MADRID
inter.noise 2019
June 16 - 19
NOISE CONTROL FOR A BETTER ENVIRONMENT

Relationship between hand-arm vibrations and subjective evaluation by a magnitude estimation method

Laroche, Luc[1]
INSA-Lyon, Laboratoire Vibration Acoustique, F-69621, Villeurbanne, France
Groupe PSA, NVH Department, Centre technique Belchamp, 25420 Voujeaucourt

Parizet, Etienne
INSA-Lyon, Laboratoire Vibration Acoustique, F-69621, Villeurbanne, France
Bornet, Fréderic
Piranda, Damien
Groupe PSA, NVH Department, Centre technique Belchamp, 25420 Voujeaucourt

ABSTRACT

Steering wheel vibration is one of the factors determining the comfort in a driving car experience. This current study aims at characterizing discomfort induced by steering-wheel vibration in terms of frequency, level and direction. Measurements were realized with seven cars of different sizes and motorizations. That study showed that the maximum level of vibration is related to the first steering column resonance, occurring between 30 and 50 Hz; vibration levels were determined between 0.3 and 5 m.s-2. Then a magnitude estimation experience has been conducted to link the perceived intensity to the steering wheel physical vibration. Two directions has been investigated: along the arm and in the normal direction of the palm. 34 subjects participated to the experiment. The relation fits Stevens' law; the exponent varied from 1.1 and 1.6, depending on the frequency and the direction of the excitation.

Keywords: Vibration, Hand-Arm, Stevens' Law, steering wheel, car, magnitude estimation

1. INTRODUCTION

Vibration inside a car cabin can arise from different interfaces and on a wide range of levels of excitation. This study will more specifically focus on translational vibrations, induced by steering wheel through the hand-arm system. A measurement campaign, realized in seven cars of different sizes and motorizations, allowed to show that the maximum level of vibration was related to the first steering column resonance. This modal response occur on vertical and horizontal axis, in two different frequency ranges (35-45 Hz in the case of vertical direction and 40-50 in the horizontal one). The energy of these resonances is dominant within the whole spectrum, so that signals are not so different from a mono-frequency one.

In terms of vibrations perceived by the Hand-arm system, steering wheel produces vibrations along the arm and in the normal direction of the palm. The current International Standard for evaluation of hand-transmitted vibrations, ISO 5349 [1],

[1] luc.laroche@insa-lyon.fr

defined a single frequency weighting, **Wh**, to describe exposure to these axis. However, it was reviewed many times [2], [3], [4], [5], in order to describe differences of sensation introduced by: directions of excitation, gripping posture or ranges of levels of vibration. Moreover, all these studies agree on the fact that using **Wh** overestimates the perceived vibration.
In this study, we focus on the influence of translational vibrations only. Morioka and Griffin [6] gave an overview of the perception of vibrations in the three directions. The experiment was conducted for a wide range of frequencies (8-400 Hz) and acceleration amplitudes (from the detection threshold to 50 m/s²). Authors concluded that Stevens' exponent is systematically less than 1(from 0.14 at 400 Hz to 0.75 at 8 Hz. Differences between directions were noted, most notably for frequencies up to 50 Hz. These results raised questions about the relevance of **Wh** and confirmed the frequency dependence of the sensation. However, this experiment was conducted on a wide range of acceleration amplitudes and on a limited panel of 12 males and no woman. The fact that this panel was not representative of a drivers population needs to be noticed.

The current study aimed to increase the reliability of previously published results, examining the effects of: magnitude from 0.3 to 2.5 m/s², frequency 30-50 Hz and direction of vibration (i.e. along the arm and perpendicular to the palm). The rate of growth in sensation with an increasing magnitude is determined using Stevens' power law [7], which describes the relationship between sensation ψ and level of excitation φ:

$$\Psi = k\,\varphi^{n} \tag{1}$$

Where **k** is an arbitrary constant and exponent **n** represents the growth of the sensation and are calculated for each frequency and direction of vibration.

2. EXPERIMENT 1

2.1 Participants

Thirty-four subjects were recruited for this experiment. They were 12 women and 22 men, aged between 19 and 54 (average 23 years old). All subjects were right-handed and with no history of occupational exposure to hand-transmitted vibration.

2.2 Apparatus

The experiment used an electrodynamic shaker associated with a cooling system, as shown in *Fig. 1*. An accelerometer is fixed on the handle in order to control the amplitude of vibration. The whole experiment was managed by Matlab®, signals being synthesized at a sampling frequency fs=1024 Hz, at a 24 bits resolution.

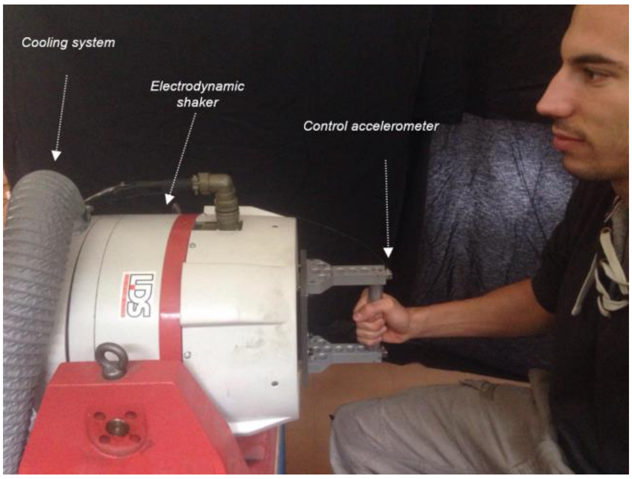

Fig. 1- Experimentation set-up

In order to evaluate perception on the two directions of excitation, the experiment is conducted in two sub-experiments; vibrations along the arm $\mathbf{e_1}$, position **P1**, and perpendicular to the palm $\mathbf{e_2}$, position **P2**, as shown *Fig. 2.*

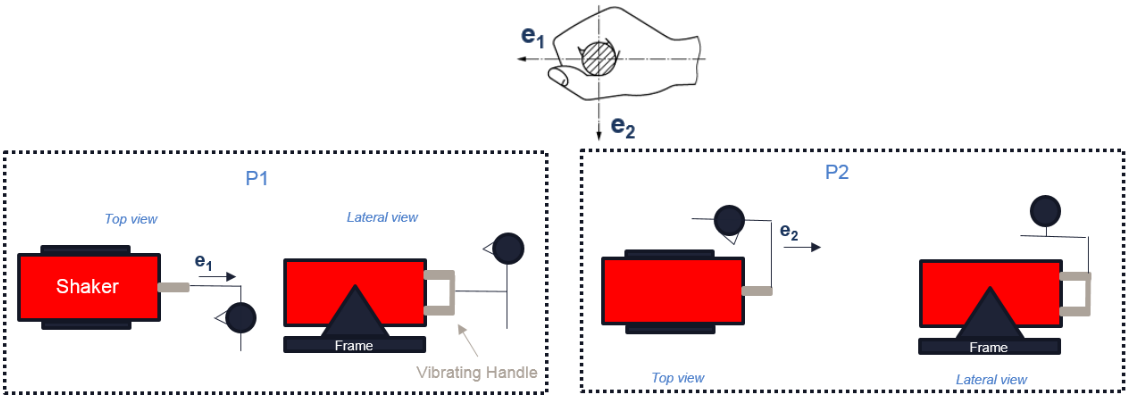

Fig. 2- Direction of excitation and position of subjects during the experiment

2.3 Calibration

As shown in previous studies ([8], [9], [10]), the effect of the gripping force on the power absorbed by the hand-arm system is significant, which can modify the perception. Thus, the amplitude of gripping should be controlled during the experiment. A load around 10N has been selected and control is achieved by a training session with a calibrated handle before the experiment.

2.4 Stimuli

Signals used during experiments were mono-frequency cosine, with a duration of 3 seconds. Amplitude and frequency of each signal is presented in *Table. 1.* A total of 5 frequencies * 8 levels = 40 stimuli were used for each of the two experiments.

Table. 1- Levels and frequency used for stimuli generation: N1 for P1 position and N2 for P2 position (dB_{vib} : reference $a_0 = 10^{-6}$ m/s²)

Frequency (Hz)	*N1 Levels (dB_{vib})*	*N2 Levels (dB_{vib})*
30	110	114
35	112.5	117
40	115	120
45	17.5	123
50	120	126
	122.5	129
	125	132
	127.5	135

2.5 Magnitude estimation method

Participants are asked to evaluate the perceived magnitude according to a magnitude estimation method without reference, as described in [11]. They should use a semi-limited scale, between 0 and +∞, where 0 represents the lack of sensation and without limit for the growth of perceived magnitude. The minimum level of stimuli was at least four times higher than the absolute threshold of hand-transmitted vibration in the 30-50 Hz frequency band, according to [12], so that no 0 answer was expected.

Each set of stimuli is presented in a pseudo-random sequence, in such a way that the magnitude difference between two subsequent stimuli was less than half the maximum magnitude difference presented in the set.

2.5 Procedure

The experiment is split in four parts: calibration, training and two subs-experiments, in position P1 and P2. Order between P1-P2 and P2-P1 is done alternatively. Training is composed of 10 stimuli, in order to give an overview of levels and frequencies played in the test. Training position is set according to the order of presentation.

For each sub-experiment, the set of 40 stimuli is played three times, in a different pseudo-random sequence. For each stimulus, subjects are asked to evaluate their magnitude perception.

This procedure leads to 120 stimuli for each sub-experiment and approximatively thirty minutes of experiment.

3. Results

3.1 Scale standardization

Collected estimations need to be standardized because the individual scales are quite different. In order to build a psychophysical scale, we chose a standard deviation method for standardization. This procedure keeps unchanged the ratios between estimations so is suitable for Stevens' power law. According to [11], the following standardization is used:

$$SV_{i,j} = \underbrace{\sum_{k=1}^{l} \frac{\log(X_{ijk})}{l}}_{\text{Mean of repeated measures}} - \underbrace{\sum_{j=1}^{m}\sum_{k=1}^{l} \frac{\log(X_{ijk})}{m.l}}_{\text{Mean of all estimation for a subject}} + \underbrace{\sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{k=1}^{l} \frac{\log(X_{ijk})}{n.m.l}}_{\text{Mean of all estimations}} \qquad (2)$$

$SV_{i,j}$: standardized value of subject *i* and stimulus *j*
$X_{i,j,k}$: raw data for subject *i*, stimulus *j* and sample *k* (k=1..3)
l: number of repetition
m: number of stimuli
n: number of subject

The two sub-experiments results are standardized together in order to allow comparison between them.

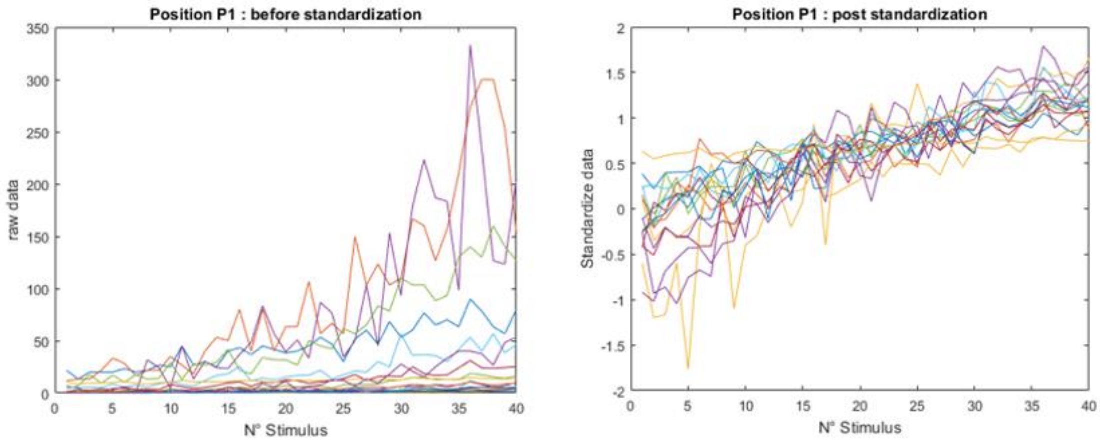

Fig. 3- Comparison between raw estimations and standardized data.
Each curve represents an individual answer.

3.3 Growth of sensation

From standardization, estimations are already in a logarithmic scale so Stevens' power law can be written as :

$$\mathbf{SV = \log_{10}(\Psi) = a.\, N_{dB} + b} \qquad (3)$$

With n = 20.a, $k = 10^{6.n+b}$ and N_{dB} the level of vibration in dB.

For position P1, this equation allows a good representation of experimental data. The determination coefficient varied between X and Y for the five frequencies used in the experiment. The slopes (parameter ***a*** in (3)) were slightly different among frequencies. A bootstrap analysis [13] shown that there were no major differences neither between 30 and 35 Hz nor between 40, 45 and 50Hz but there where slightly differences between these two groups. This leads to separate perceived magnitude in two Stevens' power law. *Fig. 4* shows Stevens' power law calculated on the average of the tested amplitudes, for frequency between 30-35 Hz and 40-50 Hz. Slope is higher in the low frequency range. For instance, when doubling the amplitude of acceleration, growth of sensation will be about 3 times at 30 Hz but 2.5 times at 50 Hz.

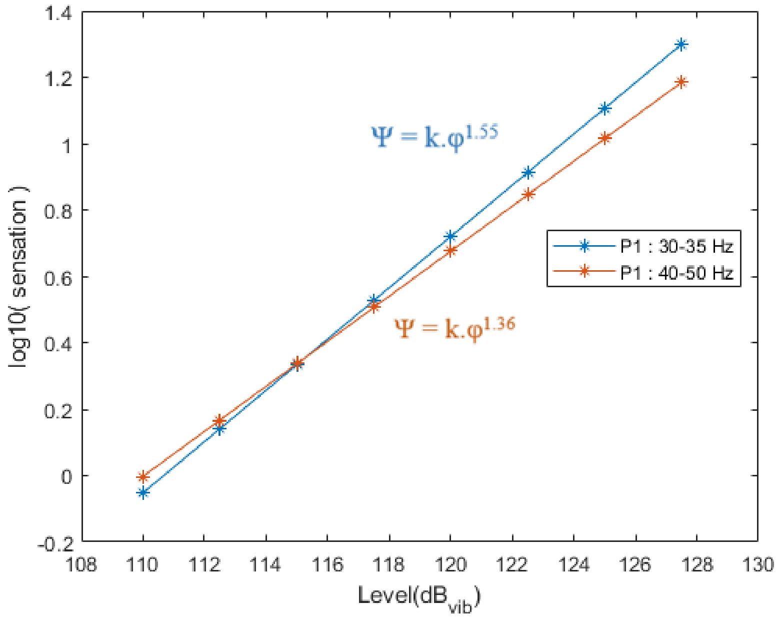

Fig. 4- Stevens power law

According to these results, equivalent comfort contours for **$\log_{10}(\Psi)$** = 0.7 and 1.4 were calculated, inverted and normalized to 50 Hz according to frequency weighting **Wh** of ISO 5349. Note that **$\log_{10}(\Psi)$** =1.4 is equivalent to the magnitude of the sensation produced by a stimulus of 5 m/s² at 50 Hz. The same stimulus corresponds to **$\log_{10}(\Psi_{Morioka})$** =100 in Morioka study [6]. So we should compare our results with **$\log_{10}(\Psi_{Morioka})$** = 50 and 100, normalized to 50 Hz too. *Fig. 5* shows together **Wh**, weighting proposed in [6] and the results of this study. The tendencies are quite similar, but **Wh** overestimates the perceived magnitude, as previously shown ([3], [4]). The difference is more important in the low frequency range, so that it is more relevant to use a specific weighting, according to levels and frequency range.

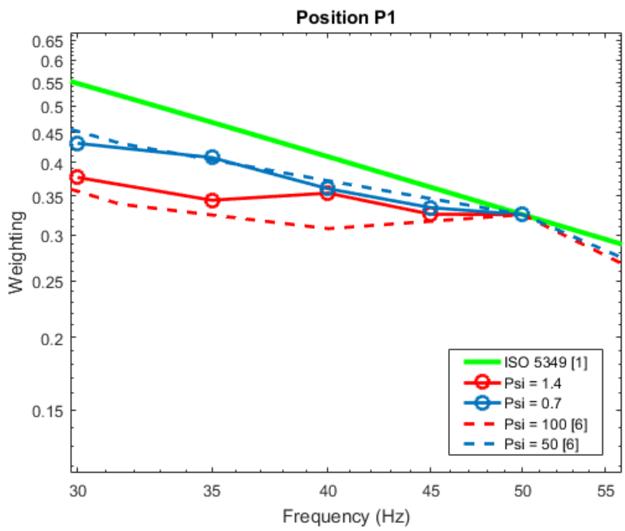

Fig. 5- Comparison between Wh weighting, results from [6] and the current study

4. CONCLUSION

When gripping a handle, frequency of vibrations seems to be one of the many factors influencing our perception. Even if the spectrum of frequency is tight, significant differences could be found in the evolution of the perception, with median Stevens' exponent about 1.55 at 30-35 Hz and 1.36 at 40-50 Hz. These results also show the limit of the use of Wh weighting, causing the overestimation of the subjective intensity.

Growth of sensation in position P2 is being analysed and should allow to conclude on the effect of the direction of excitation, along the arm or perpendicular to the palm. It will be possible to conclude on the relevance of a unique weighting for all directions of excitation, as advocated by ISO 5349 [1].

5. REFERENCES

1. International Organisation for Standardization, ISO 5349-1, 2001. Mechanical Vibration – Measurment and Assessment of Human Exposure to Hand-Transmitted Vibration – Part 1: general guidelines.

2. Reynolds, R.R., Standlee K.G., Angevine, *"Hand-arm vibration, Part III: Subjective response characteristics of individuals to Hand-induced Vibration"*, Jornal of Sound and Vibration 51, 267-282, 1977.

3. Giacomin, J., Shayaa, M.S., Dormegnie, E., Richard, L., *"Frequency weightings for the evaluation of steering wheel rotational vibration",* Industrial ergonomics 33, 527-541, 2004.

4. Morioka, M., *"Magnitude dependence of equivalent comfort contours for vertical steering wheel vibration",* 39th Meeting of the UK Group on Human Response to Vibration, Ludlow, UK, 2004.

5. Amman, S., Meier, R., Trost, K. and Gu, F., "*Equal annoyance contours for steering wheel Hand-Arm Vibration*", SAE paper 2005-01-2473.

6. Morioka, M., Griffin, M.J., *"Magnitude-dependence of equivalent comfort contours for fore-and-aft, lateral, and vertical Hand-Transmitted vibration",* Journal of Sound and Vibration 295, 633-648, 2006.

7. Stevens, S.S, *"On the Psychophysical law"*, Psychological Review 64, 153-181, 1957.

8. Aldien, Y., Marcotte, P., Rakheja, S. and Boileau P.E, *"Mechanical Impedance and absorbed power of Hand-Arm under xh-axis and role of hand forces and Posture",* Industrial Health 43, 495-508, 2005.

9. Ren G. Dong, Daniel E. Welcome and John Z. Wu, *"Modeling of biodynamic responses distributed at the fingers and the palm of the human Hand-Arm system",* Journal of Biodynamics 40, 2335-2340, 2007.

10. Ren G. Dong, Daniel E. Welcome and John Z. Wu, *"Estimation of biodynamic forces distributed on the fingers and the palm exposed to vibration",* Industrial Health 43, 485-494, 2007.

11. Howard R., Moskowitz, *"Magnitude estimation: notes on what, how, when, and why to use it",* MPI Sensorty Testing, 1977.

12. Morioka, M., Griffin, M.J, *"Perception Thresholds of vertical vibration at the hand, seat and foot"*, ForumAcusticum, 2005.

13. Efron, B., Tibshirani, T.J., *"An introduction to the Bootstrap",* 1993.