ICSV13 - Vienna
The Thirteenth International Congress on Sound and Vibration
Vienna, Austria, July 2-6, 2006

EFFECTS OF FREQUENCY, GRIP FORCE, AND GENDER ON THE PERCEPTION OF STEERING WHEEL LONGITUDINAL VIBRATION

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Abstract

The study focused on vehicle vibration simulator (VVS) tests for subjective evaluation of steering wheel longitudinal vibration. Fourteen (14) subjects (8 males, 6 females) participated in the VVS experiment applying two steering wheel grip force levels (20 N and 70 N). Two equal annoyance contours were obtained for the longitudinal steering wheel vibration, one for each of the two grip force levels. In the frequency range of 10-64 Hz, the primary factor that determined the shape of the equal annoyance contour was vibration frequency. The annoyance level decreased at a rate of 6 dB per octave (for acceleration) as the frequency increased. The annoyance responses were significantly (α=0.05) different from each other at each test frequency (10, 16, 25.5, 40.5, and 64 Hz) for both contours obtained. The equal annoyance contours obtained in low and high grip force levels were not significantly different from each other at α=0.05 level for the frequency range investigated. In addition, there was no significant gender effect on the annoyance response (α=0.05). The findings of this study showed good agreement with those of previous studies.

INTRODUCTION

In the recent years, motor vehicle manufacturers have been dedicating significant effort to improve the noise, vibration and harshness (NVH) characteristics of their products. The motivation for this effort comes from the fact that NVH related issues have been a routine part of warranty and customer satisfaction concerns [2]. In a vehicle, drivers are continually exposed to vibration from contact points such as the pedals, the floorpan, the seat and the steering wheel. Among these, the vibration energy transmitted through the steering wheel is one of the main contributors to the passenger's overall vibration discomfort.

The degree of discomfort felt by a subject due to exposed vibration energy has a close relationship with the vibration signal characteristics (i.e., magnitude and frequency). Experiments have been conducted to determine how the vibration magnitude should be adjusted (raised or lowered) in order to create the same level of discomfort at different frequencies. Those experiments resulted in the creation of a series of curves, which are known as 'equal comfort contours', which are also referred to as 'equal sensation contours' or 'equal annoyance contours.' Early works of Miwa have been a basis for many studies related to an individual's response to vibration excitation [8]. Miwa obtained equal sensation contours over a frequency range of 3-300 Hz for horizontal and vertical directions on a vibrating plate. Two levels of pressure (5 kg and 10 kg) were applied on the plate. It was found that contours did not change drastically in cases where one or two hands contacted the plate, or where 5 kg or 10 kg pressure was applied on the plate. Giacomin *et al.* [5] investigated the rotational steering wheel vibration using a test rig and a vibration simulator. The researchers aimed to obtain a frequency-weighting curve (through obtaining an equal sensation curve) for rotational steering wheel vibration. Sinusoidal excitation was used in a frequency range of 3-315 Hz. The results of this study suggested a decrease in human sensitivity to hand-arm rotational vibration with increasing frequency. The grip force was not measured in this study. The subjects were asked to "maintain the grip strength which they felt they would use when driving on a winding country road."

Amman *et al.* [1] studied the human response characteristics to the vibration transmitted to hand-arm system through a steering wheel in rotational and three translational excitation directions. The frequency ranges investigated in this study were 8-20 Hz for rotational, and 10-64 Hz for translational directions. Using the method of adjustment, equal annoyance contours were obtained for all directions. All the contours showed reduced annoyance as the frequency increased. Furthermore, an additional investigation on rotational vibration revealed that the reference vibration amplitude has little effect on the perception. The steering wheel grip force was not under control in this study. The subjects were asked to "grip the wheel with a force typical of what they would use during normal vehicle driving."

Giacomin and Onesti [4] studied the effect of steering wheel grip force by obtaining equal sensation curves in a frequency range of 8-125 Hz for rotational steering wheel vibration. The grip forces were neither measured nor kept under control. Verbal expressions such as 'loose grip' and 'tight grip' were used to define the grip force levels. The subjects were asked to adopt one of the two grip force levels. The tight grip was defined to be similar to "how they would hold the wheel when driving over a winding country road," and the loose grip was defined to be similar to "what might occur on a straight segment of motorway during relaxed driving." Statistically significant ($p<0.05$) differences were found in the results from the two grip strengths, but the differences corresponded to less than 5% magnitude change at most frequencies.

Haasnoot and Mansfield [6] studied the effects of push, pull and grip force on perception of steering wheel rotational sinusoidal vibration. Only the test frequency of 125 Hz was compared with the reference frequency (63 Hz) to investigate the effects of grip forces. It was found that the annoyance level increased with increasing grip force. The estimated magnitudes for 20 N and 80 N grip force showed almost 30% difference. The test to analyze the effect of push/pull forces on the estimated magnitude revealed that different levels of push/pull forces did not significantly influence the estimated magnitude.

METHODS AND PROCEDURES

For the purpose of investigating the effect of grip force on annoyance, two equal annoyance contours were obtained for the longitudinal steering wheel vibration. One of the contours was obtained while the subject was applying a low level (20 N) grip force, and the other was obtained while the subject was applying a high level (70 N) grip force on the steering wheel. The curves were compared statistically with respect to grip force, vibration frequency, and gender effects on the annoyance response.

Test Apparatus

Ford Vehicle Vibration Simulator

The tests were conducted using the Ford Vehicle Vibration Simulator (VVS) (Figure 1). The vehicle vibration simulator consists of vibration of the vehicle seat (6 degrees of freedom), steering wheel (4 DOF), vehicle floorpan section (1 DOF), and the brake or accelerator pedal (1 DOF). The steering wheel can be actuated in three translational (vertical, lateral, longitudinal) directions and one rotational (about the steering wheel center) direction. Further technical details related to VVS can be found in [7]. Only the steering wheel module was actuated during the tests conducted in this study. Vibration excitation was only in the longitudinal direction. The longitudinal direction on the steering wheel was defined as the direction perpendicular to the steering wheel plane (toward subject’s body).

Steering Wheel Grip Force Measurement

In this study, the method proposed to measure and monitor the grip force on the steering wheel is the use of pressure sensors placed between the steering wheel surface and subject’s hand. Pressure sensing elements that are arranged in a matrix configuration have been used for ergonomic optimization of the design of vehicle seats [9]. The XSensor® X2 Pressure Mapping System was used to measure and control the grip force. The X2 system uses polymeric capacitive film sensors. A 1 mm thick custom-made pressure pad that consists of a matrix of 390 pressure sensors was used for measuring the immediate pressure distribution on the pad as frames. The effective sensing area of the pad is 180mm in height and 105mm in width. The software is capable of calculating and recording the average grip force based on the integral of the pressure distribution over the active area.

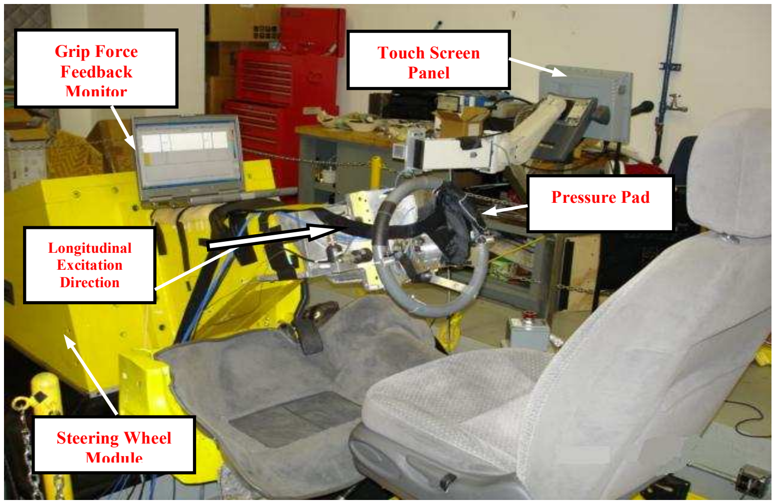

Figure 1 – Ford Vehicle Vibration Simulator and Experiment Setup

The pad was wrapped around the steering wheel at the 2 o'clock location to correspond with the right hand of the subject. The corresponding left hand side of the steering wheel was wrapped with duct tape to resemble the texture and feeling of the pressure pad under the left hand.

A laptop computer was placed in front of the subject to give feedback on the grip force. In the feedback screen, a color-coded bar is used. The target force level and the tolerance limits (as plus/minus deviations from the target) are determined by the experimenter before starting a particular segment of the experiment. A tolerance of ±5 N on the target grip force level was allowed. The middle section of the bar (green region) is the normal range that the subject is asked to stay in. If the subject moves outside the upper or lower tolerance limits, the color of the bar changes to warn the subject to readjust the grip force.

Participants

Fourteen (14) subjects (8 males and 6 females) participated in the experiments. All subjects were experienced drivers. None of the subjects had a previous occupation that required the use of vibrating tools or equipment for an extended period of time. The subject group consisted of Ford Motor Company employees and university students. Subjective information such as year of birth, weight, and height was recorded for each subject before the experiment. The descriptive statistics of the subject population are given in Table 1.

Test Signals

The frequency range of interest was 10-64 Hz. This is the frequency range for what is commonly known as steering wheel shake (10-30 Hz) and roughness (30-60 Hz) [1]. For all the tests, the 'reference' vibration signal was a pure sinusoidal with an amplitude of 1 m/s^2 r.m.s and a frequency of 25.5 Hz. Five discrete frequency points were used as 'test' frequencies (10, 16, 25.5, 40.5 and 64 Hz). These frequency points

Table 1. Descriptive statistics of subject population

	Mean	Standard Deviation	Minimum	Median	Maximum
Fourteen subjects					
Age (yrs)	40.4	10.8	24	39	58
Height (cm)	167.8	7.1	160	166	180
Weight (kg)	69.5	14.8	52	65	104

correspond to every other 1/3-octave band center frequency starting with 10 Hz. The reference frequency (25.5 Hz) corresponds to the center of the frequency range of interest.

Procedures

Five tests (one for each test frequency) were conducted at each grip force level for obtaining equal annoyance contours. The method of adjustment test procedure of psychophysics [3] was used for all equal annoyance tests. A touch screen window was used by the test administrator to control the vibration simulator (Figure 1). The window was composed of 12 buttons. Each button acted as a shortcut to activate a vibration signal on the simulator for four seconds. In this experiment, Button #1 was (always) the reference signal (1 m/s^2 at 25.5 Hz). All other buttons in a window played a test signal at the same frequency, but at different amplitudes. Buttons labeled 2 through 12 represented -15 dB to +15 dB versions of the test signal in 3 dB increments. A separate window was used for each test frequency.

During a typical test, the subject was given the 'reference signal' (1 m/s^2 at 25.5 Hz) for four seconds. The subject was asked to memorize the annoyance feeling that this vibration caused. Then, the subject was given a 'test signal' (at one of the test frequencies) for four seconds. The subject communicated with the test administrator by means of verbal cues such as "up" or "down" to request amplitude adjustment of the test signal. This process continued until the subject became certain that the annoyance of the selected test signal best matched the annoyance of the reference signal.

Five discrete frequency points were used as 'test' frequencies (10, 16, 25.5, 40.5 and 64 Hz). The order with which the test frequencies were presented to the subject was randomized. The subjects were required to grip the steering wheel with both hands during the tests. The tests for all the frequency points were conducted once while the subjects were gripping the steering wheel with low grip force level (20 N), and once while subjects were gripping the steering wheel with high grip force level (70 N). The grip force level that the subjects start the experiment was randomized. The test frequencies for each of the grip force level were also randomized within a subject. Two practice tests were conducted before the beginning of the tests at each grip force level. The test frequencies for the practice tests were 10 Hz and 40.5 Hz. In each test, the amplitude of the 'first' test signal presented to the subject was different from the amplitude of the reference signal (1 m/s^2). This was done to avoid any anticipation of the subject [3]. After each test, the subjects were given a one-minute break time to get some rest and relieve the constriction of the blood flow in the muscles due to contraction.

RESULTS

Figure 2 depicts the mean equal annoyance curves and standard deviations for each frequency and grip force level. A consistent increase in the acceleration values was observed for both grip force levels as the frequency increased. The slope of the contour in this frequency range translates into a decrease in annoyance at a rate of 6 dB per octave.

Analysis of Variance results indicated that the only significant effect on the amplitude selected by the subject was the frequency ($p<0.001$). The gender and steering wheel grip force did not have a significant effect on the annoyance response of this population ($p=0.624$ for both gender and grip force). Furthermore, none of the interactions was significant for $\alpha=0.05$ level.

Pairwise comparisons (Wilcoxon matched pairs signed-rank test) revealed that the acceleration levels selected at each frequency point were significantly different from each other ($\alpha=0.05$) for this frequency range. Only at 64 Hz, the annoyance responses of the male population at low and high grip force levels were significantly different from each other at $\alpha=0.1$ level ($p=0.063$). It was observed that the separation of the contours increased as the frequency increased for the male population. This suggests that a further investigation at higher frequency points (>64 Hz) may reveal statistically significant differences at $\alpha=0.05$ level.

A representation of the equal annoyance contours in velocity unit instead of acceleration revealed contours that are almost horizontal. This is expected due to the fact that a rate of –6 dB per octave in acceleration corresponds to constant velocity.

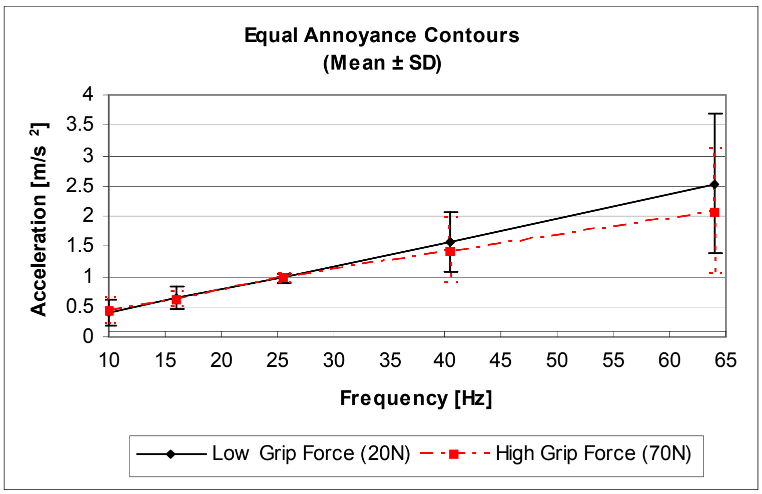

Figure 2. Mean equal annoyance contours for low and high grip force levels

DISCUSSION

The experiment results showed that frequency is the most important factor that determines the shape of the equal annoyance contours for steering wheel longitudinal vibration. In addition, the shape of the equal annoyance contours became almost horizontal when velocity was used, suggesting that the velocity is a more direct way to explain the annoyance response in this frequency range. The results of Giacomin *et al.* [5] (-6dB/octave slope in the frequency range of 6.3-50 Hz for rotational steering wheel vibration) and Amman *et al.* [1] (equal annoyance contours for longitudinal steering wheel vibration in the frequency range of 10-64 Hz) support the same conclusion.

It was observed that standard deviations increased as the distance in frequency between the reference and test frequencies increased in both directions. This is an indication of greater difficulty for the subjects to evaluate the test frequencies further away from the reference frequency. This fact was also emphasized by Miwa [8] and Giacomin *et al.* [5].

As Figure 3 indicates, the results obtained in this study were in good agreement with the results of Giacomin *et al.* [5] and Amman *et al*. [1]. It should be noted that the level difference between the contours is a result of different reference frequencies used in different experiments. Although Giacomin *et al.*'s equal sensation curve was obtained for 'rotational' steering wheel vibration, the slopes of the contours were very similar. The contour obtained by Amman *et al.* was somewhat closer to the contour obtained for high grip force level in this study. In Amman *et al.*'s study, the subjects were asked to grip the steering wheel with a force typical of what they would use during normal driving. An unpublished study conducted by the authors of the current paper revealed the fact that 70 N is approximately the mean grip force level applied by males in everyday driving conditions. The subject population in Amman *et al.*'s experiment was dominantly male. This may explain why the contour obtained by Amman *et al.* was closer to the contour obtained for high grip force level in this study.

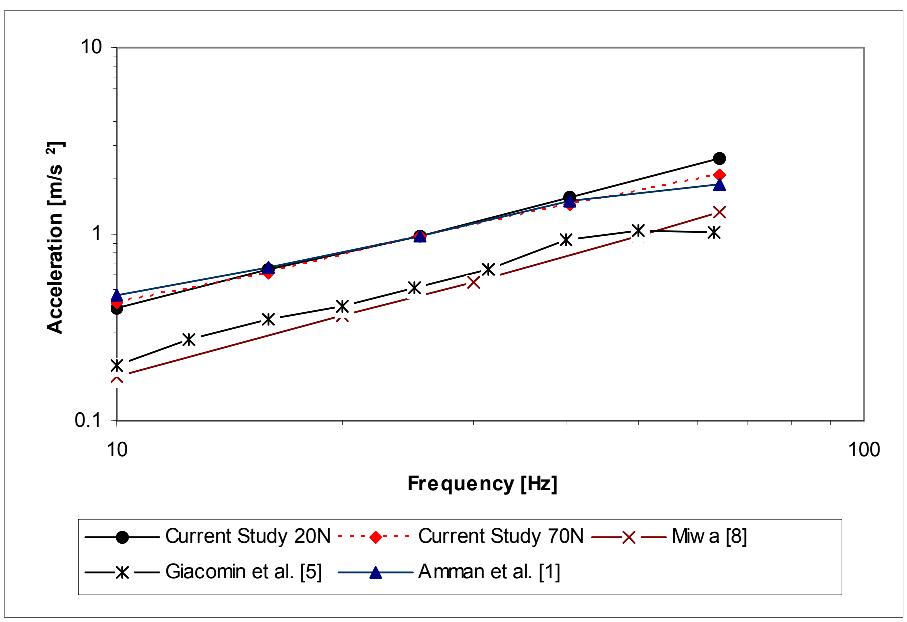

Figure 3. A comparison of equal annoyance contours

Figure 3 also depicts the comparison between the equal annoyance contours obtained in this study, and equal sensation contours obtained by Miwa [8]. The contour obtained by Miwa in the vertical direction (towards the subjects' forearm) was used for comparison. Despite the vast differences in the experimental settings, the contours were in very good agreement. Also in agreement with the results of this study is that, in Miwa's study, the shape of the contours did not change drastically whether 5 kg or 10 kg pressure applied on the plate.

CONCLUSIONS AND RECOMMENDATIONS

In this study, equal annoyance contours for longitudinal steering wheel vibration were obtained for two steering wheel grip force levels. It was seen that the vibration frequency is the dominant factor that determined the annoyance response characteristic of drivers. It is concluded that, limited to longitudinal steering wheel vibration in the 10-64 Hz frequency range, the effects of grip force and gender factors on steering wheel vibration discomfort may be ignored.

A new procedure to measure and control grip force on the steering wheel was presented in this study. This procedure is believed to be beneficial to other investigators who are, for any reason, interested in quantifying the steering wheel grip force in laboratory settings or in real life driving conditions.

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