HUMAN PERCEPTION OF SINUSOIDAL ROTATIONAL STEERING WHEEL VIBRATION.

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Abstract

This study investigated the human perception of rotational automobile steering wheel vibration. Three equal sensation tests were determined using sinusoidal test signals with reference amplitudes of 0.2 ms^{-2}, 0.4 ms^{-2} and 0.5 ms^{-2} respectively. An annoyance threshold test was performed to find the maximum vibration amplitude that subjects were willing to be exposed to for a duration of approximately 10 seconds. A total of 70 human subjects participated in this experiment and 30 subjects were chosen randomly for each test. Tests were performed on a laboratory steering wheel vibration rig using sinusoidal signals in the range from 5Hz to 315 Hz, using center frequencies on the 1/3 octave scale. The equal sensation test results showed decreased sensitivity with increasing frequency. Age, gender, height, weight, driving position and driving experience were found to have no influence on perception for the sample size used in this study. Large data variance was found in most tests, particularly above 100Hz. Regression lines were fitted (R^2=0.97 on average) to the experimental values of each curve. A steering wheel frequency weighting curve, W_s , was constructed using the normalized value of the equal sensation curves. Finally, W_s was compared to the hand vibration filter W_h taken from BS 6842.

1. Introduction

In the automotive industry significant effort has been made in recent years to define comfort indices, or quality indices, for vehicle subsystems. The sensations produced by the vibration stimuli which reach the vehicle driver can provide important information regarding the dynamic state of the vehicle, but can also provide annoyance and discomfort. Figure 1a illustrates the three main interfaces by which a vehicle transmits tactile information to the driver; namely the foot interface (floorpan and pedals), the body interface (seat cushion and backrest) and the hand-arm interface (steering wheel and gearshift).

Of the various vehicle subsystems, the steering [13,17] is very important due to its central role in controlling the vehicle and due to the importance of the hand-arm system as a source of information to the driver. Vibration can be transmitted in the x, y and z direction of a steering wheel (see Figure 1 b), depending on the irregularities of different types of roads through the interaction of different tyres [20, 21]. The energy transmitted to the steering wheel covers a wide range of frequencies, often up to 300 Hz [21]. In certain cases, the steering column and wheel can exhibit large amplitudes due to resonances above 20 Hz [20] . Although the vibrational response of the steering may not present a hazard, the hand-

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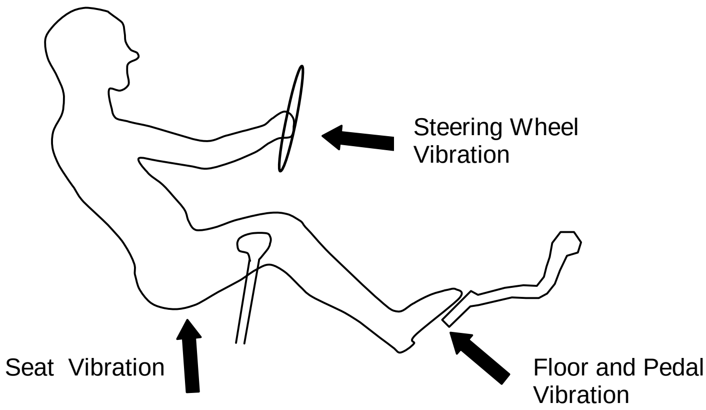
transmitted vibration can cause discomfort, annoyance and fatigue [11]. For what regards perceived comfort, research has shown sinusoidal hand vibration will produce similar levels of discomfort to whole body vibration when the vibration level is 5 to 7 times larger. Given the vibration levels typically measured in road vehicles, this indicates that the hand is likely to be a potential source of discomfort [19].



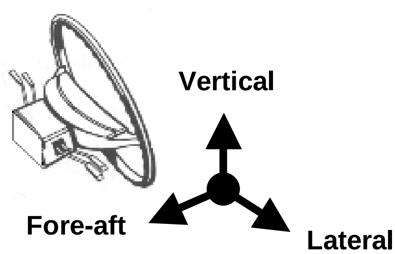


Figure 1a) Main sources of vibration disturbances in a vehicle. **1b)** Axis of vibration on a steering wheel

When the hand is in contact with a vibrating surface, perception occurs largely due to the action of the skin mechanoreceptors. Psychophysical studies have shown that there are at least two mechanoreceptors responsible for the perception of vibration stimuli of the skin; Pacinian corpuscles and Meissner's corpuscles [27] . Studies have shown that the Pacinian system responds to a wide range of frequencies; 20 – 2000 Hz [7], but the peak sensitivity of the Pacinian corpuscles is believed to occur in the region from 60 Hz to 400 Hz [27]. On the other hand, the non-Pacinian system, believed to be dominated by Meissner corpuscles, is thought to respond mainly at frequencies below 45 Hz [28] . In the range of 40 Hz to 80 Hz, either the Pacinian or the Meissner's corpuscles may be responsible for perception depending on the contact area, pressure, and other test conditions. [9].

Several studies have been performed to investigate the interaction between vibrating surfaces and the hand-arm system [9]. Reynolds et al, [22 - 25] investigated hand-arm response to vibrating handles by analyzing the mechanical and subjective responses of 8 subjects. The method of constant stimuli was used where subjects were required to adjust the vibration stimuli until it produced the same sensation as the reference vibration signal. They found that vibration at frequencies above 100 Hz was isolated primarily to the hands and fingers. For annoyance tests, they found that vibration in the y-axis (i.e along the tubular handle according to basicentric [2] coordinate system) caused the least discomfort while vertical (z-axis) caused the greatest discomfort. For equal sensation contours, 100 Hz was used as the reference frequency and vibration levels were 1.0, 10.0 and 50.1 ms^{-2} rms.

Miwa [15] performed equal sensation tests and annoyance threshold tests for 10 subjects holding their palm flat against a vibrating plate for vertical and horizontal vibration. The measurements of threshold and equal sensation were performed using the method of paired comparisons. He found that the equal sensation curves of the hand above 10Hz showed good agreement with those of the whole body; the acceleration threshold reached a maximum sensitivity at 100 Hz. He also concluded that the sensation for both horizontal and vertical vibration was equal at the same vibration acceleration level and frequency.

Burstrom and Lundstrom [3] have performed several studies which investigated the influence of vibration direction, grip force, vibration level, and hand-arm posture on the energy absorption of the hand-arm system. They concluded that energy absorption was dependent mainly on the frequency and direction of vibration. Absorption increased with both higher energy levels and firmer handgrips. They also stated that varying hand-arm postures produced only small changes in the absorption of the translational energy, while the size and mass of the subject's hand and arm greatly affects energy absorption.

A recent study by Giacomin and Onesti [10] produced equal sensation curves in the frequency range from 8 Hz to 125 Hz using reference amplitudes of 1.86 and 5.58 ms^{-2}. They concluded that a linear iso-comfort weighting might be acceptable at 5-10% accuracy for evaluating typical steering wheel vibration signals over the frequency range considered, and that grip tightness would not greatly effect the evaluation. Mechan and Versmold [14] performed an investigation using 30 subjects which produced equal sensation curves for the frequency range 4 Hz to 32 Hz and they found a linear behaviour within the frequency range considered.

Studies such as those by Miwa have lead to the development of a frequency weighting filter for the hand, W_h , as defined in BS 6842 [2]. British Standard 6842 provides guidance on measuring and evaluating hand-transmitted vibration exposure in three orthogonal axes over the frequency range 8Hz to 1000Hz. The objective is to evaluate the potential for tissue damage to the hand due to the presence of vibration. The weighting function W_h is band-limited with low pass and high pass filters at 6.3 Hz and 1250 Hz respectively. The shape of the function appears to be based on Miwa's equal sensation curves [16] ; i.e constant acceleration below 16 Hz and constant velocity above 16 Hz.

The study described in this paper represents an extension of previous research regarding the perception of steering wheel rotational vibration performed at The University of Sheffield. The main objective of this study was to investigate the human perception and to define a frequency weighting curve for the evaluation of steering wheel vibrational comfort. Equal sensation and annoyance tests were performed in the range from 5 Hz to 315 Hz using sinusoidal rotational vibration signals . A frequency weighting filter, W_s, for the steering wheel was defined and compared to the existing hand filter, W_h .

2. Experimental Method

2.1 Test Apparatus

The tests were performed using the rig shown in Figure 2 which consisted of a rigid steering wheel connected to a shaft supported by 3 radial bearings. The shaft incorporates a lever arm which is connected to an electrodynamic shaker unit by means of a stinger rod. All mechanical components (i.e steering wheel, shaft, bench) were modeled using the finite element method and were found rigid to frequencies in excess of 300 Hz. The seat, guide-rail and the bench geometric dimensions (see Table 1) were chosen based on average data from European B-segment automobiles. Seat horizontal travel and back-rest inclination were fully adjustable.

Figure 2. Steering wheel rotational vibration test rig.

Geometric Parameter	Value
Steering column angle with respect to floor	23°
Steering wheel hub centre height above floor	710 mm
Seat H point height from floor	275 mm
Horizontal distance from H point to steering wheel hub centre	390 – 450 mm
Steering wheel handle diameter	12.5 mm
Steering wheel diameter	325 mm
Natural Frequency of the test bench	310 Hz.

Table 1. Geometric dimensions of the steering wheel test rig.

The steering wheel was vibrated by means of a G&W V20 electrodynamic shaker driven by PA 100 amplifier [8], using the internal sine wave generator. The acceleration obtained at the steering wheel was measured using an Entran EGAS-FS-25 accelerometer located on the top left side of the steering wheel. The accelerometer signal was amplified by means of an Entran MSC6 signal-conditioning unit [6] and monitored by Tektronix TDS210 digital oscilloscope [26].

2.2 **Test Signals**

Three equal sensation tests; namely test 1, test 2 and test 3 were performed at different frequency and amplitude values. The selection of test frequencies and amplitudes was based on the analysis of steering wheel vibration levels obtained from tests of a Renault automobile on 7 road surfaces using 175/65 R14 and 225/45 R16 tyres driven at 45 m.p.h. [21]. An annoyance threshold test was also performed to measure the maximum level of steering wheel vibration that the subjects were willing to withstand for 10 seconds of exposure time. The frequency range of interest was chosen to be from 5Hz to 315 Hz, using the center frequencies of the 1/3 octave band scale. The reference frequencies for equal sensation test 2 and 3 were chosen at 0.2 and 0.4 ms^{-2} r.m.s respectively, both at 10 Hz. However, due to the limitation of the shaker, equal sensation test 1 was performed with reference amplitude of 0.5 ms^{-2} r.m.s at 40 Hz. Table 3 summarizes the reference frequencies and amplitude levels.

Types of Test	Reference Frequency (Hz)	Reference Amplitude Acceleration (m/s2 r.m.s)
Equal Sensation Test 1	40	0.5
Equal Sensation Test 2	10	0.2
Equal Sensation Test 3	10	0.4

Table 3. Frequencies and amplitudes of the reference signals.

2.3 Test Methods

A variation of the method of constant stimuli [4, 9] was used for the equal sensation tests. A reference vibration stimuli was used for generating each of the three equal sensation curves. The three reference stimuli were 0.5 ms^{-2} r.m.s at 40 Hz, 0.2 ms^{-2} r.m.s at 10 Hz and 0.4 ms^{-2} r.m.s at 10 Hz. Each reference stimuli was presented to the test subjects for 20 seconds, then the frequency of the stimulus was changed and the subjects were asked to give verbal instructions so as to adjust the amplitude of the new stimuli until it produced a similar sensation to the reference. During each test, the subject was required to compare the test signal to the reference within a 30 second time interval so as to remain within human short term memory [1]. All 1/3 octave band frequencies in the range from 5 Hz to 315 Hz (i.e 5, 10, 12.5, 16, 20, 25, 31.5, 40, 50, 63, 80, 100, 125, 160, 200, 250 and 315 Hz) were tested. Since human judgement has been shown to be relative rather than absolute [4], stimuli comparisons were limited to occur between frequencies which were no more than one full octave (i.e doubling of frequency) apart.

For each octave band, a set of test frequencies was defined. Each equal sensation test consisted of exposing a subject to the reference then to one of the test frequencies chosen randomly from the set for the octave band in question. When all test frequencies for the band were completed, the highest frequency was set as the new reference signal for the next octave band under investigation and the amplitude given by the test subject during their test of that frequency was taken as the new reference amplitude. By means of this procedure, and starting from the lowest reference frequency of the particular equal sensation curve (either 10 or 40 Hz), the tests were propagated to higher frequencies until all 1/3 octave band frequencies were tested from 5 to 315 Hz. Setting new reference signals after every doubling of frequency produced reference signals at 10, 20, 40 ,80 160 and 315 Hz. By means of this procedure every frequency from 10 Hz to 160 Hz was tested twice, once with reference to a lower frequency and once with reference to a higher frequency. The average of the two results was taken for all calculations.

For the annoyance threshold tests, an approach known as "Up and Down" Method of Limits (i.e Von Bekesy Method) was used [4,9]. In this approach the experimenter made adjustments which depended on the response of the subject. The adjustments involved three steps. The magnitude of vibration was first increased in small increments until the subjects perceived it as "annoying". The subjects were asked to indicate the vibration level which produced an annoyance that they could withstand for 10 seconds. Then the magnitude was decreased until they perceive it as "not annoying". To increase the accuracy and avoid overshooting the magnitude by the experimenter, the vibration level was increased again until the subjects perceive it as "annoying". All center frequencies of 1/3 octave band from 5 Hz to 315 Hz were used as the test signals. Signals were presented in a random order to avoid learning effects.

2.4 Test Protocol

Each equal sensation test lasted approximately 30 minutes and each annoyance test lasted about 20 minutes. Each test consisted of 7 main phases as outlined in Table 4. Prior to testing, a consent form was given and information was gathered from each subject regarding their anthropometry, health, driving experience and previous vibration exposure. A trial run was conducted to familiarize the subjects with the method before acquiring any data. Not more than two tests were allowed for each subject in a day to avoid fatigue and learning effects. During all tests, subjects were asked to wear ear protectors and blind glasses to avoid visual and audio interferences.

Phase	Tasks performed and information obtained
Consent Form and Questionnaire (~3 minutes)	The subject was asked to read the intended purpose of the experiments and to sign a consent form. Each subject furnished all personal details by means of a short questionnaire.
Adjustment of Driving Posture (~1 minute)	The subject was asked to remove heavy clothing, watches, and jewellery. They were then asked to adjust the sitting posture to a comfortable position, simulating the driving task as realistically as possible.
Measurement of Posture Angles (~1 minute)	Four postural angles; arm, wrist, back and shoulder angles were measured using a full circle goniometer.
Preparation for Test (~1 minute)	Instructions were given to the subject. Each subject was asked to wear ear protectors and to wear blind glasses before gripping the steering wheel. They were also required to maintain a constant grip force with both hands on the steering wheel as if they were driving over a winding country road at 50 m.p.h.
Familiarization (~2 minutes)	The test subjects were familiarized with the signals and methods used. A maximum of two test runs were performed.
Equal Sensation Test * (25 minutes)	* To avoid fatigue and learning effects, each subject was allowed to perform a no more than two equal sensation tests on a given day.
Break (~ 3 minutes)	A short break was given after finishing the first set of tests to avoid fatigue.
Annoyance Test (15 minutes)	An annoyance test was performed on each subject.

Table 4. Main phases of the test protocol.

2.5 Test Subjects

30 subjects were chosen randomly for each test from a database of 70 subjects. The 70 subject population consisted mostly of students and staff from within the University of Sheffield. 49 of them were male and 21 females aged from 18 – 50 years with an average of 21.5 years and standard deviation of 6.5 years. Their height ranged from 1.5 to 2.0 metres, with an average of 1.7 metres and standard deviation of 0.1 metres. Weight of the subjects ranged 45 to 90 kg, with an average of 62.6 kg and standard deviation of 13.1 kg. More than 50% of the subjects ranked the comfort level of their vehicles as being "good" based on the questionnaires given. Only one subject responded "slight discomfort". On average, 55% of the subjects drove 1 to 2 hours daily, but 10% had no driving experience. All subjects were in good health and physically fit to undergo the vibration experiments.

3. Results

3.1 Effect of Frequency and Amplitude

Figure 5 presents the average equal sensation contours and the annoyance curve for 30 subjects plotted in terms of r.m.s acceleration amplitude as a function of frequency from 5 to 315 Hz. The results show approximately linear behaviour in all tests from 5 to 60 Hz. Above 60 Hz the curves were observed to increase rapidly in a non-linear manner. The equal sensation curves, except for test 1, were found to converge towards the annoyance threshold level above 100 Hz.

To investigate whether the equal sensation curves varied as a function of reference signal amplitude, statistical significance tests were performed using a one-factor ANOVA and post-hoc Tukey Test [12] at 0.01 confidence level for each equal sensation curve. Results of paired comparison Tukey tests showed equal sensation test 2 and test 3 may come from the same distribution. However, significant differences were found for equal sensation test 1 ($p<0.0001$).

A transition was found to occur in the behaviour of all the curves in the frequency region between 50 Hz to 80 Hz. The behaviour of the curves in this region was assumed to occur due to the combined behaviour of the Pacinian and non-Pacinian systems. As reported by Verillo [27], the strongest action of the Pacinian corpuscles is believed to occur in the frequency range from 60Hz to 400 Hz. Meissner's corpuscles are believed to be the main contributors to the perception of skin vibration at frequencies approximately below 45 Hz. The transition which was found to occur in all four curves somewhere in the neighbourhood of 60 Hz to 80 Hz can be hypothesized to be due to the action of the Pacinian corpuscles which begin to dominate the nervous response to the vibration stimuli.

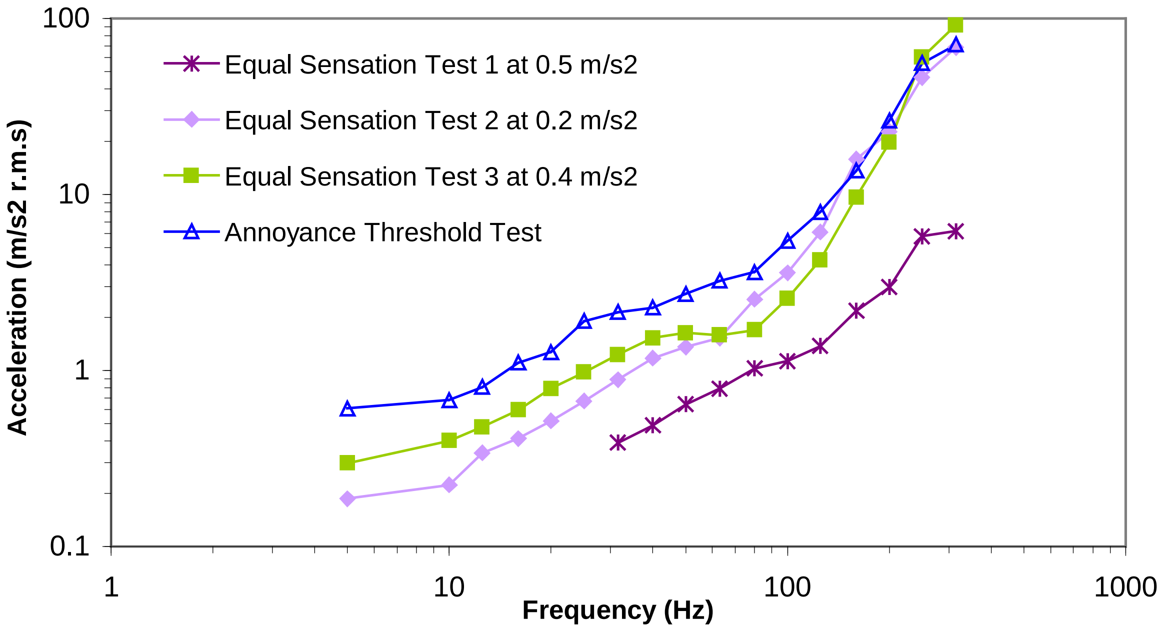


Figure 5. Mean experimental values of the equal sensation tests and annoyance threshold test for 30 subjects.

The standard deviations were observed to increase with increasing frequency, with large values being found above 100 Hz for all tests except for equal sensation test 1 (See Table 5). Above 100Hz, the vibration stimuli was localized primarily to the hands and fingers [22].

Frequency (Hz)	Equal Sensation Tests			Annoyance Threshold Test
	Test 1	Test 2	Test 3	
5	-	0.10	0.19	0.15
10	-	0.06	0.08	0.09
12.5	-	0.16	0.19	0.10
16	-	0.21	0.29	0.15
20	-	0.32	0.45	0.16
25	-	0.42	0.63	0.29
31.5	0.01	0.61	0.70	0.29
40	0.01	0.78	1.08	0.26
50	0.02	1.01	1.30	0.30
63	0.02	1.51	1.21	0.33
80	0.03	3.16	1.84	0.33
100	0.03	4.11	1.92	0.60
125	0.03	7.13	3.84	1.02
160	0.06	22.04	13.19	2.33
200	0.09	28.11	27.34	6.96
250	0.27	47.87	96.97	24.91
315	0.24	64.70	129.70	32.28

Table 5. Mean standard deviation (ms $^{-2}$ r.m.s) calculated for each frequency for 30 subjects.

3.2 Effect of Test Subject Anthropometry, Driving Posture and Experience

One Factor ANOVA and pos-hoc Tukey tests were applied to the data to determine whether age, gender, height, weight, driving posture or driving experience significantly effected the vibration test results. At a 0.05 confidence level and for the sample size (n=30) considered, no significant differences were found. Although the vibration testing results were unaffected by the above factors, gender was found to be a significant factor affecting the driving posture. Significant differences were found for the arm and the back angle of the driving posture between male and females (p=0.031 and p<0.0001 respectively). Female subjects preferred driving postures with smaller arm and back angles; 133° and 102° on average. Male subjects, on the other hand, preferred a more open posture [19] with arm angle of 143° and back angle of 110° on average.

3.3 Regression Lines

The equal sensation and annoyance curves were modeled as consisting of three distinct segments as shown in Figure 6. Below 6.3 Hz a line of constant acceleration was fitted as an extrapolation based on Miwa's equal sensation curves [15]. A line of constant velocity (i.e acceleration increasing in proportion with frequency) was fitted by linear regression from 6.3 Hz to 63 Hz. From 63 Hz to 315 Hz a line of constant displacement (i.e acceleration increasing in proportion with the square of the frequency) was fitted using a 2nd order polynomial. Regression lines at 0.05 confidence level showed good fit on all curves with R^2 = 0.97 on average. The regression lines were fitted using the least square method [12] performed in *Analyze-it* ™ [30].

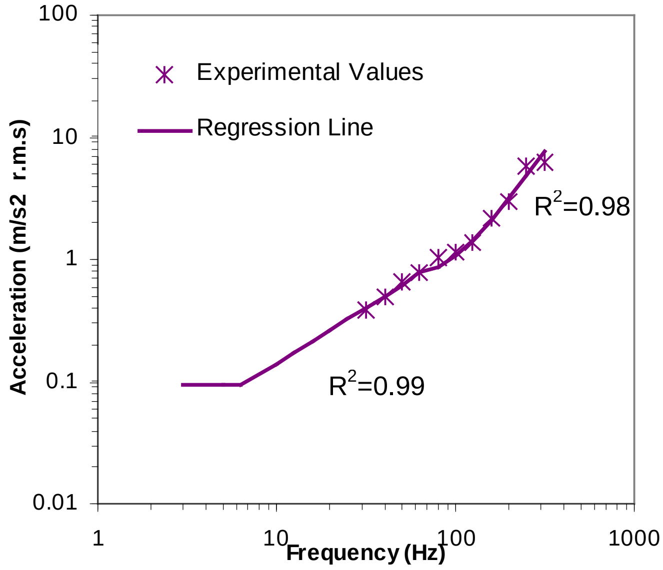


Figure 6a. Equal Sensation Test 1
(0.5 ms^{-2} r.m.s at 40 Hz reference signal)

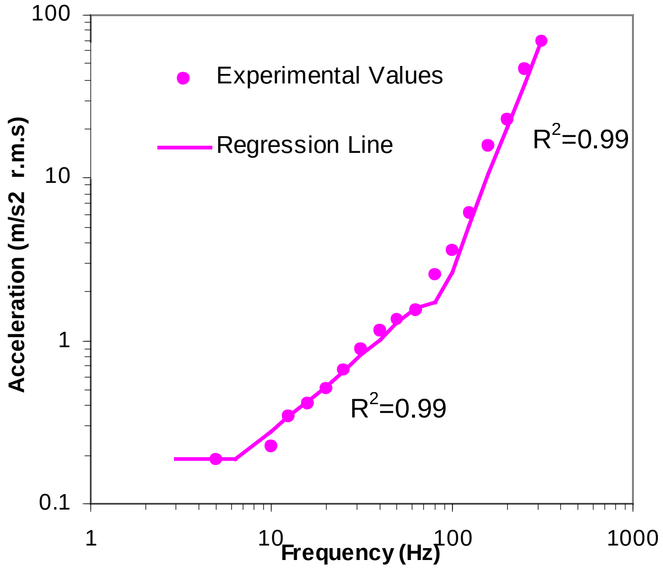


Figure 6b. Equal Sensation Test 2
(0.2 ms^{-2} r.m.s at 10 Hz reference signal)

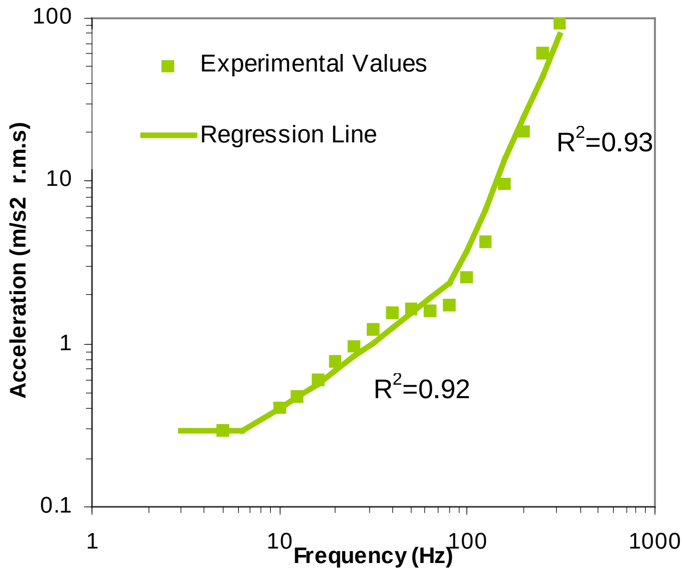


Figure 6c. Equal Sensation Test 3
(0.4 ms^{-2} r.m.s at 10 Hz reference signal)

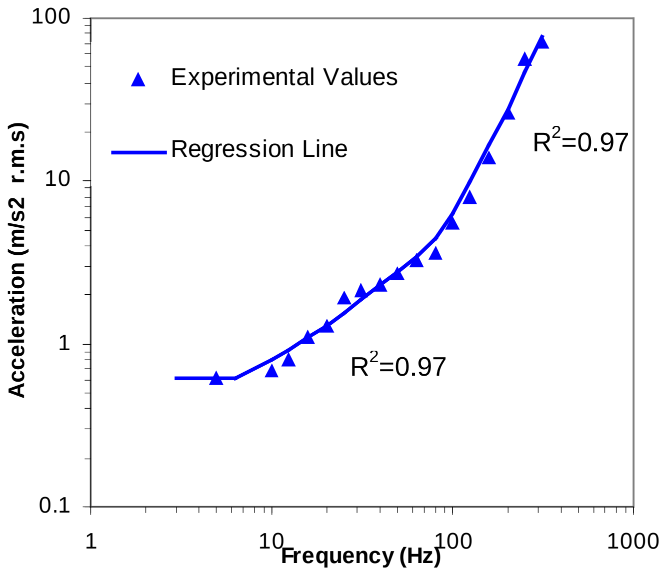


Figure 6d. Annoyance Threshold Test

Figure 6(a-d). Regression lines fitted for the frequency range from 6.3 Hz to 63 Hz and for the frequency range from 63 Hz to 315 Hz. (Regression line below 6.3 Hz was approximated by Miwa's work [15].)

3.4 Frequency Weighting Curve of the Steering Wheel Rotational Vibration.

A frequency weighting curve, here called W_s , was defined by taking the average values of the asymptotic weightings of the equal sensation curves. The intended purpose of the W_s curve is to weigh the frequency components measured at the steering wheel for the purpose of quantifying the perceived comfort. The values were normalized against the lowest value of the r.m.s acceleration and were expressed in terms of decibels (dB). Three segments were defined : 1, 2, and 3. The segments were from 3Hz to 6.3 Hz, from 6.3 Hz to 63 Hz, and from 63 Hz to 315 Hz respectively (see Figure 7 below). Two transition points were set at 6.3 Hz and 63Hz.

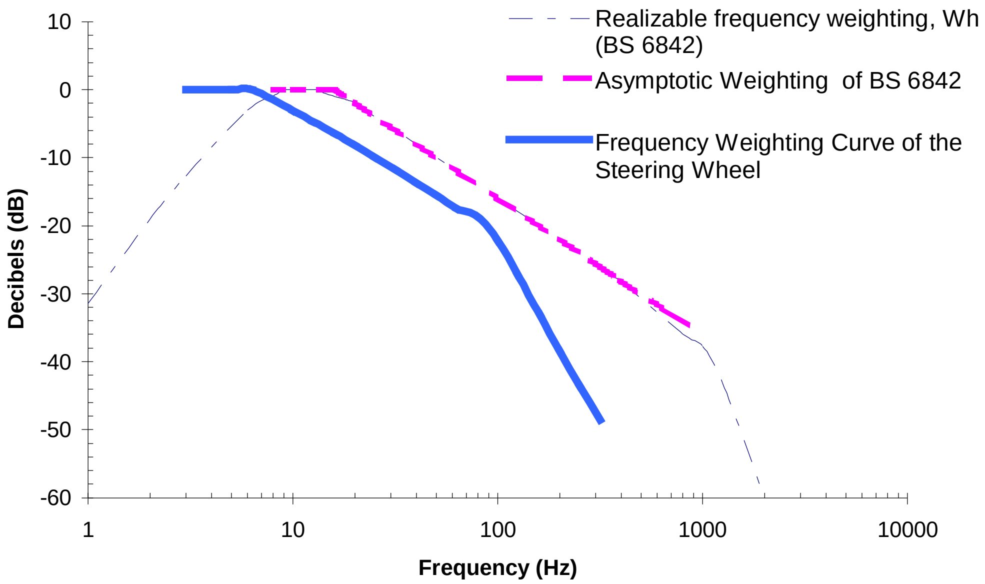


Figure 7. Asymptotic weighting curve of rotating steering wheel, W_s and asymptotic weighting of the hand, W_h taken from BS 6842

From 3 Hz to 6.3 Hz, the slope of the asymptotic curve was defined as 0 dB per octave based on the extrapolation of Miwa's work [15]. From 6.3 Hz to 63 Hz, the slope was found to be approximately -5.5 dB per octave, and -16.3 dB per octave from 63 Hz to 315 Hz. The values of the slope were rounded to -6 dB from 6.3 Hz to 63Hz and to -16dB from 63 Hz to 315 Hz.

The W_s weighting curve developed as part of the research described in this paper was found to have significant differences in shape compared to the asymptotic weighting curve of the hand, W_h , described in BS 6842 [2] . It was observed that W_s had a lower turning-point frequency at 0 dB compared to W_h (i.e 6.3 Hz for W_s and 16 Hz for W_h respectively). This implies that the decrease in sensitivity to vibration occurs at a lower frequency for two hands gripping a rotating steering wheel as opposed to a single hand on a pressing a horizontal vibrating plate.

5. Conclusions.

Equal sensation tests performed at 0.2 ms^{-2}, 0.4 ms^{-2} and 0.5 ms^{-2} reference amplitudes and an annoyance threshold test showed a general tendency of reduced skin sensitivity with increasing frequency, indicated by the positive slope of the curves. A frequency weighting curve for steering wheel rotational vibration, W_s , was defined using the mean normalized values of the equal sensation curves. The frequency weighting curve W_s showed different shape and characteristics compared to the asymptotic weighting curve of the hand filter W_h [2]. The slope of W_s was approximated to 0 dB per octave from 3 Hz to 6.3 Hz, -6 dB per octave from 6.3 to 63 Hz and -16 dB per octave from 63 Hz to 315 Hz. An investigation is under way to determine a weighting curve for vibration of the steering wheel in the for-aft direction.

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