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EFFECTS OF FLIGHT DECK MOTIONS ON PILOTS PERFORMANCE

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1 - INTRODUCTION -

1.1 - Motivation of the study and aim -

Cockpit motions induced by turbulence are likely to impair aircrew performance, either by a direct and a short term impact on the task achievement (e.g. tracking) or by the effects of prolonged exposure on fatigue. In the context of the certification of large transport aircraft, it is necessary to ensure that cockpit motions are maintained within acceptable limits and thus, do not significantly impair the ability of the aircrew to operate the flight. These objectives are consistent with the requirements of the Joint Aviations Authorities (JAA) (JAR 25.251 and ACJ 25.143), but neither the thresholds nor the measurements are given in these regulations.

The objective of this work is then to provide the JAA the necessary information for a basis to develop an advisory material allowing the certification team to ensure that the induced vibrations are maintained at an acceptable level.

In order to provide information in a practical and useful way, the data collected in this study are incorporated in a basic database in which motions features and task components are crossed. It is therefore easy to retrieve published data on the effects of a given motion on a given task.

1.2 - Scope and limitations of the study -

In order to limit the results of this study to the most relevant information, the works pertaining to the following aspects have been excluded from the study :

- shocks, g-forces, acoustics,
- passengers and cabin crew,
- crew rest areas, cabin,
- locomotion.

Furthermore, a large amount of work have been conducted on motion sickness related to low frequency. This work has not been included in this review as it is not directly in the scope of this review.

On the contrary, addressing the following aspects have been included in this work:

- oscillatory motions and vibration, turbulences,
- wide-body aircraft, fixed wings,
- pilots,
- flight deck.

2 - WORKING GROUP PRESENTATION (LAA) -

This work, coordinated by the LAA, is the result of a cooperation among the European Committee for Aircrew Scheduling and Safety (ECASS) group which includes 5 Human Factors research institutes :

- the DLR Institute of Aerospace Medicine (Germany),
- the TNO (The Netherlands) - Human Factors Research Institute,
- QuinetiQ (UK),
- the Karolinska Institute (Sweden) - Division of Work Environment and Health,
- the LAA (France).

Over the last years, these institutes have developed a broad expertise in the area of fatigue and performance in the aerospace field and have conducted studies on vibration.

3 - METHOD AND PROCEDURES : LITERATURE SOURCES –

3.1 – Literature review

About 40 articles have been collected from different database consultation :

- bibliographic database of LAA,
- Ergonomics Abstracts,
- bibliographic database of Institut National de Recherche et de Sécurité,
- bibliographic references from ECASS.

Different handbook and journals have been used :

- Engineering Data Compendium,
- NASA-STD 3000, Applied Ergonomics,
- Aviation, Space and Environmental Medicine,
- Physiological Reviews,
- Journal of Low Frequency, Noise and Vibrations,
- Ergonomics,
- Human Factors,
- other reviews: *doctoral thesis of Moseley, M.J. (1986).*

The references are given in chapter 9.

3.2 – Classification of flight deck motions

Flight deck motions can be classified into 3 ranges of frequency:

- low frequency (< 1 Hz),
- medium frequency (from 1 to 8 Hz),

high frequency (> 8 Hz).

Moreover, vibrations spread in 3 axis :

- horizontal (from front to rear), (x-axis),
- lateral (from right to left), (y-axis),
- vertical (from the top to the bottom), (z-axis).

3.3 – Production and use of a matrix to retrieve available information

The different modes of vibrations lead to build a matrix in which motions features and tasks components are crossed. This matrix was constructed in Powerpoint. By a click on a cell of this matrix a page opens containing :

- the effects of vibrations on task or crew performance,
- the physical description of the stressor (frequency, direction, magnitude, duration, regularity, crest…),
- the threshold of acceptability (if available)
- the effects of exposure duration,
- the conditions of the study (lab, field, aviation or other),
- the sample sizes and characterisation : type (pilot or other), experience, gender, age, body measures…),
- the task or measure / activities description : input details (display size, position), performance measures, training,
- additional comments,
- the references of the article.

4 - REVIEW OF STANDARDS ON HUMAN EXPOSURE TO VIBRATION -

This section summarizes (inter)national standards on the effects of mechanical vibration on humans, with emphasis on disturbances to task performance. Obviously, many other vibration standards exist, but these do not specifically address interference with activities, but rather discomfort (motion sickness), perception, and health and safety. The following documents are discussed here:

- British Standard BS 6841 (1987): “Guide to measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock”,

- ISO 2631: Part 1 (1997) “Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration. Part 1: General requirements”,
- ISO 6954 (1984) “Mechanical vibration and shock – Guidelines for the overall evaluation of vibration in merchant ships”,
- ISO 9996 (1996) “Mechanical vibration and shock - disturbance to human activity and performance - classification”,
- NASA-STD-3000.

In general, the standards provide procedures for the recording and reporting of vibrations, as well as methods for calculating a normalized vibration magnitude that can be used to evaluate the expected effect on humans. To some extent, the standards also provide guidance for acceptable levels of vibration, although strict “limits” are seldom given for it is recognized that these are very context-dependent. Therefore, the definition of such limits is often left to experts of the responsible institutions. The evaluation of vibration effects is always performed in relation to a specific human response, or so-called “criterion”. The following criteria are distinguished in the various standards:

- health and safety,
- (dis)comfort,
- perception,
- motion sickness,
- interference with activities,
- fatigue-induced proficiency.

As agreed during the meeting with the ECCAIRS Steering Committee in Brussels on April 15, 2004, this project is concerned with the criterion “interference with activities”. The British Standard 6841 (1987) seems to provide the most useful data in this respect. Therefore, this standard will be discussed in most detail. However, the ISO 9996 will be briefly discussed first, since it provides a classification of operator tasks and vibration effects.

4.1 - International standard ISO 9996: 1996(E) -

The ISO 9996 “Mechanical vibration and shock – disturbance to human activity and performance – classification” provides an overview on operator tasks that may be affected by mechanical vibration. Among other functions, it is recognised that task performance may be influenced by vibrational effects on:

- Visual system (e.g. signal detection, visual acuity),
- Central processing (e.g. pattern recognition, visual search, spatial perception),
- Motor skills.

Possible mechanisms that are mentioned include:

- Direct mechanical interference:
  - Degradation of sensory input,
  - Impairment of human motor output (i.e. the input to the activity or task).
- Indirect or central effects:
  - Impairment of sensory input and perception (e.g. visual function, vestibular function).
- Impairment of cognitive function:
  - Perceptual distraction,
  - Spatial disorientation, motion sickness,
  - Sopite syndrome, (is numbness or dizziness meant?)
  - Arousal level,
  - Fatigue.
- Degradation of task execution (motor output).

The schematic representation in Figure 1 summarizes the locations where vibration may affect a human operator.

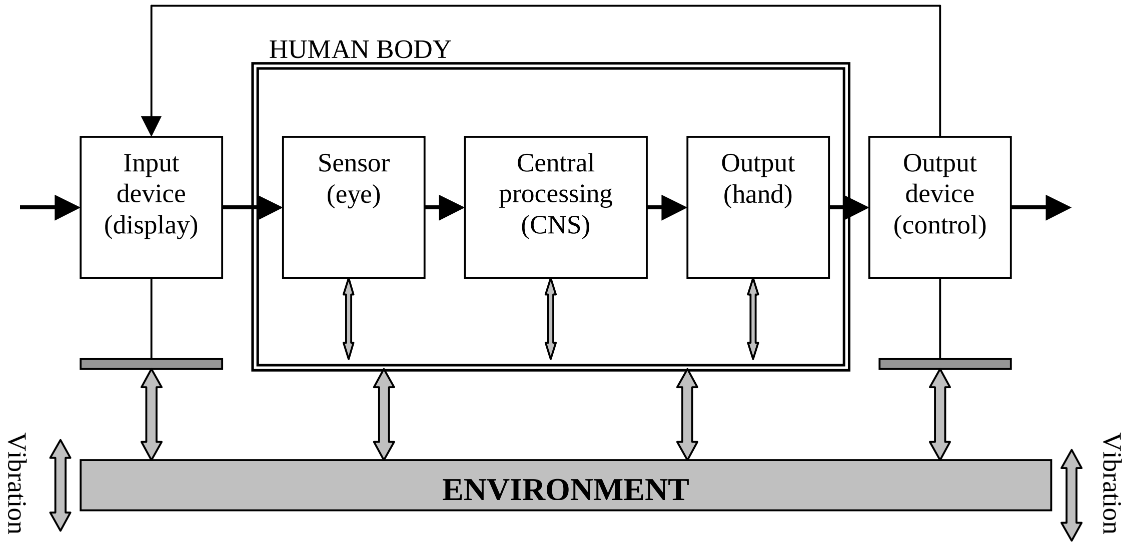


Figure 1. Scheme of vibration effects on sensori-motor tasks (adapted from Griffin 1990).

4.2 - British Standard BS 6841 (1987) -

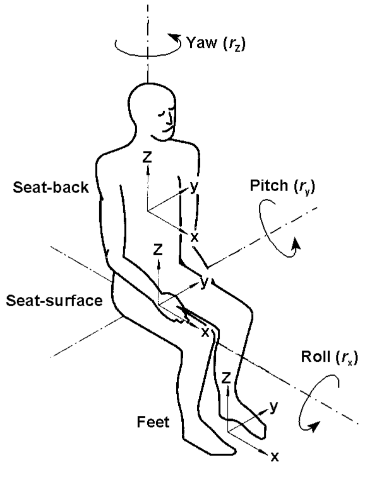
- General description -

The BS 6841 (1987) “Measurement and evaluation of human exposure to whole-body mechanical vibration and shock” describes the possible effects of whole-body vibration on the effects: (i) health, (ii) activities, (iii) comfort, and (iv) motion sickness, and applies to frequencies between 0.5 Hz to 80 Hz for the first three criteria, and 0.1-0.5 Hz for motion sickness. The effects of vibration depend on its magnitude, frequency, direction, and input position. These variables are reasonably taken into account in the analysis (see next paragraph). Furthermore, there are many other factors that determine the effect of vibration, such as population variables (age, sex, size, fitness, etc.), experience, body posture, and activities. These variables are much more difficult to generalize, and thus require an expert’s opinion as to whether or not the standard applies to a certain situation.

- Quantification of vibration magnitude -

Vibration measurements should take place in body-centered coordinates (as defined in ISO 5805 – 1997), and at the locations where the vibration enters the body. The co-ordinate system for a seated subject is given in Figure 2. It is recommended that the primary quantity to evaluate vibration levels is the root-mean-square (RMS) acceleration, after it has been frequency-weighted:

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



a) Seated position

Figure 2. Prinicipal basicentric axes for describing vibrational motion in seated subjects (ISO 2631-1).

Where a_w is the frequency-weighted acceleration (in m/s^2 for translations, and rad/s^2 for rotations), and T is the duration of the measurement (in s). The standard gives six different frequency weightings (w) for the principal body axes and for the various points where vibrations are transmitted to the body (see Table 1). For this project, weightings *W*d and *W*g that apply to hand control and vision (shaded columns) are of special interest. Frequency weightings result from so-called equivalent comfort contours, that are experimentally obtained (e.g. Corbridge and Griffin 1986). These contours show how much the vibration magnitude should be lowered or raised to create the same comfort level at different frequencies. A frequency weighting curve can be considered the inverse of equivalent comfort contours, and is used to calculate the "effective" vibration magnitude from the measured time histories. By this way, the effect of vibrations at different frequencies and directions are scaled to a certain reference value. Figure 3A and B depict the frequency weightings *W*d and *W*g, respectively.

Frequency weighting	**Health**	**Hand control**	**Vision**	**Discomfort**	**Perception**	**Motion sickness**
*W*b	z-seat	-	-	z-seat x-,y-,z-feet z-standing vertical lying	z-seat z-standing vertical lying	-
*W*c	x-back	-	-	x-back	-	-
*W*d	x-seat y-seat	x-seat y-seat	-	x-seat y-seat x-,y-standing horizontal lying y-,z-back	x-seat y-seat x-,y-standing horizontal lying	-
*W*e	-	-	-	r_x,r_y,r_z seat	-	-
*W*f	-	-	-	-	-	z-vertical
*W*g	-	z-seat	z-seat	-	-	-

Table 1. Frequency weightings used in BS 6841: 1987

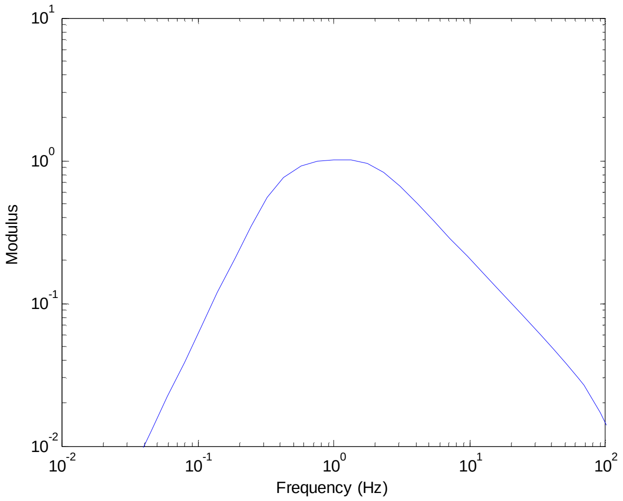


Figure 3A. Frequency weighting curve *W*d for x- and y-axis acceleration of the seat (BS 6841: 1987)

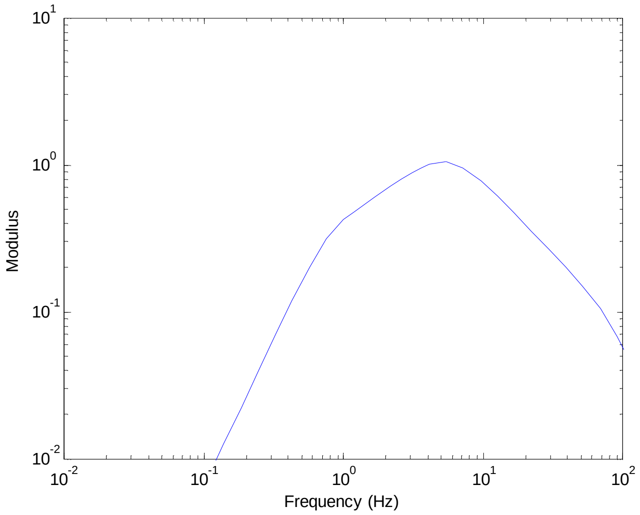


Figure 3B. Frequency weighting curve *W*g for vertical accelerations of the seat (BS 6841:1997)

The RMS is considered appropriate as long as the vibrations are "well-behaved", such as with continuous sinusoidal motion. However, when the motion contains occasional shocks or transient vibrations, its magnitude with respect to comfort is underestimated by the RMS. The decision whether a vibration should be considered continuous or transient, is usually based on the crest factor, i.e. the ratio between peak acceleration value and root-mean-square:

$$crest\ factor = \left| \frac{peak\ a_w}{r.m.s.} \right|$$

This standard considers the RMS as inadequate to assess the effects of intermittent or transient motions with a crest factor that exceeds 6.0. In those cases, a fourth power method is recommended.

In relation to the criterion health, the use of the *Vibration Dose Value* (VDV) is recommended, which is defined as follows:

$$VDV = \left\{ \int_0^T \left[a_w(t) \right]^4 dt \right\}^{\frac{1}{4}}$$

Where a_w(t) is the frequency-weighted acceleration (in m/s^2 for translation, and rad/s^2 for rotation), and T is the total period (in s) of exposure. The unit of the VDV is m.s$^{-1.75}$. The VDV is a cumulative measure, giving an estimate of the total vibration energy that a person is being exposed to, which makes the VDV particularly suitable for quantifying intermittent exposures.

The VDV can also be approximated by the estimated VDV (eVDV), as follows:

$$eVDV = 1.4 a_w T^{\frac{1}{4}}$$

Where a_w is the frequency-weighted RMS acceleration (in m.s^{-2} or rad/s^2), and T is the duration of exposure (in s). For regular motions, such as sinusoids, the eVDV will produce a larger estimate than the "true" VDV, while for vibrations with a high crest factor the eVDV will yield a smaller estimate than the VDV. The British Standard recommends the use of the VDV for variable periods of high and low vibrations. Furthermore, it is stated a VDV in the region of 15 m.s$^{-1.75}$ will cause "severe discomfort", and that "increased exposure to vibration will be accompanied by increased risk or injury". A similar limit for milder levels of discomfort is not presented in the standard, although table 2.2 in the previous section of this report may give indicative values.

In addition to the VDV, the *root-mean-quad* (RMQ) is defined for use with the criterion comfort:

$$r.m.q. = \left\{ \frac{1}{T} \int_0^T \left[a_w(t) \right]^4 dt \right\}^{1/4} = \frac{VDV}{T^{1/4}}$$

Where a_w is the frequency weighted acceleration (in m/s^2, or rad/s^2), T is the duration of measurement (in s).

- *Exposure limits* -

Similar to other standards, this standard does not provide definite vibration limits, but tentative numerical guidance for the different criteria is presented in Annexes, based on consensus of opinion on possible effects. Still, at various places in the standard it is marked that the application of these numbers may depend on the situation and the activity of the persons.

- *Evaluation of vibration with respect to effects on human activities* -

Together with Appendix B, clause 5 of BS 6841 concerns the evaluation of the effects on human activities of vibrations transmitted to the body in the frequency range 1 to 80 Hz. As could already be recognized from the weighting factors *W*d and *W*g in Table 1, the guidance on this matter applies only for seated subjects.

The frequency weightings nicely summarizes, and is largely in agreement with, findings on the vibration effects on visuo-motor tasks as described in various papers (e.g. Lee and King, 1971; Moseley and Griffin, 1986; Griffin and Hayward 1994; Moseley et al. 1982; Huddleston 1970; Griffin 1976; McLeod and Griffin 1990; Collins 1973).

No clear data are available on vibration effects on speech, postural control, cognitive processes, attention, and fatigue. Therefore, clause 5 primarily relates to the effects of vibration on the coordinated control of hand movements and vision. Only effects are considered that arise during the exposure to low-crest factor motion. Long-term effects fall outside the scope of the standard.

- Hand manipulation -

Effects on hand-controlled tasks depend on the vibration magnitude, direction and point of contact with body. Task characteristics are also relevant (such as hand-held control device), so that precise guidance is difficult. The relative effects on task performance may be assessed from the frequency weightings *W*d and *W*g. In situations where there is vibration of the body and the control, *W*d may also be applied to x- and y-axis vibration, and *W*g to z-axis vibration measured on the controls. The coupling of the hand with some controls may require additional multiplication of the frequency-weighted acceleration before assessing the effects.

Tentative limit

As a rough indication it is mentioned that where hand (or finger) control is required to an accuracy of within 5 mm r.m.s., the weighted acceleration mangitude in any axis should not exceed 0.5 m/s^2, thus: $\boldsymbol{a_w < 0.5 \mathrm{m/s}^2}$. With less resolution, the weighted values should be increased in linear proportion.

- Vision -

Of all perceptual mechanisms, vision is most easily affected, since only small movements of visual image over retina may already degrade visual acuity. The effects depend on vibration magnitude, frequency, and direction. Other variables involved are illumination, viewing distance, form and size of viewed objects. Moreover, effects depend on whether the human body, the object, or both are vibrating. Interaction effects between motions in more than one axis may lead to larger decrements in vision than motion in either axis alone. This largely depends on the phase relationship between the two motions.

The relative effects on vision may be acquired by frequency weighting *W*g that applies to vertical motion of the seat. Although x- and y-axis vibration of the seat surface seems to have no effect on affect vision, it is mentioned in a note that it is recommended to always report these vibrations using *W*d in relation to vision, since vibration of the backrest in the x-direction does influence visual performance.

Tentative limit

The current consensus that is included in Appendix B says that the frequency weighted acceleration should not exceed 0.5 m/s^2 in order to resolve visual detail less than 2 minutes of arc at the eye. For every increase by a factor √2 in the size of the detail, the vibration magnitude could be doubled.

These figures are based on a 5% increase in error reading rate in alphanumeric reading tasks, and assumes persons with normal vision (Schnellen acuity of 6/6 or better), and optimum contrast and illumination.

- Discomfort -

Although discomfort has not the highest priority to this project, the provisional guidance on this criterion is briefly presented here. Table 2 provides some rough indications of the relationship between frequency-weighted (weighting factors *W*d and *W*b) vibration magnitude and feelings of (dis)comfort. Again, the values are not meant as absolute limits, but represent the current consensus. However, various experiments at TNO Human Factors have shown that the values in Table 2 often underestimate the subjective discomfort rated by subjects.

Value	*Comfort rating*
Less than 0.315 $m.s^{-2}$	not uncomfortable
0.315 to 0.63 $m.s^{-2}$	a little uncomfortable
0.5 to 1 $m.s^{-2}$	fairly uncomfortable
0.8 to 1.6 $m.s^{-2}$	uncomfortable
1.25 to 2.5 $m.s^{-2}$	very uncomfortable
Greater than 2 $m.s^{-2}$	extremely uncomfortable

Table 2. Expected discomfort for frequency-weighted RMS
(from Annex C, BS 6841: 1987).

4.3 - International Standard ISO 2631-1 (1997) -

Among the ISO standards, the ISO 2631-1(1997) “Mechanical vibration and shock – Evaluation of human exposure to whole-body motion – Part 1: General requirements” is the most appropriate to the problem at hand. The latest revision of the ISO 2631-1 was strongly influenced by the BS 6841 (1987). Because ISO is not concerned with the criterion “human activities”, we will not describe this standard in much detail here.

Similar to the British Standard, ISO also recommends the use of the RMS as the principal vibration quantity. However, it employs a maximum crest factor of 9.0 for motion regularity, as opposed to a crest factor 6.0 used in the British Standard. Besides the use of VDV and RMQ, ISO suggests to use the *Maximum Transient Vibration Value* (MTVV) with higher crest factor motions. The MTVV is calculated from the *running r.m.s.*:

$$\textit{running r.m.s.}\quad a_w(t_0) = \left\{ \frac{1}{\tau} \int_{t_0-\tau}^{t_0} \left[a_w(t) \right]^2 dt \right\}^{1/2}$$

Where $a_w(t_0)$ is the instantaneous frequency-weighted acceleration (in m.s^{-2}), τ is the integration time for running averaging (usually 1s), t is the time as integration variable, and t_0 is the instantaneous time. From this, the MTVV is determined as the maximum value of $a_w(t_0)$ that occurs during period T.

4.4 - International Standard ISO 6954 (1984) -

- *General description* -

The standard ISO 6954 (1984) “Mechanical vibration and shock - Guidelines for the overall evaluation of vibration in merchant ships” offers methods for evaluating vibration of ship structures “based on technical as well as human performance/discomfort criteria.” It is applicable to turbine and diesel-driven merchant ships of at least 100 m length, and to vertical and horizontal vibrations in a frequency range of 1-100Hz. For the measurement of vibration data, reference is made to ISO 4867 (1984) and ISO 4868 (1984). The latter two documents are primarily concerned with vibrations of the superstructure, excited by the propulsion system and the main machinery, thus it can be assumed that this is also the case for ISO 6954.

- Quantification of vibration magnitude -

The standard recommends to analyse the vibration magnitude by means of the peak acceleration value (in m.s^{-2}), also referred to the "Maximum Repetitive Value". The maximum repetitive value is defined as the product of the RMS and the crest factor ($C_f\sqrt{2}$). When C_f can not be determined experimentally, a tentative value of 1.8 should be assumed. How the peak value of a complex vibration, consisting of multiple frequency components, must be determined, is not specified.

- Comfort boundaries -

In contrast to ISO 2631-1 (1997) and BS 6841 (1987), this standard provides absolute guidance on the acceptable level of vibration. A range of peak acceleration values is presented which is confined by two comfort boundaries: a lower limit below which "adverse comments are not probable", and an upper limit above which "adverse comments are probable." In the frequency range from 5 to 100 Hz these levels are given in terms of constant velocity, and for frequencies under 5 Hz (1-5Hz) levels are in terms of constant acceleration. The lower and upper limit are 0.126 m.s^{-2} and 0.285 m.s^{-2}, respectively. It is not explained how these limits have been determined. Obviously, the limits must be coarse approximations, since the constant velocity and acceleration is much simpler than the more detailed frequency weightings presented in ISO 2631 and BS 6841.

- Perception thresholds -

Griffin (1990) provides values for the expected strength of perception of vibration magnitudes. These values are of special interest, since they fill the gap between the absolute threshold of vibration perception (about 0.0015m.s^{-2}) and the lower threshold for discomfort (about 0.3m.s^{-2}). The values are presented in Table 3.

Perception strength	weighted RMS (m.s^{-2})
Very strong perception	0.16 – 0.315
Strong perception	0.08 – 0.16
Very clear perception	0.04 – 0.08
Clear perception	0.02 – 0.04
Perception probable	0.01 – 0.02
Perception improbable	0.005 – 0.01

Table 3. Perception of frequency weighted RMS vibration (Griffin 1990).

4.5 - NASA-STD-3000 -

This NASA standard is related to the physical environment in space operations, and as such it provides exposure criteria to vibrations. Compared to the other standards, the text is rather compact, and emphasis is given on graphical presentation of limits. Also in contrast to the other standards, the NASA STD-3000 provides guidance on fatigue decreased proficiency, but this will not be further reviewed here.

- *Performance effects* -

The standard recognises that performance may be degraded by modified perception or control movements. The frequencies of observer motion that produce visual blur are shown in Figure 4 for displacement amplitudes subtending more than ±2 minutes of arc (based on a visual acuity of about one minute of arc visual angle).

QuickTime™ et un décompresseur
Photo - JPEG sont requis pour visualiser
cette image.

Figure 4. Vibration boundaries for ±2 minute of arc visual angle
(taken from NASA-STD-3000).

Vibration effects on hand-controlled tasks are said to be greatest at 5 Hz.

4.6 - Conclusion -

This review revealed that, due to limited and sometimes contradicting experimental data, the (inter)national standards do not provide detailed numerical guidance on the exposure limits to vibrations. Besides a rough graphical presentation of boundaries in the NASA-3000, the only standard that presented indicative values of the effects of vibration on task performance was the British Standard. Although it is explicitly stated in the document that the vibration effects are task-dependent and additional analysis may be required, the suggested frequency-weighting is in correspondence with the literature on this matter. Therefore we conclude that, to our knowledge, the guidance given in BS 6841 (1987) is the most useful to the question of this project that is currently available.

5 - RELEVANT ANTHROPOMETRIC DATA -

The effects of vibrations may vary according to the anthropometric variability of the population. Therefore, it is necessary to take into account this variability in the measures and the interpretation of the effects of vibrations in the flight deck. This can be done by using anthropometric standards that are used for workplace design. The table 4 shows the main anthropometric criteria based on ERGODATA database and NASA-STD-3000. The figure 5 gives the definition of these measures. The criteria (from 5% to 95%) should be used to select a population to be included in the measures of vibration. These criteria concern three main components (number in brackets refer to table 4 and figure 5):

- the seated posture (from 1 to 10),
- the reach area and manipulation which are determined by the length of the arms (11 and 12),
- the vision that may be impacted by the head mass. This mass can be detected from the volume of the head (13 to 15).

6 - CLASSIFICATION OF PILOT TASKS -

In order to help the retrieval of relevant data, the references have been ordered into a matrix where vibrations features are crossed with main pilot tasks. The classification of pilot tasks have been established using a simple separation of demands (table 5): sensory (input), central processing and motor activities (output). Several tasks may cover 1 or two kind of demands. For example tracking which is a motor activity needs a sensory input.

Well-being has been included as it is a factor that is often cited as affected by vibrations. It covers the 3 demands.

	Demands		
Tasks	**Sensory (Input)**	**Central processing**	**Motor activities (outpout)**
Tracking (e.g. sidestick)	**X**		**X**
Manipulating (e.g. programming, selecting, É)			**X**
Reading (check-list, displays, É)	**X**	**X**	
Communicating (ATC, crew)	**X**	**X**	

Well-being	**X**	**X**	**X**

Table 5. Pilot tasks and main demands classification.

Anthropometric criteria for workplace and rest area design
(ERGODATA database and NASA -STD-3000 Man-Systems Integration Standards)

					Female			Male	
Nb	**Mesures**	**Measurements**	**ERGODATA**	**5%**	**50%**	**95%**	**5%**	**50%**	**95%**
1	Stature	Stature	STATURE	1489	1570	1651	1697	1799	1901
2	Taille Assis redressé	Sitting height	VTEXSIE4	783	848	912	889	942	995
3	Hauteur Yeux-Siège	Eye height, sitting	YEUXSIE4	681	738	796	768	819	869
4	Longueur Fesse-genou	Buttock-knee length	PLPFESGEN6	489	533	578	568	613	658
5	Hauteur Genou-Sol	Knee height, sitting	GENSOL6	416	456	495	528	567	609
6	Fesse creux poplité	Buttock-popliteal length	PLPFESCRPOP6	379	417	455	469	512	555
7	Hauteur creux poplité-sol	Popliteal height	CRPOPSOL6	347	383	419	406	444	481
8	Largeur maxi fesses assis	Hip breadth, sitting	LARMAXFES6	304	337	370	346	384	423
9	Largeur coude à coude	Forearm-forearm breadth	LARCDECDE	408	487	566	488	551	615
10	Largeur des épaules	Bideltoid (shoulder) breadth	LARBI2DELT	356	389	421	446	489	532
11	Longueur main-avant bras	Forearm-hand length	OLECDACTY	373	417	446	437	473	508
12	Longueur épaule-coude	Shoulder-elbow length	ACROMOLEC	272	298	324	337	366	394
13	Largeur tête	Head breadth	LARMAX TET	144	156	168	148	157	165
14	Longueur tête	Head length	LONMAX TET	167	182	196	188	200	211
15	Périmètre tête	Head circumference	PERTET	532	552	572	555	578	602

Values in millimeters

These values are derived from different surveys concerning worldwide population including East South Asia countries

Table 4

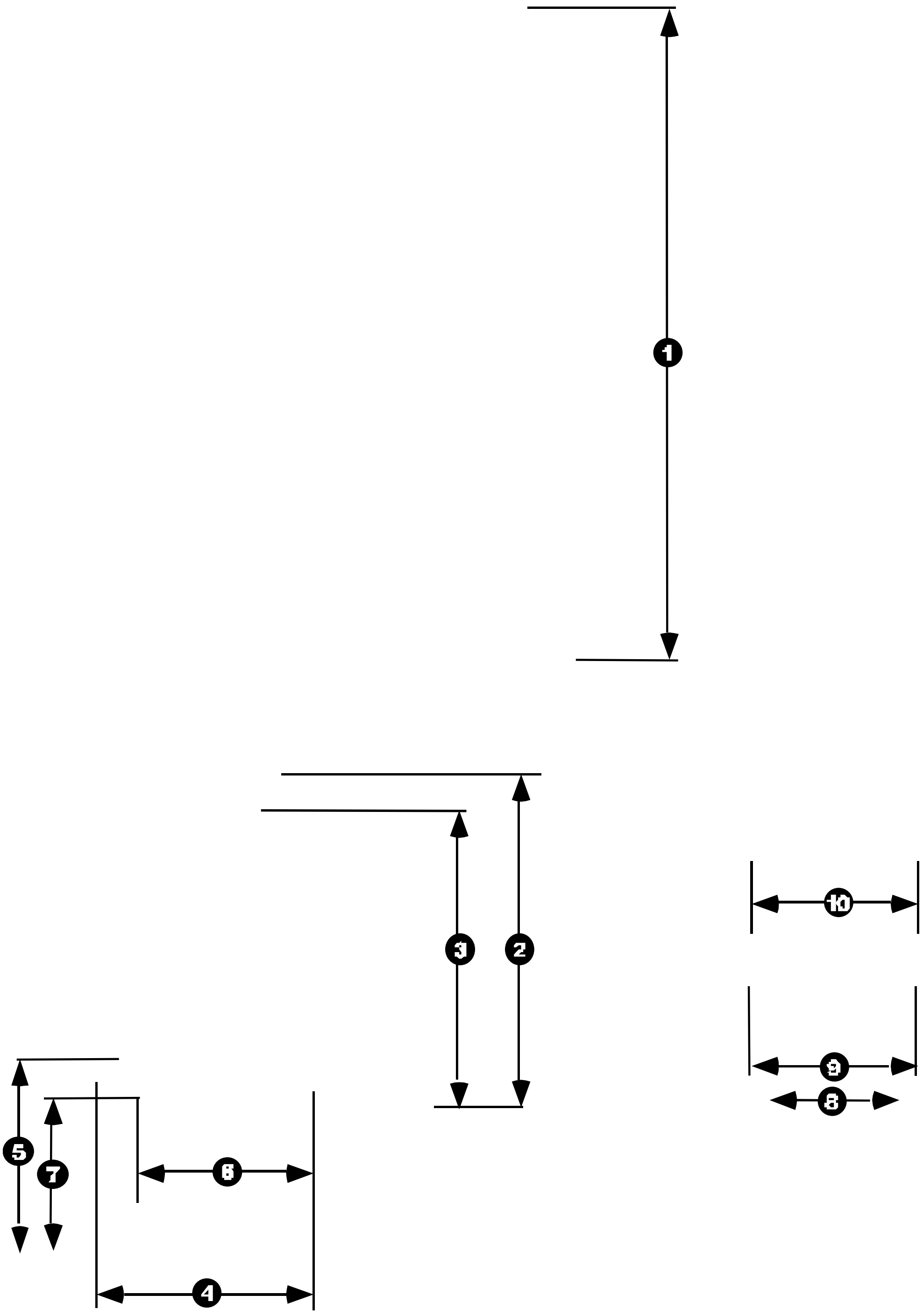


Figure 5. Definition of anthropometric criteria (see table 4).

7 - SYNTHESIS OF RESULTS -

There is not much literature available on the effects of vibration in aircraft on aircrew performance and fatigue. Hence, valid relationships related to motion acceleration and frequency (especially in the relevant range from 0.1 to 4 Hz) and corresponding thresholds above which performance declines and fatigue increases have not been established yet.

A total of 70 references have been collected and analysed. Out of these 70 references, 25 studies relevant for the objectives of the project were analysed in detail and integrated in a matrix describing both independent and dependent variables. For each physiological and psychological parameter, the main effects of relevant motion were summarised into a table with regard to performance and fatigue (effects of exposure duration). Furthermore, the sample, the experimental set-up and design of each study were outlined. This matrix has been integrated into a simple tool, a Powerpoint presentation. The first slide presents the matrix structure where all the tables can be easily accessed by clicking on the cells. In each cell the number of references included is presented. As some studies cover several factors (e.g. several frequencies or axis) a single reference can be found in several cells. This matrix can be easily updated by adding new references. All the tables are also provided in the Appendices of this report. The references have been selected among the most relevant studies regarding the objectives of this review. This is the reason why there is a majority of references in the medium frequencies (42 out of 67). Furthermore, most studies included in this matrix are focussed on 2 tasks : tracking (19 references) and reading and data processing (34 references). Only a few studies deal with selecting (1 reference) and communication (4 references).

The main results of several papers are given below.

The different kinds of vibrations have different effects on physiological functions and human performance components (e.g. tracking, visual and auditory tasks, displays reading, communications).

Griffin and Hayward, in 1994, observed a decrease of speed and efficiency reading with subjects under 0.5 to 0.63 Hz lateral vibrations. Malvache, in 1983, specified that rolling motions (vibrations in z-axis) were less disruptive movements than twisting (y-axis) and pitching (x-axis). For low frequency vertical vibrations, performance impairments in manual tasks may be reduced by colliminating relevant displays (Mc Leod and Griffin, 1990).

Hall (1985) found that errors in tracking tasks increase significantly as a function of RMS acceleration.

Generally, these low frequency vibrations are responsible for motion sickness, as described by Roure (1982) : e.g. paleness of skin, perspiration, sickness, nausea

For higher frequency vibrations, Mc Leod and Griffin showed in 1988, that disruption of continuous performance increased from 4 Hz, up to 15 % at 5 Hz. A visual mechanism is assumed to account for the increased disruption at higher frequencies. Subjects under about 5 Hz vertical vibrations presented a significant decrement of their tracking task performances, visual acuity and higher reaction time than static condition (Grether et al, 1971). Nevertheless, authors did not observe performance modification in communication task or mental calculation.

Tracking performance on the x-axis is consistently better than on the z-axis. Holland, in 1967, found that the 5 Hz spectrum was the most detrimental on tracking performance.

Nevertheless, Shoenberger (1967) thinks there is very little evidence that vibration induces performance decrements: direct mechanical interference with the motor aspects of the task is the most significant factor contributing to performance decrements. But he showed that vibration produces significant effects in probability monitoring response time at 5 Hz and in warning lights detection at 7 Hz and 11 Hz.

Some papers cover the combination of vibration and other stressors, in particular noise. Some of them show that there is an additive detrimental effect of noise and vibration on tracking task performance (Harris and Sommer, 1973), with a greater impact of vibration on the vertical part of the tracking task than on the horizontal.

Other studies have shown that combined-stress conditions (heat, noise, vibration) was less disturbing to the subjects and their performance better than with vibration alone for tracking and complex psychomotor tasks (Grether et al, 1971 ; Harris and Shoenberger, 1980), and for communication tasks (Grether et al, 1971).

Besides, a modification of quality of speech is noted with vertical medium frequency vibration (Bond and Moore, 1990) with an increase of amplitude modulation and voice tremolos (about 15 % in comparison to the control condition).

Nixon and Sommer (1963) showed that pilot communications were less intelligible when vibrations were horizontal, at 6-8 Hz, and seated pilots were slightly inclined. In this condition, pilots tend to shorten communication duration (Vilkman and Manninen, 1986), voice tremolos appear, and vowels are splitted (Bond and Moore, 1990). Lewis and Griffin (1980) showed reading performance decrements (errors, slowness) at these same frequency ranges.

Reading task is also disturbed by horizontal and vertical medium frequency vibrations. But horizontal vibrations have a more important effect on reading speed than lateral vibration probably because of transmission of vibration by backrest seat (Griffin and Hayward, 1994).

Moreover, for frequencies below 4 Hz, display vibration produces the largest performance decrements (Moseley and Griffin, 1986). Whole-body vibration with a stationary display produces significantly worse performance than simultaneous vibration of both subject and display, but significantly better performance than display vibration alone.

Shoenberger (1967) considers that sinusoidal 5 Hz frequency vibrations have a positive effect on performance because they reduce responses latency to visual stimuli. These vibrations also reduce performance decrement in an auditory vigilance task (Wilkinson and Gray, 1974).

Poulton (1977) explains also the positive effect of 5 Hz vibrations on performance by an increase of activation of resonance frequency of trunk. At this frequency, shoulder muscles vibrations amplitude is 2.7 times higher than at the buttocks (Guignard, 1965).

However, trunk muscles voluntary contraction allows reducing this amplitude. This contraction increases the activation of the central nervous system, with a beneficial effect on vigilance.

Nevertheless, at 7 and 11 Hz, the subject relaxes trunk muscles in order to try to reduce the vibration amplitude at the shoulder. This relaxation leads to a decrease of the activation.

Performance in tracking tasks decreases according to the amplitude of vibration. Tracking performance also decreases according to the direction of vibration : vertical tracking is more impacted by vertical vibration. Horizontal tracking is more impaired by lateral vibration.

On the other hand, with tri-axial vibrations, Shoenberger (1967) notices that x-axis and y-axis vibrations provoke more impairment of vertical and horizontal tracking, than z-axis vibrations.

Vibrations effects on tracking or other motor tasks are explained by their direct mechanical action on the body: they interfere with subjects motion (Grether, 1971).

These results are more significant for high frequency vibrations (above 8-10 Hz). But the importance of the effect depends also on the type of seat (with or without backrest, with or without stationary foot rest) and the axis of vibration (vertical, lateral, horizontal) (Lewis and Griffin, 1980).

In particular, the effects of vibration level on reading accuracy are significant at all the highest frequencies of z-axis vibration (up to 63 Hz). They are also significant for x-axis vibration with a rigid flat seat with backrest, but not for x-axis vibration with a rigid flat seat, without backrest but a stationary foot rest, or for y-axis vibration with either seat.

The effect also depends on the nature of vibration, sinusoidal or random. In example, Moseley and Lewis (1982) showed that random vibration produced significantly less effect on reading performance than sinusoidal vibration of similar frequencies. Measurements of rotational head motion show that it is due to differences in the eye velocity distributions produced by different motions.

As medium frequency vibration, 8-25 Hz vibrations modify speech quality, with an increase of amplitude modulation and voice tremolos, about 30 % in comparison to the control condition (Bond and Moore, 1990).

Floru et al. (1987) studied effects of sinusoidal vibrations on pilot performance. Among sensorial modifications, visual acuity decreases with 15-25 Hz vibrations, for vision at 4 meters. Visual acuity for vision at 0.4 –to 1 meter distance is more reduced by 5 Hz vibrations. An increase of lighting improves visual acuity.

Berthoz studied effects of very high frequency vibrations on subjects, and showed a visual acuity decrease, between 20 and 40 Hz. Between 60 Hz and 80 Hz, he showed performance decrements (increase of reaction time, errors in manual pursuit tasks…). Between 50 Hz and 80 Hz, some reflexes are suppressed, and between 20 Hz and 200 Hz, subjects can feel an illusion of limb movements or length variations, due to the stimulation of musculoskeletal mechano-receptors. A long-term exposure can produce modifications of vibro-tactil perception threshold, and pain detection threshold.

But finally, not many studies deal with long-term vibration exposure, in particular in the aviation field.

Village and Lott (2000) submitted drivers to vibrations with an acceleration higher than 0.63 m/s^2 during 8 hours. Back pains appear, confirming Haex's results on measurements and modelling of the skeleton under low frequency vibrations. Their results show that back muscles are an inefficient protection system against vibrations.

Seidel and Heide (1986) studied effects of long-term vibration exposure applied to the whole body. It results in a high risk for health, in particular for the vertebral column and peripheral nervous system (lumbago, sciatica, and curvature of vertebral column).

Hornick and Lefritz (1966) noted a decrement of performance to visual stimuli during a 4-hour exposure to random 1-2 Hz vibrations. But Grether (1971) attributed this effect to the impairment of visual functions.

8 - RECOMMENDATIONS -

The recommendations derived from this work are classified into 3 main topics :

- measures and instrumentation procedures,
- definition of thresholds,
- recommended research actions.

8.1 - Measures and instrumentation procedures -

As vibrations are filtered by the body, it is necessary to measure vibrations at different locations on the body. Taking into account the position of the main activities of pilots it is recommended that measures should be taken:

- on the head, especially on the forehead. This will allow to capture the vibrations induced on the eyes and then their impact on vision and audition. Furthermore, the location of the sensor on the head should be achieved regarding the anatomical references on the head,
- on the left and right hands as they are mainly involved in the interaction with commands and entering data activities.

However, measurements at these different locations of the body should be complemented by data assessment at different locations of the cockpit:

- displays and keyboards,
- sidestick or rudder,
- seat and armrest.

These data measured both on the pilots and on the cockpit elements should be compared in order to measure the differences between the vibrations (frequency and acceleration) received by the body and these elements. In fact, the larger the differences, the higher the impact on performance.

The instrumentations to be used should be tri-axial accelerometers in order to capture the vibrations in the 3 axes: x, y and z.

Considering the large variations in the level of vibrations and the crew activity and communications induced by the different flight phases (take-off, climb, cruise, descent and landing) these measures should be conducted in these various phases of real flights and/or in high fidelity simulators.

The large variability between individuals should be also taken into account and it is therefore recommended that these measurements should be applied on a sample of pilots presenting various anthropometrics features. The NASA-3000 standards already presented in the chapter 5 should be used to select the pilots on whom the measures will be done.

8.2 - Thresholds definition -

Although various standards are existing on the impact of vibrations on performance (see chapter 4), more of these standards provide task-oriented threshold. The various data provided in this review allow to give some orientations.

The table 6 shows some tentative boundaries on sensitive frequencies for which published data have been found in the analysed references. The last column of the table gives the number of papers pertaining to each task and included into the matrix. It shows that for most tasks the sensitive frequencies are found in the middle frequency ranging from 1 to 20 Hz. For manipulating task, the value is based on 1 relevant study and no upper limit can be provided.

Pilot Tasks	Sensitive Frequency (Hz)	Number of articles
Tracking	**3 > SF > 8**	**19**
Manipulating	**4 > SF > ?**	**1**
Reading	**5.6 > SF > 11.2**	**31**
Communication	**1 > SF > 20**	**4**

SF : Sensitive Frequency

Table 6 : Sensitive vibration frequencies affecting performance indifferent pilot task.

8.3 - Recommended research action -

Considering the scope of this review that excludes works about motion sickness, low frequency vibrations constitute a minor part of this study. This explains that there is no article about the impact of these vibrations on tracking, manipulating or communication tasks, as it can be noticed in the matrix.

On the contrary, medium frequency vibrations constitute the bulk of research, in particular concerning tracking, reading and data processing tasks. Nevertheless, it is worth to note that the effects of vibrations on pilot tasks such as manipulating and communicating should be more investigated as these tasks would be more and more prominent in future aircraft such as the A380 (e.g. manipulating a trackball). Furthermore, vibrations but has not been studied would heavily affect the use of tactile displays.

In the field of aviation, high frequency vibrations seem to be less relevant as they involved tools on machines generating high frequency.

9 - CONCLUSION -

The review presented in this report covers the potential impacts of flight deck motions on pilot performance. Existing standards have been analysed in this review. However, this analysis shows that these standards do not provide task-oriented thresholds which are needed for instance for the certification of aircraft. Therefore an extensive review of literature was needed to try to (1) identify the main impacts of vibration on pilot tasks and (2) identify the frequency ranges or tasks that have not been sufficiently studied in previous works. More than 70 references have been analysed and 25 have been selected for their relevance regarding the scope of this study (i.e. civil aviation aircrew). In order to make this information useable, they have been analysed in a standardized way allowing their inclusion into a matrix crossing different pilot tasks and frequency ranges and directions. This matrix has been included into a Powerpoint presentation to allow an easy access to the information. From this analysis, it has been possible to provide for each category of the pilot task some boundaries indicating the sensitive frequency ranges. As expected, the most sensitive frequencies are within the middle frequency ranges. However, for some tasks, such as manipulating, theses boundaries are based only on a small amount of data. It is then recommended that more studies should be conducted on these kinds of tasks which are more relevant for civil aircrew. In fact, the design of modern aircraft is likely to increase the interactions of pilots with keyboards, trackball and these manipulations might be largely affected by flight deck motions. The principles for measuring flight deck motions are also presented in this review. It is recommended to measure vibrations both on the various elements of the flight deck (display, sidestick,…) but also on the pilot him(her)self. The data interpretation should take into account the differences between the vibrations measured on the pilot and the flight deck. These measurements should be applied taking into account the anthropometric criteria presented in this report as the variability between pilots may affect the effects of vibration on their performance. Furthermore, these measures should be taken for different phases of flights as the induced vibrations and task may vary largely between these phases.

10 - REFERENCES -

1. BERTHOZ (A.).- Effets des vibrations sur l'homme. In : Précis de physiologie du travail. Notions d'ergonomie./ J. Scherrer et coll.- Paris : Masson, 2^{e} édition, pp. 341-375.
2. BOND (Z.S.) ; MOORE (T.J).- Effects of whole-body vibration on acoustic measures of speech.- Aviation, Space, and Environmental Medicine, November, vol.61, 1990, pp. 989-993.
3. BOWMAN (J.S.) ; VON BECKH (H.J.).- Physiologic and performance measurements in simulated airborne combined stress environments.- Aviation, Space and Environmental Medicine, vol. 50, 1979, pp. 604-608.
4. CLARKE (M.J.).- A study of the available evidence on duration effects on comfort and task proficiency under vibration.- Journal of Sound and Vibration, vol. 65, 1979, pp. 107-123.
5. COLLINS (A.M.).- Decrements in tracking and visual performance during vibration.- Human Factors, vol. 15, n° 4, 1973, pp. 379-393.
6. CORBRIDGE (C.C.) ; GRIFFIN (M.J.)- Vibration and comfort: vertical and lateral motion in the range 0.5 to 5.0 Hz. Ergonomics, vol. 29, 1986, pp. 249-272.
7. FLORU (R.) ; CNOCKAERT (J.C.) ; DAMONGEOT (A.).- Vigilance et nuisances physiques.- Les Cahiers de notes documentaires, n°128, 3^{e} trimestre, 1987, pp. 331-335.
8. GAUTHIER et al.- Les laboratoires français effectuant des études de vibrations en relation avec l'être humain : le Laboratoire de psychophysiologie de l'Université de Provence. In : Les vibrations industrielles.- Doc INRS. Mars 1983, pp. 134-135.
9. GRAYBIEL (A.) ; KENNEDY (R.S.) ; KNOBLOCK (F.E.) ; GUEDRY (F.E.) ; HERTZ (W.) ; MCCLEOD (M.) ; COLEHOUR (J.K.) ; MILLER (E.F.) ; FREGLY (A.).- Effects of exposure to a rotating environment (10 rpm) on four hour aviators for a period of twelve days.- Aerospace Medicine, vol. 36, 1965, pp. 733-754.
10. GRETHER (V.).- Vibration and human performance.- Human Factors, vol. 13, 1971, pp. 203-216.
11. GRETHER (W.F.) ; HARRIS (C.S) ; MOHR (G.C) ; NIXON (C.W) ; OHLBAUM (M.) ; SOMMER (H.C.) ; THALER (V.H.) ; VEGHTE (J.H.).- Effects of combined heat, noise and vibration stress on human performance and physiological functions.- Aerospace Medicine, vol. 42, n° 10, 1971, pp. 1092-1097.
12. GRETHER (W.F.) ; HARRIS (C.S.) ; MOHR (G.C.) ; NIXON (C.W.) ; OHLBAUM (M.) ; SOMMER (H.C.) ; THALER (V.H.) ; VEGTE (J.H.).- Further study on combined heat, noise and vibration stress.- Aerospace Medicine, vol. 42, 1971, pp. 1092-1097.
13. GRIFFIN (M.J.).- Levels of whole-body vibration affecting human body.- Aviation, Space and Environmental Medicine, vol 46, n°8, 1975, pp 1033-1040.
14. GRIFFIN (M.J.) ; LEWIS (C.H.).- A review of the effects of vibration on visual acuity and continuous manual control, Part I: visual acuity.- Journal of Sound and Vibration, vol 56, 1978a, pp. 383-413.
15. GRIFFIN (M.J.) ; LEWIS (C.H.).- A review of the effects of vibration on visual acuity and continuous manual control, Part II: continuous manual control. Journal of Sound and Vibration, 56, 1978b, 415-457.
16. GRIFFIN (M.J.) ; HAYWARD (R.A.).- Effects of horizontal whole-body vibration on reading.- Applied Ergonomics, vol. 25, n° 3, 1994, pp. 165-169.
17. GRIFFIN (M.J.).- Eye motion during whole-body vibration.- Human Factors vol. 18, n° 6, 1976, pp. 601-606.

18. GRIFFIN (M.J.).- Handbook of human vibration. London: Academic Press, 1990.
19. GUIGNARD (J.C.), KING (P.F.).- Aeromedical aspects of vibration and noise.- Neuilly-sur-Seine : Advisory Group for Aerospace Research and Development, AGARD-AG-151, 1972.
20. GUIGNARD (J.C.). Vibration. In : A textbook of aviation physiology. / S.A. Gillies ed.- Oxford : Pergamon Press, 1965, pp. 813-894.
21. HAEX (B.), DRUYTS (H.), HOTENS (I.), de CRAECKER (W.), HYUSMANS (T.), COOREVITS (P.), VANDERSTRAETEN (G.), Van AUDEKERCKE (R.), HAMON (H.).- A composite approach towards whole-body vibration comfort analysis.- In : Proceedings of the XVth Triennal Congress of the International Ergonomics Association and The 7th Joint Conference of Ergonomics Society of Korea / Japan Ergonomics Society "Ergonomics in the Digital Age" August 24-29, 2003 Seoul, Korea, 4 p.
22. HALL (L.C.).- The effect of low frequency whole body vibration and impacts on human tracking performance.- Journal of Low Frequency Noise and Vibration, vol. 4, 1985, pp. 154-162.
23. HANCOCK (P.A.).- The effects of skill on performance under an environmental stressor. Aviation, Space and Environmental Medicine, vol. 57, 1986, pp. 59-64.
24. HARRIS (C.S.), SOMMER (H.C.).- Combined effects of noise and vibration on mental performance.
25. HARRIS.(C.S.), SHOENBERGER (R.W.).- Combined effects of noise and vibration on psychomotor performance.- Aerospace Medical Research Laboratories, May 1970.
26. HARRIS (C.S.) ; SOMMER (H.C.).- Interactive effects of intense noise and low-level vibration on tracking performance and response time. Aerospace Medicine, vol. 44, 1973, pp. 1013-1016.
27. HARRIS.(C.S.), SHOENBERGER (R.W.).- Combined effects of broadband noise and complex waveform vibration on cognitive performance. Aviation, Space and Environmental Medicine, vol. 51, 1980, pp. 1-5.
28. HOLLAND (C.L.). – Performance and physiological effects of long term vibration.- Aerospace Medical Research Laboratories, October 1966.
29. HOLLAND (C.L.).- Performance effects of long-term random vertical vibration.- Human Factors, vol. 9, 1967, pp. 93-104.
30. HORNICK (R.J.) ; LEFRITZ (N.M.).- A study and review of human response to prolonged random-vibration.- Human Factors, vol. 8, 1966, pp. 481-492.
31. HUDDLESTON (J.H.F.).- Tracking performance on a visual display apparently vibrating at one to ten hertz.- Journal of Applied Psychology, vol. 54, n° 5, 1970, pp. 401-408.
32. KEINAN (G.) ; FREIDLAND (N.) ; YITZHAKY (J.) ; MORAN (A.).- Biographical, physiological and personality variables as predictors of performance under sickness-inducing motion.- Journal of Applied Psychology, vol. 66, 1981, pp. 233-241.
33. LANDSTRÖM (U.) ; LUNDSTRÖM (R.).- Changes in wakefulness during exposure to whole body vibration. Electroencephal. Clin. Neurophysiology, vol. 61, 1985, pp. 411-415.
34. LANDSTRÖM (U.) ; LÖFSTEDT (M.).- Noise, vibration and changes in wakefulness during helicopter flight. Aviation, Space and Environmental Medicine, vol. 58, 1987, pp. 109-118.
35. LANDSTRÖM (U.) ; KJELLBERG (A.) ; LUNDSTRÖM (R.).- Combined effects of exposure to noise and whole-body vibration in dumpers, helicopters and railway engines.- Journal of Low Frequency Noise and Vibration, vol. 12, 1993, pp. 75-85.

36. LEE (R.A.) ; KING (A.I;).- Visual vibration response.- Journal of Applied Physiology, 1971, February, 30 (2), 281-286.
37. LEWIS (C.H.) ; GRIFFIN (M.J.).- The effects of vibration on manual control performance.- Ergonomics, vol. 19, 1976, pp. 203-216.
38. LEWIS (C.H.) ; GRIFFIN (M.J.).- The interaction of control gain and vibration with continuous manual control performance.- Journal of Sound and Vibration, vol. 55, 1977, pp. 553-562.
39. LEWIS (C.H.) ; GRIFFIN (M.J.).- Mechanisms of the effects of vibration frequency, level, and duration on continuous manual control performance. Ergonomics, vol. 22, 1979a, pp. 855-889.
40. LEWIS (C.H.) ; GRIFFIN (M.J.).- The effect of the character size on the legibility of numeric displays during vertical whole-body vibration.- Journal of Sound and Vibration, vol. 76, 1979b, pp. 562-565.
41. LEWIS (C.H.) ; GRIFFIN (M.J.).- Predicting the effects of vertical vibration frequency, combinations of frequencies and viewing distance on the reading of numeric displays. Journal of Sound and Vibration, vol. 70, 1980a, pp. 355-377.
42. LEWIS (C.H.) ; GRIFFIN (M.J.).- Predicting the effects of vibration frequency and axis and seating conditions on the reading of numeric displays. Ergonomics, vol. 23, 1980b, pp. 485-501.
43. LOVESEY (E.J.).- The occurrence and effects upon performance of low frequency vibration.- In : Infrasound and low frequency vibration./ W. Tempest ed.- London: Academic Press, 1976, pp. 235-266.
44. MALVACHE (M.).: Les laboratoires français effectuant des études de vibrations en relation avec l’être humain: le Laboratoire d’automatique indus. et hum. de l’Univ. de Valenciennes. In: Les vibrations industrielles. Doc INRS. Mars 1983, pp 135-136.
45. Mc LEOD (R.W.) ; GRIFFIN (M.J.).- Performance of a complex manual control task during exposure to whole-body vertical vibration between 0.5 and 5.0 Hz. Ergonomics, vol. 31, 1988, 1193-1203.
46. Mc LEOD (R.W.) ; GRIFFIN (M.J.).- A study of the effect of the duration of exposure to whole-body vibration on the performance of a complex task. In : from: Handbook of human vibration./ M.J. Griffin ed.- London: Academic Press, 1990.
47. McLEOD (R.W.) ; GRIFFIN (M.J.).- Effects of whole-body vibration waveform and display collimation on the performance of a complex manual control task.- Aviation, Space and Environmental Medicine, vol. 61, 1988, pp. 211-219.
48. MOSELEY (M.J.) ; LEWIS (C.H.) ; GRIFFIN (M.J.).- Sinusoidal and random whole-body vibration: comparative effects on visual performance.- Aviation, Space and Environmental Medicine, vol. 53, 1982, pp. 1000-1005.
49. MOSELEY (M.J.) ; GRIFFIN (M.J.).- Effects of display vibration and whole-body vibration on visual performance.- Ergonomics, vol. 29, 1986, pp. 977-983.
50. MOSELEY (M.J.).- The effects of vibration on visual performance and display legibility. Ph.D. Thesis. University of Southampton, 1986.
51. NASA-STD-3000.- Revision A., vol. 1, Man-Systems Integration Standards (October, 1989).
52. NIXON (C.W.) ; SOMMER (H.C.).- Influence of selected vibration upon speech (range of 2 cps - 20 cps and random).- Dayton, OH : Aerospace Medical Research Laboratories, 1963 ; AAMRL - TDR - 63-49.
53. POLLACK (J.G.) ; WILSON (K.P.) ; WALLICK (M.T.).- Effects of low frequency oscillatory motion on human performance.- Journal of Low Frequency Noise and Vibration, vol. 7, 1988, pp. 131-141.
54. POULTON (E.C.).- Arousing stressed increased vigilance.- In : Vigilance. / R. Mackie ed.- New York, Plenum Press, 1977, pp. 423-460.

55. ROTONDO (G.).- Workload and operational fatigue in helicopter pilots.- Aviation, Space and Environmental Medicine, vol. 49, 1978, pp. 430-436.
56. ROURE (L.).- Effets des vibrations sur l'Homme. Revue Acoustique, vol. 60, 1982, pp. 55-58.
57. SANDOVER (J.).- The fatigue approach to vibration and health: is it a practical and viable way of predicting the effects on people?.- Journal of Sound and Vibration, vol. 215, 1998, 699-721.
58. SEIDEL (H.) ; HEIDE (R.) : Long-term effects of whole-body vibrations : a critical survey of the literature.- International archives of occupational and environmental health, vol. 58, 1986, pp. 10-26.
59. SHOENBERGER (R.W.).- Investigation of the effects of vibration on dial reading performance with a NASA prototype Apollo Helmet.- Aerospace Medical Research Laboratories, February 1968.
60. SHOENBERGER (R.W.).- Effects of vibration on complex psychomotor performance. Aerospace Medicine, vol. 38, 1967, pp. 1264-1269.
61. SHOENBERGER (R.W.).- An investigation of human information processing during whole-body vibration. Aerospace Medicine, vol. 45, 1974, pp. 143-153.
62. SHOENBERGER (R.W.).- Subjective response to very low-frequency vibration. Aviation, Space and Environmental Medicine, vol. 46, 1975, pp. 785-790.
63. SHOENBERGER (R.W.).- Effects of vibration on complex psychomotor performance. Aerospace Medicine, vol. 12, 1967, pp. 1265-1269.
64. STAVE (A.M.).- The effects of cockpit environment on long-term pilot performance. Human Factors, vol. 19, 1977, pp. 503-514.
65. STAVE (A.M.).- The influence of low frequency vibration on pilot performance (as measured in a fixed base simulator). Ergonomics, vol. 22, 1979, pp. 823-835.
66. VILLAGE (J.) , LOTT (M.). – Work-related and threshold limit values for back disorders due to exposure to whole body vibration. – In : Proceedings of the IEA 2000/HFES 2000 Congress "Ergonomics for the New Millenium" July 29 - August 4, 2000 San Diego, California USA, vol. 5, p. 620.
67. VILKMAN (E.) ; MANNINEN (O.).- Changes in prosodic features of speech due to environmental factors. Speech communication, 5, pp. 331-345.
68. VOGT (L.H.).- Mechanical impedance of the sitting human being under sustained acceleration.- Aerospace Medicine, vol. 39, 1968, pp. 665-679.
69. VOGT (L.H.).- Mechanical impedance of suspine humans being under sustained acceleration. Aerospace Medicine, vol. 44, 1973, pp. 123-128.
70. VOGT (L.H.).- Head movements induced by vertical vibration. AGARD, Lissabon, 1979, B11, 1-13.
71. VOGT (L.H.) ; MERTENS (H.) ; KRAUSE (H.E.).- Model of suspine human body and its reactions to external forces. Aviation, Space and Environmental Medicine, vol. 41, 1978, pp. 270-278.
72. WILKINSON (R.T.) ; GRAY (R.).- Effects of duration of vertical vibrations beyond the proposed ISO fatigue - decreased proficiency time, on the performance of various task. In : Vibration and combined stress in advanced systems./ Von Gierke ed.- AGARD Conference proceedings, 1974, n°145.

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