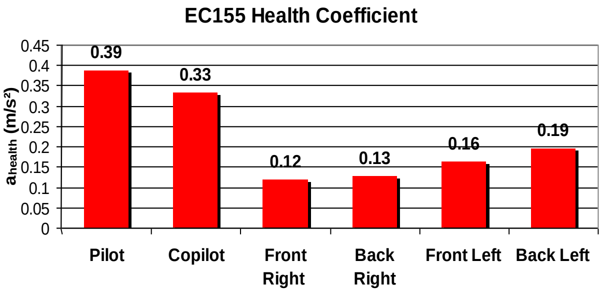

Figure 9: Health coefficients

Concerning health considerations, the results appear on *Figure 9*. In the cabin, the levels are very low since they do not exceed 0.2 m/s². In the cockpit, the levels are somewhat higher. The pilot is more exposed to vibrations since the equivalent acceleration is 0.39 m/s². But in general, all measured seats have very low health coefficients so it has no impact at all for health. It highlights that passengers or crew members would stay more than 8 hour in this aircraft without any possibility to have long term impact on their health.

The results on EC155 show that the cabin comfort levels are excellent for an helicopter as they are widely considered as "comfortable". In the cockpit, only the pilot seat is labelled as "slightly uncomfortable" by the ISO2631 scale which is still a good result for the helicopter field. But the most important is that, in any case, the measured vibrations levels have no possible effects on the health of passengers or crew members.

The good result gathered on EC155 are obviously due to low vibration level induced by this H/C but also due to an adapted seat dynamic behaviour. For instance according the frequency weighting factors (*Figure 5*), the vertical accelerations at the buttock are preponderant in the health coefficient calculations. Therefore a seat with good vertical filtering properties is a good way to minimize the impact of vibration on human body.

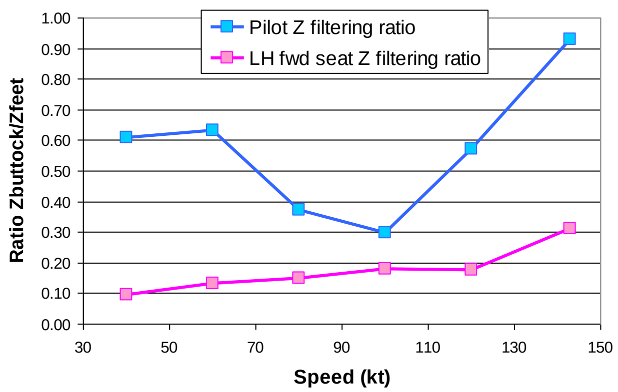

Figure 10: EC155 seats vertical filtering ratios at the N/rev frequency

The *Figure 10* shows the EC155 seat filtering capability by the acceleration ratios at the floor and at the buttock for the N/rev frequency. The comparison is performed on the pilot and the left forward seat.

The difference of vertical dynamic behaviour between these two types of seat, induced by different cushion foam properties, mainly explains the gap between cabin and cockpit results.

These results show once the seat transfer function identified, it makes possible through the comfort and health coefficients to easily highlight the most preponderant vibration axis and thus establish priorities in the vibration reduction.

As explained previously, the Z axis (vertical) is the most preponderant because even if in some cases the axis weighting factors are higher for coplanar accelerations (see Table 1), the frequency weighting factors around the main rotor harmonic frequencies are strongly penalizing for the Z accelerations. However, depending on the seat measured: its type, its integration and as at second order the individual seated on, the results might change significantly.

To highlight it, another weighted coefficient can be calculated which obviously takes into account the frequency and axis weighting factors presented previously but also the transfer function of the seat. Therefore, the comfort and health coefficients could be directly defined with the acceleration at the feet level via these global weighted factors λ.

$$a_{confort} = \begin{pmatrix} \lambda x_{confort}.ax_{feet}{}^{2} + \lambda y_{confort}.ay_{feet}{}^{2} \\ + \lambda z_{confort}.az_{feet}{}^{2} \end{pmatrix}^{1/2}$$

$$a_{health} = \begin{pmatrix} \lambda x_{health}.ax_{feet}{}^{2} + \lambda y_{health}.ay_{feet}{}^{2} \\ + \lambda z_{heath}.az_{feet}{}^{2} \end{pmatrix}^{1/2}$$

With λx, λy, λz the global weighting factors taking into account the seat transfer function

The comfort and health factors have not the same λ factors as they do not consider the measurement spots. The higher the λ coefficients are, the more important the impact of vibrations along the concerned axis on comfort and health coefficient will be. The λ coefficients are plotted for one crew seat at the N/rev frequency as a function of speed.
The results *Figure 11* show the preponderance of the vertical axis only for low airspeed. For high speeds the lateral axis coefficients becomes the axis along which the vibration must be reduced in priority. For example a limit of 1,15 m/s² for the health coefficient could be reached during the maximum speed level flight with 0,32 g along Z or 0,3 g along X or 0,24 g along Y. This result confirms the lateral axis preponderance.

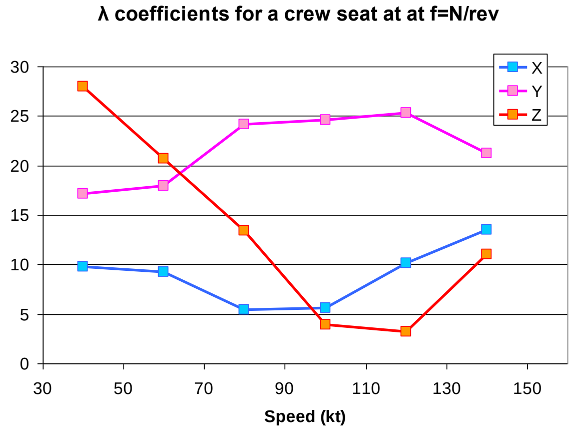

Figure 11: λ coefficients for one seat

Even if the EC155 results are already very satisfying it would have several improvement ways that is to say:

- Improve the seat design to reduce its lateral amplification factor or add a lateral anti-vibration device
- Reduce the lateral acceleration at the floor

Tests and results analysis on the EC135

The EC135 features a 4-bladed main rotor with an one axis isolation system in vertical direction between gear box and airframe. An absorber below the cabin floor reduces the lateral cockpit vibrations. During development test flights as well as during the acceptance test procedure usually accelerometers are located on the cabin floor for monitoring the overall cabin vibration behaviour of the helicopter. The reference flight condition is the maximum level flight speed (v_H). According to the method already described above, the pilot seat vibrations were measured in some cases for comparison.

By use of the nominal rotor speed frequency of the EC135 the weighting coefficients have been calculated. Besides the most important 4/rev the 1/rev and 8/rev accelerations are considered by typical levels for a virtual example (amplitudes):

4/rev: 0.12 g
8/rev: 0.05 g
1/rev: 0.01 g

The contribution of location and direction of the acceleration on the health coefficients is depicted in *Figure 12 and 13.* It has to be noticed that only the vibrations of the seat (x,y,z) and the longitudinal motion (x) of the back have to be taken into account. In this case the dominating contribution comes from the vertical motion of the seat.

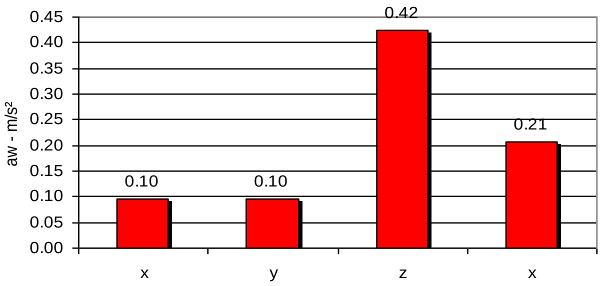

Figure 12: Contributions by axis for the calculation of the health coefficient

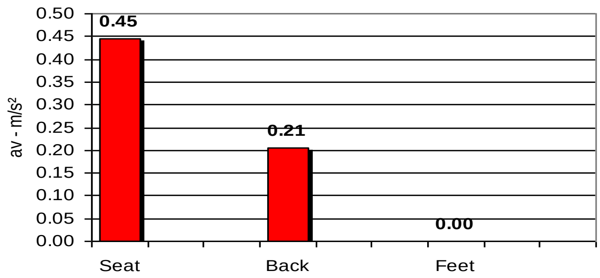

Figure 13: Contributions by location for the calculation of the health coefficient

The overall equivalent vibration level sums up to a value of 0.49 m/s², which is just below the exposure limit of 0.5 m/s². The vertical 4/rev accelerations on the seat (third bar of the upper diagram) is dominating the final acceleration coefficient. It amounts more than 85% of the total value. For summing up the individual parts the root mean square method has to be applied.

A comparison of the vertical accelerations of the seat and the associated position on the floor shows *Figure 14* during level flight conditions. There is a similar characteristic at both positions. For high speed conditions, a reduction of up to 20% is encountered on the seat in comparison to the floor. This effect is of importance for the calculation of the equivalent vibration level as far as only floor measurements are available.

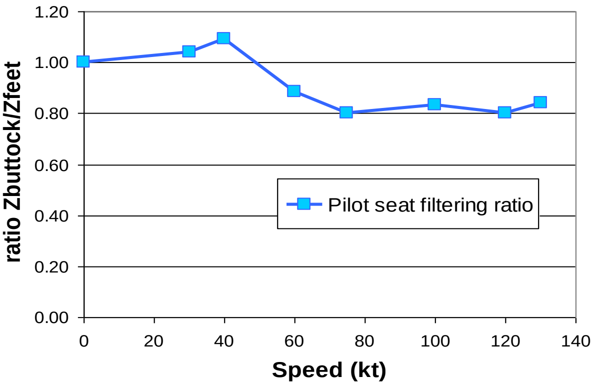

Figure 14: EC135 pilot seat vertical acceleration ratio at the N/rev frequency

Above considerations are focused on the reference flight condition at v_H. *Figure 15* shows the main groups of the standard mission profile. The mission time of steady forward flight conditions is dominating and amounts around 60%, whereas the appropriate accumulated vibration dose is only 50%. The compensation takes place at manoeuvring flight conditions where the vibration excitation in general is higher. Summing up the whole mission profile the resulting vibration dose is slightly lower (5% to 10%) compared to the dose which is extrapolated from the reference condition at v_H. Therefore the approach via the single reference condition is a little more conservative. Despite that this condition occurs only at a time fraction of 6.6% within the EC135 flight spectrum, it is suitable to represent the whole mission profile.

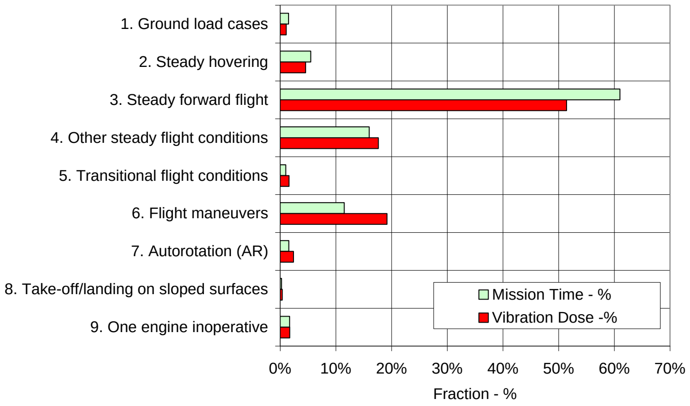

Figure 15: EC135 mission profile in terms of time and vibration dose

The presented results on EC155 and EC135 show the comfort and health coefficients are widely acceptable and even excellent in some cases. These good results are mainly due to a global architecture optimised for vibration but also in both cases due to appropriate vibration reduction means. For example, the EC135 cabin anti-vibration systems minimize the lateral accelerations which allow to ensure the absence of impact on crew heath, whereas the EC155 seat vertical filtering properties give it also an optimised comfort label.

Conclusions

After the study of biodynamics of human body, Eurocopter defined an appropriate method to perform the evaluation of its range with reliability. The process should soon be applied to the whole range during test flights and in middle term available for "at home evaluation" on costumer's helicopters.

This new method has several interests:

- First, it will permit to confirm the whole EC fleet, and even the oldest helicopters, have no high vibration levels leading to involve irreversible effects on user's health whatever the configuration and the mission performed.

- Then, it will also permit to demonstrate the new developments or the most recent versions are safe even for prolonged exposure duration and have optimized comfort criteria as the EC155 and the EC135 for example.

This way, global vibration levels will be guaranteed on every model and mission; local abnormally-high levels will be detected and thwarted with the help of further device.

In addition, the study of these coefficients shows basically that the floor acceleration is not the most relevant criteria in any case. Using some other criteria better taking into consideration the human body reaction is a good way to optimise the efficiency of vibration reduction means with regards to human feeling. Indeed, these criteria allow to easily highlight the most preponderant frequency, axis and ways of action, permitting to optimise the comfort and health coefficients. It is very helpful to relevantly steer our design, from the rotor to the seats.

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