# Effect of Frequency and Grip Force on the Perception of Steering Wheel Rotational Vibration

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**Abstract**

This paper describes an experimental study which investigated human perception of rotational steering wheel vibration. Tests were performed with a rigid steering wheel rotating under sinusoidal excitation in the frequency range from 4 to 125 Hz at 1.86 $m/s^2$ and 5.58 $m/s^2$. Twenty-five human subjects participated in the study, and two grip strengths were tested. The perceived discomfort caused by steering wheel vibration was found to be highly dependent on frequency. Equal sensation curves (iso-comfort curves) were plotted and were found to be approximately linear over the frequency range considered. Statistically significant ($p<.05$) differences were found in the results from the two grip strengths, but the differences were less than 5 percent at most frequencies. The equal sensation curves were compared to results from the literature obtained for translating handles, and were found to be similar.

**Keywords:** steering wheel, perception, ride comfort

## 1. Introduction

In the automotive industry significant effort has been made in recent years to define comfort indices, or quality indices, for vehicle subsystems. These metrics translate the measurable mechanical (objective) quantities which define human-vehicle interaction into perceived (subjective) quantities which indicate the likely response of a test jury to questions about the vehicle or subsystem. Once defined, such metrics are used in the process of vehicle design and testing, and several examples can be found including studies performed by the authors [4,5].

Of the various vehicle subsystems, the steering [8,10,16] is important due to its central role in controlling the vehicle and due to the importance of the human hand as a source of information to the driver [3]. The human hand-arm system is of interest to car designers both as a mechanical impedance attached to the steering system, and as a sensor relaying information to the driver. Much research has already been performed to investigate the interaction between the human hand and simple handles of the type found on power tools and other sources of high level vibration in the workplace. Two types of investigation are of particular relevance to car designers: mechanical impedance measurements of the hand-arm system and investigations of human perception of hand-arm vibration.

Reynolds and Soedel [17] investigated the effect of arm position, grip tightness and contact pressure on the vibration response of the hand when holding a vibrating handle. For a given arm position and grip, the response of the hand to sinusoidal vibration in the frequency range from 20 to 500 Hz was concluded to be linear. Arm position was found to have little effect on the impedance of the hand, while grip tightness and hand pressure were found to influence the vibration response for frequencies above 60 Hz. The size and weight of the test subjects was not found to influence the test results. The study concluded by developing a 6 degree of freedom (DOF) spring-mass model consisting of two DOF for each of the three translational vibration axis.

Reynolds and Keith [18] measured the mechanical mobility of the hand-arm system in the frequency range from 5 to 1000 Hz and developed a 3 DOF spring-mass model with a separate set of coefficients for each translational axis, grip type and grip force value. The results suggested that most of the vibrational energy was dissipated by the hand-arm system for frequencies above 100 Hz in the vertical direction, and at all frequencies in the horizontal and axial directions. Again using a vibrating handle, Reynolds and Angevine [19] performed measurements which demonstrated that vibration is localised in the hand itself for frequencies above 100 Hz, with vibration being mostly confined to the fingers at frequencies greater than 150 Hz. Mishoe and Suggs [13] developed a three degree of freedom model of the hand-arm system and identified the grip forces and grip directions which minimise the transmission of power into the hand from the vibrating handle.

Burstrom and Lundstrom [2] have measured the absorbed energy in the frequency range from 4 to 1000 Hz when gripping a vibrating handle. Their results indicate that energy absorption in the hand depends mainly on the frequency and direction of the vibration stimulus, and that higher energy absorption resulted from the use of higher vibration levels or stronger grip forces. They found that arm postures had only a small influence on the amount of energy absorbed. Lundstrom and Burstrom [12] also investigated the mechanical impedance of the hand-arm system in the frequency range from 20-1500 Hz. Firm grips as well as higher vibration levels resulted in higher impedance magnitudes for frequencies above 100 Hz. Below 100 Hz, increasing the vibration input actually lowered somewhat the hand-arm impedance, while the grip force had little or no influence. All impedance curves had a pronounced minimum in the frequency range from 50-150 Hz, while the overall tendency outside that frequency range is of increasing impedance with increasing frequency, indicating that remote elements of the arm become less and less active as the frequency rises, eventually reaching a situation where only the fingers vibrate with the handle.

Jandak [9] has recently measured the mechanical impedance of the hand-arm system using a handle vibrating under random excitation in the frequency range from 4 to 1000 Hz. The system response was found to be significantly dependent on the direction and frequency of vibration. Grip and feed forces were found, however, to have only a small effect on the measured mechanical impedance, while changes in arm posture had a much more pronounced effect.

Perception thresholds and equal sensation contours have been investigated by several researchers. In a landmark investigation, Miwa [14] determined vibration perception thresholds and equal sensation contours over the frequency range from 3 to 300 Hz for a hand pressed against a flat plate. The threshold curve was u-shaped, with the area of greatest sensitivity (lowest amplitude) in the range from 100 to 150 Hz. Reynolds, Standlee and Angevine [20] investigated the sources of the vibration sensation, concluding that low frequency sensation was the work of joint capsules, Ruffini endings and Meissner's corpuscles, while high frequency vibration was largely perceived through the action of Merkel disks, Ruffini endings and Pacinian corpuscles. They also concluded that the mecanoreceptors were not aiding in the perception of the energy dissipated within the hand-arm system, thus suggesting that subjective response data is of questionable use when trying to establish limits for hazardous hand-arm vibration. Difference thresholds and Weber Fractions were recently determined by Morioka [15] for sinusoidal vibration at frequencies from 8 to 500 Hz applied to a wooden handle. The results indicated that the difference thresholds for hand-transmitted vibration were constant at 15-18% of the vibration magnitude and were unaffected by vibration frequency

For what regards handles, previous research has helped to clarify the effects of vibration frequency, vibration direction, grip force and arm posture on the mechanical response of the hand-arm system. Equal sensation curves have also been obtained for several levels of vibration including threshold, and Weber Fractions at threshold have been determined and found constant across a wide range of frequencies. The authors found no results in the literature relative to rotational movements of handles, and in particular no results were found which were directly applicable to the vehicular steering wheel. International standards [1,6,7] treating hand-arm vibration provide no suggested methods for evaluating comfort. The study described in this paper determined equal sensation (iso-comfort) curves for a rigid rotating steering wheel by means of a test bench which simulates the general sitting posture of a European B segment automobile. Sinusoidal test signals were used, and two different grip forces were investigated.

## 2. Experimental Method

## 2.1 Equipment

Figure 1 presents the test bench which was constructed for this study. It was designed so as to expose human subjects to rotational steering wheel vibrations while maintaining the typical sitting posture of a European B segment automobile. The seat was taken from a B segment vehicle, and the original seat guide inclination was maintained. The main geometric dimensions of the bench which define the sitting posture are given in Table 1.

Figure 1) Steering wheel rotational vibration test rig.

| Geometric Parameter | Value |
|---|---|
| steering column angle with respect to floor | 23 ° |
| steering wheel hub centre height above floor | 700 mm |
| steering wheel diameter | 325 mm |
| horizontal distance from seat H point to steering wheel hub centre | 390-450 mm |
| seat H point height from floor | 275 mm |

Table 1) Bench geometric dimensions which affect sitting posture.

The test bench incorporates a G&W V20 electrodynamic shaker driven by a PA100 amplifier. The acceleration obtained at the steering wheel was measured by means of an ENTRAN EGAS-FS-25 accelerometer, while the shaker piston movement was also monitored by means of a second accelerometer of the same type. Both accelerometer signals were amplified by means of an ENTRAN MSC6 signal conditioning unit and were monitored by means of a Tektronix TDS210 digital oscilloscope. The experimental layout is illustrated in Figure 2.

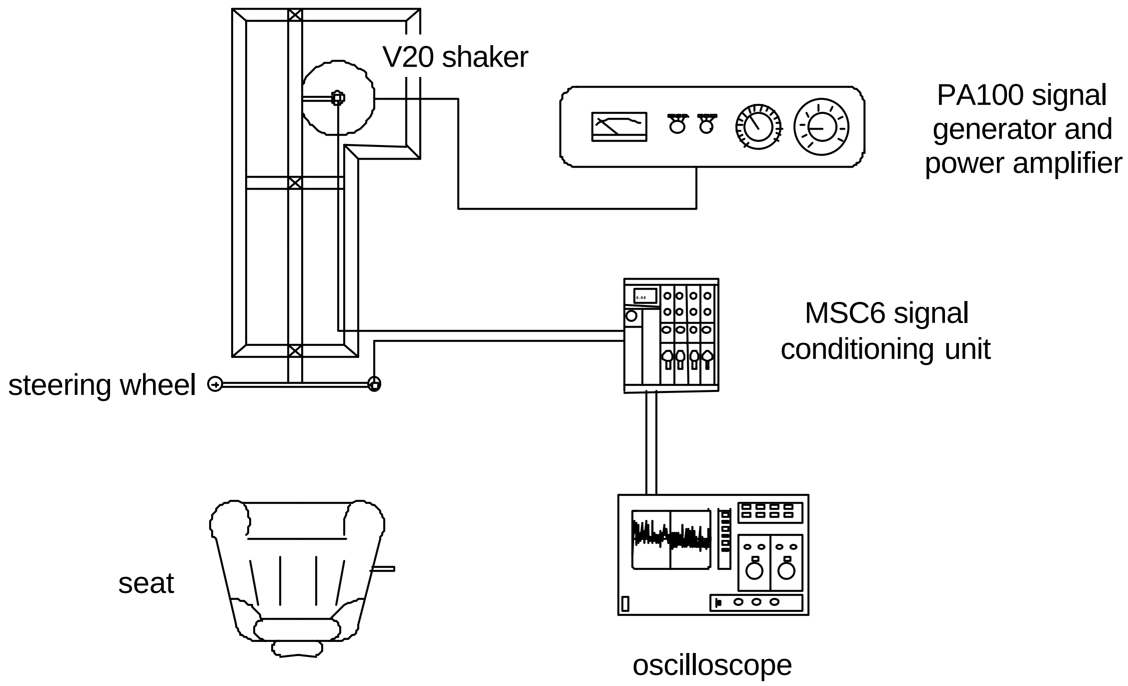


Figure 2) Experimental layout.

## 2.2 Selection of Test Frequencies and Amplitudes

Preliminary testing was performed in order to evaluate the ability of human subjects to compare sinusoidal vibrations of different frequencies so as to define the test signals. Several conclusions were drawn from the preliminary tests:

- at low frequencies up to about 30 Hz the complete hand-arm system was felt to vibrate with the steering wheel and the overall sensation was a complex integration of information from several body regions.

- at frequencies above roughly 30 Hz the vibration was perceived as localised to the fingers and hand

- test subjects found it difficult to directly compare vibrations at different frequencies because different body parts were involved in the motion

- as predicted by theoretical argument [11], the variance in the amplitude estimates increased with widening difference between test and reference frequency, with large variances occurring for ratios greater than two

Based on the above observations, the tests were divided into two frequency regions: less than 30 Hz and greater than 30 Hz. The decision to separate the frequency regions emphasised the different nature of the sensations produced. One reference frequency was chosen for each of the two regions, 16 Hz for the lower and 63 Hz for the upper. Reference amplitudes were chosen which were representative of road data measured on the steering wheels of B and C segment European automobiles. After reviewing data from several sources, 1.86 $m/s^2$ and 5.58 $m/s^2$ were chosen because they were similar to the overall vibration levels found in several vehicles when driving on smooth motorway surfaces and rough pave' surfaces

## 2.3 Test Protocol

The test group consisted of 13 men and 12 women. Subject ages ranged from 18 to 50 years, with an average age of 26.9 and a standard deviation 1.27. All subjects were in good health and none used vibration producing tools as a regular part of their work. When the subjects arrived they were given an instruction sheet and a consent form to read and sign. Next they were asked to remove any watches and jewellery that they were wearing as these might effect the test results. The subjects were then asked to sit and adjust the seat for-aft position so as to reproduce a comfortable driving position similar to that normally used in their own vehicle. The distance between seat h-point and steering wheel hub centre was then measured by means of a pointer and scale system built into the test bench. The distances chosen by the 25 test subjects were found to range from 490 to 660 mm, with an average value of 575.5 mm and a standard deviation of 1.8 mm. Each subject was next asked to grasp the steering wheel with both hands placed symmetrically about the wheel centre. The arm posture in the test position was recorded using a Diagnostic and Measuring Instruments goniometer. The angle of elbow flexion was recorded, as was the wrist position which was taken as the angle formed by the midline of the subject's forearm and the midline of the third metacarpal, with the goniometer fulcrum placed over the capitate. Measured elbow flexion for the test group ranged from 21 to 71 degrees with an average value of 50.6 degrees and a standard deviation of 2.0 degrees. Measured wrist position ranged from 4 to 12 degrees with an average value of 7.3 degrees and a standard deviation of .8 degrees.

During tests, subjects were asked to close their eyes to avoid visual cues. They were also asked to wear ear protectors so as not to hear the sound of the shaker head which was clearly audible at the higher test frequencies. The test sequence was similar to that used by Reynolds, Standlee and Angevine [20] for determining their equal sensation curves. First the subject was asked to adopt one of the two test grips, "tight" or "loose". It was suggested to the subject that the "tight" grip be similar to how they would hold the wheel when driving over a winding country road, and it was asked that the "loose" grip be similar to what might occur on a straight segment of motorway during relaxed driving. The reference sine wave of fixed frequency (either 16 or 63 Hz) and amplitude (either 1.86 $m/s^2$ or 5.58 $m/s^2$) was then applied to the wheel and the subject was given about 10 seconds of time to memorise the sensation produced by the vibration. The frequency of the sine wave was then moved upward or downward, and the test subject was asked to indicate upward or downward changes to the amplitude until the produced sensation was similar to that of the reference. The signal was adjusted by the experimenter until the test subject indicated that there was a match in sensation, at which point the amplitude of the test signal was recorded on paper and the reference signal was repeated in preparation for the next test. The sequence of test signals presented to the subject was randomised in order to reduce learning and fatigue effects.

## 3. Results

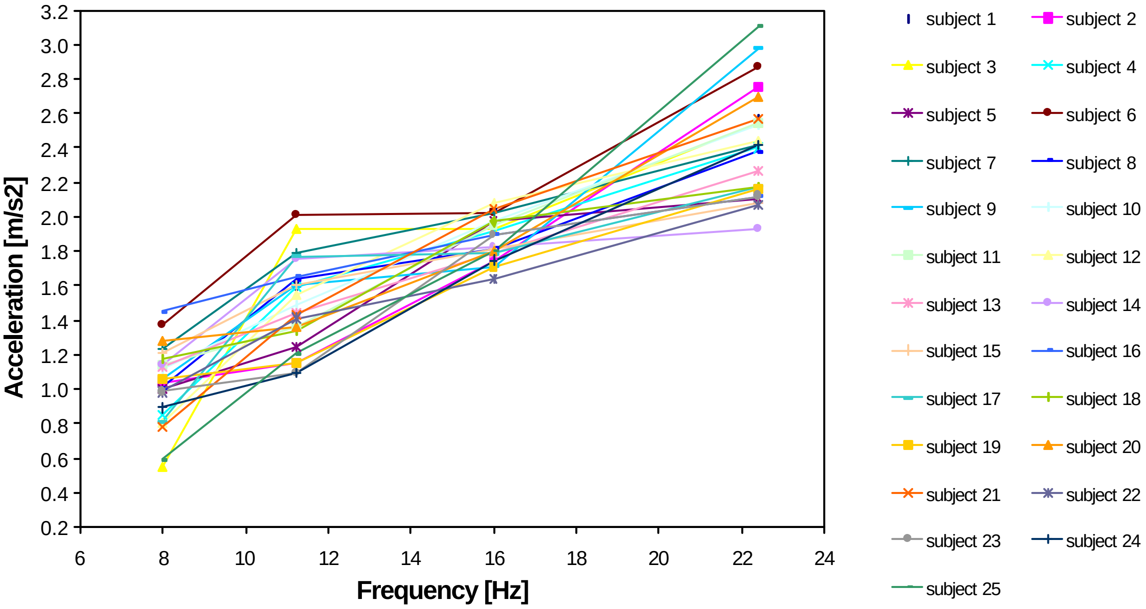


Figure 3) Results from all subjects obtained using the 16 Hz reference signal at 1.86 m/s2 with loose grip.

Figure 3 presents the responses obtained from the 25 test subjects for the 16 Hz, 1.86 m/s$^2$ reference signal when using the loose grip. It can be seen that the inter-subject variability is large, and that the overall variance in the data increases as the distance between the test and the reference frequency increases. It can also be seen that there is some irregularity in the amplitude estimates of the individual subjects. Table 2 presents a summary of the results for the 16 Hz reference sinusoidal signal, while Figure 4 plots the equal sensation curves. The differences between the equal sensation curves obtained using the two grip conditions were found to be statistically significant ($p<.05$) for all frequencies from 8 to 22.5 Hz for both reference amplitudes when compared by means of a two-tailed t-test, using either a paired comparison or an unequal variances assumption.

| Reference Amplitude [m/s$^2$] | Grip Strength | Test Frequency (Hz) | Average Amplitude [m/s$^2$] | Standard Deviation [m/s$^2$] |
|---|---|---|---|---|
| 1.86 | Loose | 8.0 | 1.03 | 0.22 |
| | | 11.2 | 1.49 | 0.25 |
| | | 16.0 | 1.88 | 0.12 |
| | | 22.4 | 2.42 | 0.30 |
| | Tight | 8.0 | 1.18 | 0.28 |
| | | 11.2 | 1.50 | 0.30 |
| | | 16.0 | 1.82 | 0.32 |
| | | 22.4 | 2.39 | 0.50 |
| 5.58 | Loose | 8.0 | 3.05 | 0.65 |
| | | 11.2 | 4.21 | 0.81 |
| | | 16.0 | 5.23 | 0.37 |
| | | 22.4 | 5.94 | 0.51 |
| | Tight | 8.0 | 3.26 | 0.90 |
| | | 11.2 | 4.13 | 0.85 |
| | | 16.0 | 5.14 | 0.56 |
| | | 22.4 | 6.07 | 0.85 |

Tabel 2) Test results obtained using the 16 Hz reference signal.

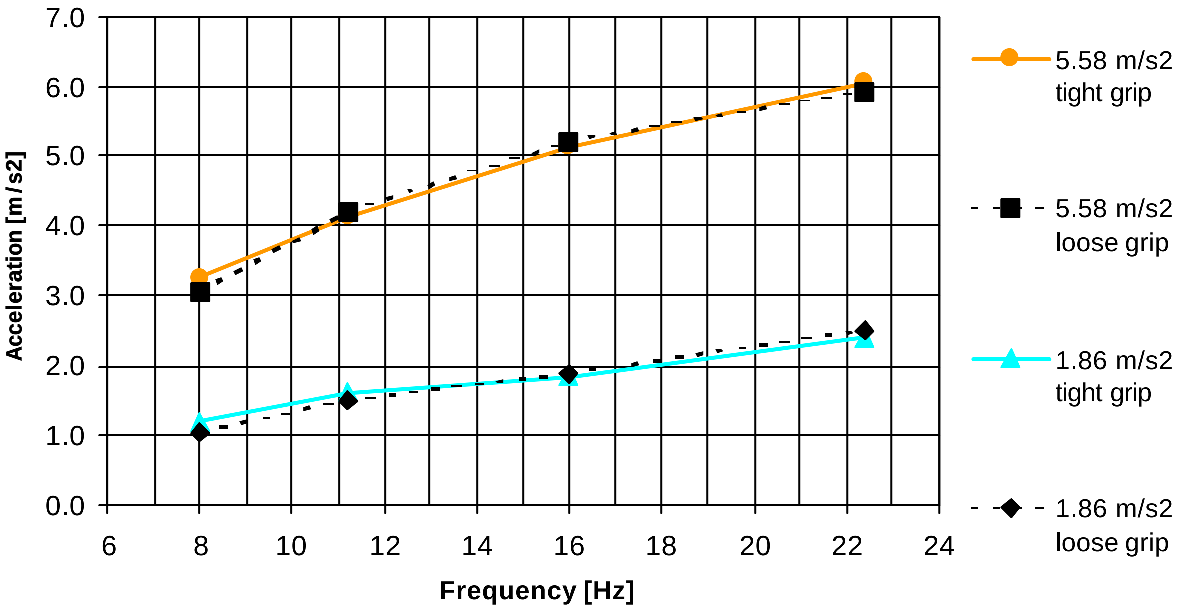


Figure 4) Average equal sensation curves from the tests using the 16 Hz reference signal.

| Reference Amplitude [m/s²] | Grip Strength | Test Frequency (Hz) | Average Amplitude [m/s²] | Standard Deviation [m/s²] |
|---|---|---|---|---|
| 1.86 | Loose | 31.5 | 1.10 | 0.26 |
| | | 45 | 1.43 | 0.17 |
| | | 63 | 1.88 | 0.29 |
| | | 90 | 2.20 | 0.74 |
| | | 125 | 2.83 | 1.20 |
| | Tight | 31.5 | 1.25 | 0.30 |
| | | 45 | 1.43 | 0.25 |
| | | 63 | 1.83 | 0.22 |
| | | 90 | 2.36 | 0.74 |
| | | 125 | 3.36 | 1.27 |
| 5.58 | Loose | 31.5 | 2.86 | 0.93 |
| | | 45 | 3.81 | 0.73 |
| | | 63 | 5.19 | 0.51 |
| | | 90 | 5.91 | 1.16 |
| | | 125 | 7.46 | 1.40 |
| | Tight | 31.5 | 2.95 | 0.85 |
| | | 45 | 4.17 | 0.76 |
| | | 63 | 5.30 | 0.38 |
| | | 90 | 6.12 | 0.90 |
| | | 125 | 7.64 | 1.90 |

Tabel 3) Test results obtained using the 63 Hz reference signal.

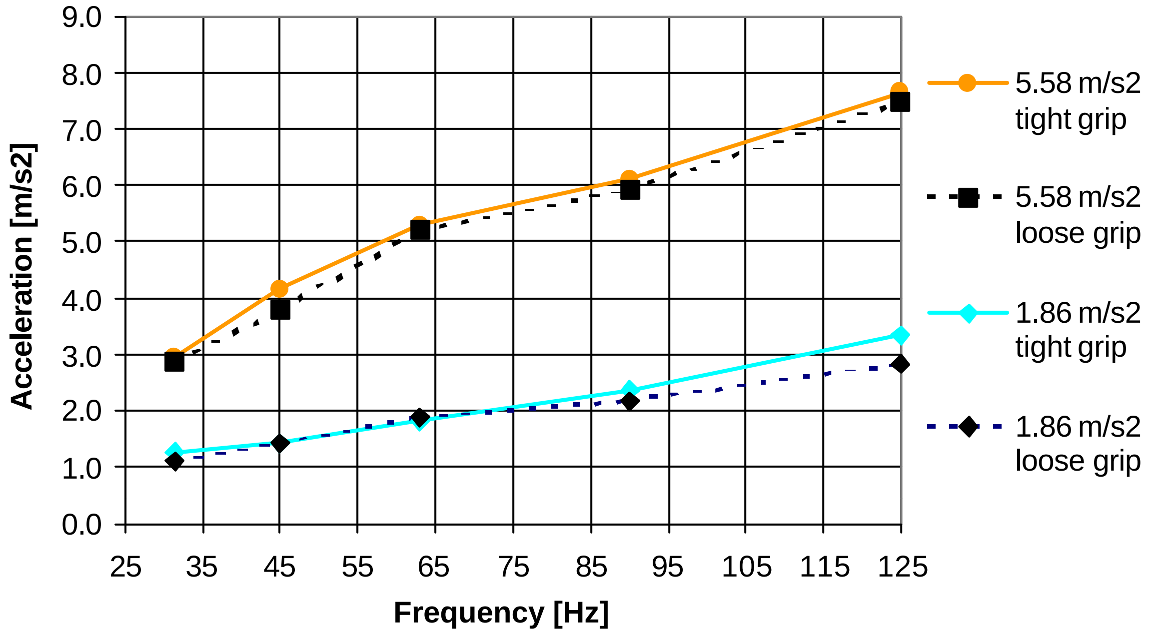


Figure 5) Average equal sensation curves from the tests using the 63 Hz reference signal.

Table 3 and Figure 5 present the results from the tests performed using the 63 Hz reference signal with 1.86 m/s² and 5.58 m/s² amplitudes. Again the two grips produced similar results, and again differences between the results obtained using the two grips were found to be significant (p<.05) when using a two-tailed t-test with either a paired comparison or an unequal variances assumption. Figure 6 presents a comparison between the equal sensation curves obtained in this study for the rotating steering wheel and the threshold and annoyance level curves obtained by Reynolds et. all. for a 2 pound finger grip on a vibrating handle in the vertical direction [20]. It can be seen that the equal sensation curves obtained in the current study show a similar behaviour to those obtained using vibrating handles.

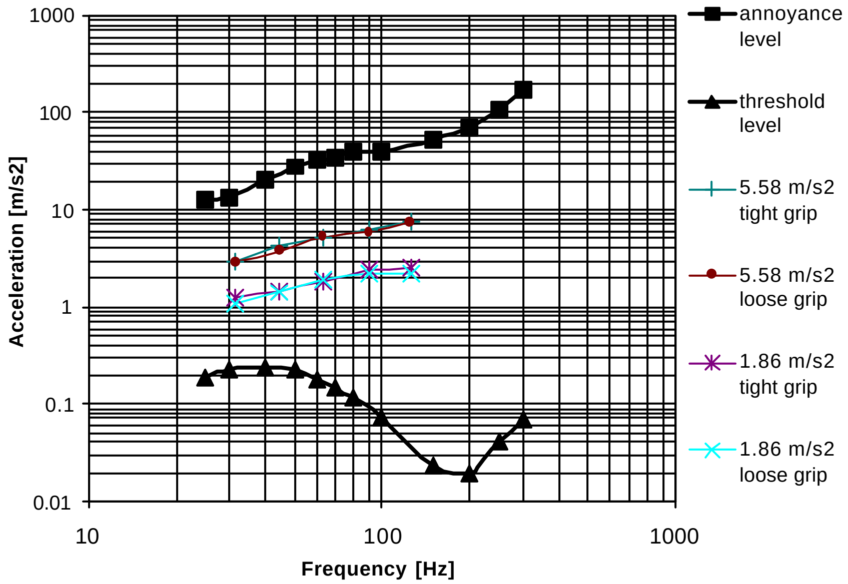


Figure 6) Comparison between the equal sensation curves determined using the 63 Hz reference sinusoid and threshold and annoyance curves [20] for the vertical direction of a vibrating handle.

## 4. Discussion

As evidenced by previous literature relative to simple handles, the movement of the hand-arm system was found to change as a function of test frequency. While direct acceleration measurements along the arm were not made in this study, the arm movement was strongly perceived by the test subjects. At frequencies below about 30 Hz there was evident movement of the complete hand-arm system, while increasing the frequency of the steering wheel vibration localised the movement more towards the parts of the hand in the immediate vicinity of the vibrating surface. The sensations produced by the vibration changed in nature and intensity as a consequence of the body parts involved. For frequencies above 30 Hz the disturbance was principally perceived as localised to the fingers and hand. The different nature of the physical movements suggested the division of the test program into two frequency regions; one below 30 Hz and the other above 30 Hz.

As predicted from theoretical argument [11], both preliminary testing and the final set of results confirm that the variance in the amplitude estimates provided by the test subjects increased with increasing distance between the frequency of the reference signal and that of the test signal. The results from preliminary testing suggested the use of frequency ratios no greater than two for the testing program. Inspection of the column reporting the standard deviation about the estimated mean in Tables 2 and 3 provides evidence of an increasing scatter in the amplitude estimates as the test frequency becomes more distant from that of the reference sinusoid. The amplitude estimates made at the same frequency as the reference signals provide a useful reference for judging the results from the higher and lower frequencies.

The equal sensation (iso-comfort) curves produced by the current study for a rotating wheel show a behaviour similar to that found in the literature for translating handles. Human perception was found in this study to have a relatively linear behaviour in the frequency range from 8 to 125 Hz at the amplitudes of 1.86 and 5.58 $m/s^2$ tested, with the most pronounced deviation from linearity being for frequencies in the neighbourhood of 90 Hz. The approximate linearity of the subjective response for the vibration amplitudes tested suggests that it may be possible to quantify human response to steering wheel rotational vibration by means of a linear weighting filter. While equal sensation curves defined in the literature for handles demonstrate that the assumption of linearity will become unacceptable at low amplitudes near threshold or high amplitudes near the endurance limit, the results from this study would suggest that a linear filter may be an acceptable method of evaluating typical road vehicle vibration. The slopes of the equal sensation curves defined in this study were found to vary as a function of the signal amplitude, but an iso-comfort weighting filter based on an average curve may still provide an acceptable evaluation method.

The current study investigated two grip conditions; “loose” and “tight”. The equal sensation curves for the two grips were found to present statistically significant differences at a 5 percent confidence level. Figures 4 and 5 also suggest that there is a slight tendency for stronger grips to require higher acceleration amplitudes than loose grips to produce the same level of sensation (same comfort level). A peak difference of 18% was found at 125 Hz, but most of the frequencies tested produced a relative difference of less than 5%. The results from all tests suggest that the effect of the grip strength is much smaller than that of the excitation frequency. The usefulness of this finding lies in the fact that it is difficult to control steering wheel grip during experimental testing of real vehicles. The findings suggest that for wheel rotational vibration it may not be necessary to measure the grip strength during vehicle testing if a 5-10% accuracy in the comfort estimate can be tolerated and if the grip strength does not greatly affect the overall impedance loading on the vehicle steering system.

## 5. Conclusions and Recommendations

Equal sensation (iso-comfort) curves were determined for rotational vibration of a rigid steering wheel for frequencies in the range from 8 to 125 Hz at amplitudes of 1.86 and 5.58 $m/s^2$. The curves, plotted in terms of acceleration, were found to be approximately linear over the frequency interval and were found to be similar in slope. The curves were compared to results found in the literature for translating handles and were found to be similar. The variance in the subjective estimates was found to increase with increasing distance between reference frequency and test frequency, emphasising the limited human capacity to formulate absolute judgements of subjective discomfort.

While grip force was not measured mechanically, tests were performed using two suggested strengths. The test subject was asked to use a “tight” grip similar to how they would hold the wheel when driving over a winding country road, and to use in a separate test a “loose” grip which was to be similar to what might occur on a straight segment of motorway during relaxed driving. Statistically significant differences were found between the two equal sensation curves produced by the two grips at all frequencies, but the magnitude of the difference was only greater than 10 % at three of the frequencies tested. The results suggest that grip force may possibly be neglected in practice when performing vehicular comfort measurements.

The amplitude levels used for this study were typical of those encountered in practice in real vehicles, and were thus in the middle of the range defined by the threshold of perception the endurance limit. The relative linearity found in the results suggests that it may be possible to define an average linear weighting filter which can serve to evaluate human perception of steering wheel vibration. Future research will define and test an average filter under random vibration to ascertain the potential of the approach for steering wheel comfort evaluation.

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