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Non-linear dependency of the subjective perceived intensity of steering wheel rotational vibration

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Abstract

The present study has established equal sensation curves for steering wheel hand-arm rotational vibration. Psychophysical response tests of 20 participants were performed in a steering wheel rotational vibration simulator using the category-ratio Borg CR10 scale procedure for direct estimation of perceived vibration intensity. The test stimuli used were sinusoidal vibrations at 22 third octave band centre frequencies in the range from 3 to 400 Hz, with acceleration amplitudes in the range from 0.06 to 30 m/s^2 r.m.s. A multivariate regression analysis was performed on the mean perceived intensity Borg CR10 values as a function of the two independent parameters of the vibration frequency and amplitude. The results suggested a nonlinear dependency of the subjective perceived intensity on both the steering wheel rotational vibration frequency and amplitude. The equal sensation curves were found to be characterised by a decreased sensitivity to hand-arm vibration with increasing frequency from 10 to 400 Hz, but by an increased sensitivity with increasing frequency from 4 to 10 Hz. A 6th order polynomial model has been proposed as a best fit regression model from which the equal sensation curves for steering wheel rotational vibration are derived.

Relevance to industry. For the manufactures of automobiles, steering systems and other automobile components this study provides a mathematical model from which one or more new frequency weightings for the use in evaluating the perceived intensity of steering wheel rotational vibration are derived.

Keywords: Vibration; Perception; Hand-Arm; Weighting; Steering; Automobile

1 Introduction

Automobile drivers are continuously exposed to vibrational stimuli. Of the vibrating surfaces to which drivers are exposed, the steering (Pak et al., 1991) is particularly important due to the sensitivity of the skin tactile receptors of the hand (Gescheider et al., 2004) and due to the lack of intermediate structures such as shoes or clothing which can attenuate vibration. During driving, steering wheel power spectral densities can reach frequencies of up to 350 Hz with vibrational energy mostly present in the range between 10 and 60 Hz (Fujikawa, 1998). They are typically characterised by low frequency excitation in the range from 8 to 20 Hz due to 1st order tyre non-uniformity forces and tyre-wheel unbalance, and due to 2nd order engine and mechanical unbalance in the frequency range from 20 to 200 Hz during engine idle (Ajovalasit and Giacomin, 2003).

The human subjective response to hand-arm vibration caused by the automotive steering wheel has been found to depend on factors such as the amplitude modulation of the waveform (Ajovalasit and Giacomin, 2005), the frequency bandwidth contained in the steering wheel vibration (Woo and Giacomin, 2006), and the repetition rate of transient events caused by the road surface irregularities (Giacomin and Berber-Solano, 2006).

Most psychophysical hand-arm vibration research has been performed using different types of handle in order to develop equal sensation curves whose shape describes the combinations of frequency and amplitude that give rise to judgments of equal subjective perceived intensity. Miwa (1967) performed equal sensation and annoyance threshold tests using a paired comparison method (Gescheider, 1997) for 10 test participants who held their palm flat against a plate which was vibrated in either the vertical or horizontal directions using a reference frequency of 20 Hz. Miwa’s studies established three equal sensation curves at the three acceleration amplitudes of 0.31, 3.1 and 31.1 m/s^2 r.m.s over the frequency range from 2 to 300 Hz. When plotted in terms of acceleration amplitude, human subjective response was found to decrease monotonically as a function of frequency. Reynolds et al. (1977) performed perception, annoyance and equal sensation tests using the method of adjustment for eight test participants who gripped a handle with one hand which was vibrated in either the vertical, axial or horizontal directions using a reference frequency of 100 Hz. The study established three equal sensation curves at the three acceleration amplitudes of 1.0, 10.0 and 50.0 m/s^2 r.m.s. over the frequency range from 16 to 1000 Hz. The three curves suggested a nonlinear acceleration dependency of the perceived intensity of hand-arm vibration and a general trend of reduced sensitivity with increasing frequency.

Giacomin et al. (2004) established equal sensation curves using the method of adjustment for 15 test participants who held a rigid rotating steering wheel with both hands. The study used a reference frequency of 63 Hz at acceleration amplitudes of 1.0 and 1.5 m/s^2 r.m.s. over the frequency range from 3 to 400 Hz. All the equal sensation curves were found to be similar in shape. A constant acceleration dependency was noted from 3 to 5 Hz and a decrease in the human sensitivity to hand-arm rotational vibration was found with increasing frequency from 5 to 315 Hz. The slope of the equal sensation curves presented two transition points at about 6.3 and 63 Hz.

Amman et al. (2005) have recently established equal sensation curves for hand-arm vibration using the method of adjustment for 28 test participants who held an automotive steering wheel with both hands. The study used a reference frequency of 25.5 Hz and acceleration amplitude of 1.0 m/s^2 r.m.s. in the three translational directions over the frequency range from 8 to 64 Hz, and used a reference frequency of 14 Hz at two acceleration amplitudes of 0.8 and 1.6 m/s^2 r.m.s in the rotational direction over the frequency range from 8 to 20 Hz. Amman et al’s equal sensation curves showed a general trend of decreasing sensitivity to vibration with increasing frequency.

Morioka and Griffin (2006) have determined perception thresholds and equal sensation curves using the psychophysical method of magnitude estimation (Gescheider, 1997) for 12 test participants who gripped a cylindrical handle with one hand which was vibrated in either the vertical, axial or horizontal directions. At suprathreshold levels, the human sensitivity to hand-arm vibration was found to be highly dependent on vibration magnitude. At high acceleration magnitudes greater than about 2.0 m/s^2 r.m.s., the equal sensation curves suggested a decreased sensitivity to hand-arm vibration with increasing frequency from 8 to 400 Hz. At lower acceleration magnitudes, the curves suggested instead an increased sensitivity to vibration magnitude with increasing frequency from 20 to 100 Hz. At all vibration magnitudes, the curves suggested decreased sensitivity with increasing frequency from 8 to 16 Hz.

The equal sensation curves developed by Miwa and other researchers have contributed to the definition of the Wh frequency weighting which is currently used in both International Organisation for Standardization 5349-1 (2001) and British Standards Institution 6842 (1987). The Wh weighting was primarily defined for use in measuring and reporting hand-arm exposures for the purpose of quantifying health effects and risk of injury over the frequency range 8 to 1000 Hz. As the only available frequency weighting for the hand-arm system, Wh has often be applied to the evaluation of the perception of hand-arm vibration. Several criticisms have been raised, however, regarding the use of Wh for modeling the human perception of vibration at magnitudes lower than the vibration exposure limits or in the case of vibration having significant energy below 8 Hz or above 1000 Hz. Studies on the subjective response to hand-arm vibration (Neely et al., 2001) have suggested that the Wh frequency weighting underestimates the perceived intensity of hand-arm vibration. Further, in the steering application, it is not obvious whether Wh is appropriate in the case of steering wheel rotation. Giacomin et al. (2004) have proposed a new hand-arm frequency weighting for steering wheel rotational vibration, called Ws, which presents significant differences with respect to the Wh weighting at low (3 to 6.3 Hz), intermediate (6.3 to 50 Hz) and high (above 50 Hz) frequencies. An important difference is the higher human sensitivity to hand-arm vibration indicated by Ws at frequencies below 6.3 Hz, and the constant velocity weighting from 6.3 to 50 Hz as opposed to the constant acceleration weighting from 8 to 16 Hz of Wh. The constant velocity contour of Ws has been found to be in agreement with the equal sensation curves for steering wheel rotational vibration developed by Amman et al. (2005) which suggested a constant velocity weighting in the frequency range from 8 to 20 Hz.

A recent study by Gnanasekaran et al. (2006) has evaluated the correlation between the weighted acceleration obtainable when applying the Wh or Ws weightings and the subjective perceived intensity responses provided by test participants for eight different types of steering vibration stimuli. Human subjective responses were quantified by means of the psychophysical method of the category-ratio Borg CR10 scale (Borg, 1998), which has been found to be reliable in quantifying the human perception of hand-arm vibration, with reliability coefficients ranging from 0.841 to 0.986 (Wos et al., 1988). The data suggested that the Ws weighting provided a slightly better correlation than the Wh weighting.

The research presented in this paper was performed to investigate the effect of vibration frequency and magnitude on the human perception of rotational hand-arm vibration. The objective was to establish a family of equal sensation curves for different perceived intensities of steering wheel rotational vibration.

2 Materials and methods

2.1 Test facility

Figure 1 presents a schematic representation of the steering wheel test rig adopted in this study and of the associated signal conditioning and data acquisition systems. The main geometric dimensions of the test rig, which were based on average data taken from a small European automobile, are presented in Table 1. The rotational steering system consisted of a rigid 325 mm diameter aluminum wheel connected to a steel shaft which was mounted onto two precision bearings which were encased in a square steel casing. The steering wheel consisted of a 5 mm thick central plate with 3 mm thick cylinders welded at the extremities. The steering wheel was made of aluminium in order to obtain a first natural frequency greater than 350 Hz. The use of a rigid steering wheel guaranteed that no vibration attenuation occurred before reaching the hand-arm system. Rotational vibration was applied by means of a G&W V20 electrodynamic shaker, which was connected to the shaft by means of a steel stinger rod, and which was driven by a PA100 amplifier (Gearing and Watson Electronics Limited, 1995). Vibration control and data acquisition were performed by means of LMS Cada-X 3.5 E software and a 12-channel Difa Systems Scadas III front-end unit (LMS International, 2002). The acceleration obtained at the steering wheel was measured using an Entran EGAS-FS-25 accelerometer located on the top left side of the wheel, and amplified by means of an Entran MSC6 signal-conditioning unit (Entran Devices Inc, 1991). The acceleration was measured in the tangential direction. The car seat was fully adjustable in terms of horizontal position and back-rest inclination as in the original vehicle. The safety features of the test rig, and the acceleration levels used, conform to the health and safety recommendations outlined by British Standards Institution 7085 (1989).

[Insert here Figure 1]
[Insert here Table 1]

2.2 Test stimuli

The frequency range of the sinusoidal test stimuli was chosen to be from 3 to 400 Hz which, based on previous research (Ajovalasit and Giacomin, 2003, Fujikawa, 1998, Giacomin et al., 2004), appears to be the frequency range in which road vehicles present significant levels of steering wheel vibration. The maximum stroke of the test rig shaker unit (±25mm) limited the maximum achievable acceleration at the steering wheel which, in turn, limited the minimum test frequency to 3 Hz. For frequencies lower than approximately 3 Hz, accurate sinusoidal acceleration signals could not be achieved at the rigid wheel. The test frequencies for the study were therefore chosen to be 1/3 octave band center frequencies in the range from 3 to 400 Hz (i.e. 3, 4, 5, 6.3, 8, 10, 12.5, 16, 20, 25, 31.5, 40, 50, 63, 80, 100, 125, 160, 200, 250, 315 and 400 Hz). A total of 78 acceleration magnitudes in the range from 0.06 to 30 m/s^2 r.m.s. were chosen as test amplitudes so as to cover a grid of uniformly spaced magnitudes over the frequency range from 3 to 400 Hz from which the equal sensation curves were derived. The 78 vibration stimuli used in the experiment are listed in Table 2.

[Insert here Table 2]

2.3 Test protocol

A total of 20 university students and staff participated in the experiment. A consent form and a short questionnaire was presented to each prior to testing, and information was gathered regarding their anthropometry, health, driving experience and history of previous vibration exposures. The participants consisted of 12 males and 8 females, aged from 21 to 45 years with a mean value of 27.8 years. Height ranged from 1.50 to 1.92 meters with a mean value of 1.76 meters. Weight ranged from 46 to 100 kg with a mean value of 74.4 kg. All participants had more than one year of driving experience, and declared themselves to be in good physical and mental health.

Before commencing testing, each participant was required to remove any heavy clothes such as coats, and to remove any watches or jewelry. They were then asked to adjust the seat position and backrest angle so as to simulate a driving posture as realistically as possible. Since grip type and grip strength (Reynolds and Keith, 1977) are known to effect the transmission of vibration to the hand-arm system, the participants were asked to maintain a constant palm grip on the steering wheel using both hands. In addition, they were asked to maintain the grip strength which they felt they would use when driving on a winding country road. The participants were also asked to wear ear protectors to avoid any auditory cues. The psychophysical method of the category-ratio Borg CR10 scale (Borg, 1998), shown in Figure 2, was used to provide direct estimation of the perceived vibration intensity. The information describing the experiment was presented to the test participant by the experimenter using the instruction provided by Borg (Borg, 1998) for the scale's administration. The test participants were further asked to judge each test stimuli on its own merits, independent of preceding stimuli, in order to avoid possible bias due to the order of presentation of the stimuli (Gescheider, 1997). The test participants were asked to focus their eyes on a board which was placed about 1 meter ahead at eye level, which presented the Borg rating scale. Before starting the experiment, two trial runs were performed so as to familiarize the participants with the test procedure.

In order to assess the individual's ability to rate stimuli, all the 78 stimuli were repeated three times in three single blocks, for a total of 234 assessment trials for each test participant. In order to minimize any possible bias resulting from learning or fatigue effects the order of presentation of the test signals was randomized for each participant and for each block. A break of 3 minutes after the presentation of each block was used to reduce annoyance effects. All the stimuli had the same time duration of 10 seconds. A 10 second stimulus duration was used so as to provide a stimulus which remained within human short-term memory (Sinclair and Burton 1996), thus one which could be judged without reliance upon the long-term storage of stimuli information by the test participant. A complete test required approximately 60 minutes to complete. Room temperature was maintained within the range from 20 to 25 °C so as to reduce effects on skin sensitivity (ISO13091-1, 2001).

[Insert here Figure 2]

2.4 Multivariate regression analysis

Mean Borg CR10 subjective intensity values were determined for each of the 78 combinations of frequency and amplitude tested. A multivariate linear regression analysis based on a least-squares fit method (Draper and Smith, 1981) was then used to establish a mathematical model to express the Borg CR10 subjective intensity as a function of the two independent variables of frequency and magnitude. A linear fitting procedure was chosen since nonlinear fitting methods often suffer from convergence problems (Mathworks Inc., 2002). A multivariate linear regression model was applied to the set of n linear algebraic equations of the general form:

$$\hat{z}_i = a_0 p_0 + a_1 p_1 + a_2 p_2 + a_3 p_1 p_2 + ... + a_m p_m \quad (i = 1,\dots n) \qquad (1)$$

where $\hat{z}_i$ is the Borg value which is determined by the fitted model, $a_0, a_1,...a_m$ are the m+1 unknown coefficients estimated by means of least-squares regression, $p_0, p_1,... p_m$ are the m+1 different polynomial terms of the independent variables of frequency and magnitude and n is the number of data points. The regression coefficients of the model were determined using the MATLAB software environment (Mathworks Inc., 2002) by means of a Singular Value Decomposition (SVD) technique.

The selection criteria for choosing an optimal model were taken to be the following (a) the fitted model should produce the highest goodness-of fit as defined by the coefficient of determination r^2 (Draper and Smith, 1981) and by the smallest residual mean-square-error (MSE), (b) the equal sensation curves which can be determined using the regression model should present similar frequency dependency characteristics to those published by previous studies on the physiology of vibro-tactile perception, and (c) the fitted mathematical equation should be as simple a model as possible in light of possible practical application.

A baseline value of the coefficient of determination, r^2, equal or greater than 0.95 was chosen for use in the model selection, following the recommendations of Draper and Smith (1981). A baseline value of the residual MSE of 0.5 was chosen based on the just-noticeable value of the Borg CR10 scale, which in the case of Borg CR10 rated hand-arm vibration is approximately 0.3 (Neely et al., 2001).

As not every independent variable term in the regression equation is expected to have the same effect on the dependent variable, various combinations of multivariate polynomial expression were analysed which differed in (I) the use of either a linear or a logarithmic form for the independent variable, (II) the order of the polynomial, (III) the number of regression coefficients included in the equation, and (IV) the type of polynomial term included in the equation (i.e. single terms versus interaction terms whereby single terms are multiplied together).

3 Results

3.1 Effect of polynomial variable type and polynomial order

In order to identify which type of parameter variable and polynomial order should be present in the regression equation, the goodness-of-fit statistics were evaluated for different orders of a full polynomial model containing all the possible terms (single terms and interaction terms) in either the linear or the logarithmic form. Table 3 presents the goodness-of-fit statistics in terms of the residual MSE and the coefficient of determination, r^2, obtained for different polynomial orders. The data suggest that, for all the polynomial models from 1st to 8th order used in this study, a logarithmic form for both the frequency and acceleration variables produced lower mean-square-error values and higher coefficients of determination than a linear or a semi-logarithmic form. Further, the goodness-of-fit statistics for lower polynomials of up to 3rd order indicate a poor fit, as did the use of polynomial orders greater than 7th. A useful model was achieved using a 6th order polynomial, expressed in logarithmic form for both frequency and acceleration. In the case of this model the coefficient of determination was found to be 0.97 and the mean-square error was 0.32.

[Insert here Table 3]

Figure 3 presents the equal sensation curves of constant perceived intensity obtained using full polynomial models of 4th, 5th and 6th order when expressed in linear, semi-logarithmic and logarithmic form for the independent variables of frequency and acceleration. For a fixed Borg CR10 value of perceived intensity, the equal sensation curve was determined by expressing the combination of the r.m.s. acceleration amplitude and of the frequency which determined the same Borg value. For the parameter range from 3 to 400 Hz and from 0.06 to 30 m/s^2 r.m.s. used in this study, the observed Borg CR10 perceived intensity of steering wheel rotational vibration varried from approximately 0.5 to 8.0. As suggested by the data of Figure 3, the use of a logarithmic transformation for both the frequency and acceleration values provided a more accurate description of the physical phenomena contained in the dataset across all polynomial orders. A key indicator of the more realistic behaviour being the dip contours of the equal sensation curves in the vicinity of both 10 and 100 Hz.

[Insert here Figure 3]

3.2 Effects of single terms, interaction terms and number of regression coefficients

In order to identify which type of term should be present in the regression equation, the goodness-of-fit statistics were evaluated for each polynomial regression expression determined by adding progressively to the equation each possible term of the underlying order of the polynomial. Regression equations using polynomial orders up to the 6th were considered since the use of higher order polynomials did not provide any useful model. In addition, both the frequency and acceleration values were considered only in terms of their logarithmically transformed values since this representation resulted in better fits than either the linear or semi-logarithmic forms.

In order to assess the effects of single regression terms on the goodness-of-fit of the model, regression analysis was performed by including one at a time only single terms into the equation without any interaction terms. For all possible polynomial equations, the evaluated goodness-of-fit statistics of the regression model indicated a poor fit, meaning high residual MSE values ranging from 0.93 to 2.05 and a low coefficient of determination ranging from 0.79 to 0.86. The goodness-of-fit statistics suggested that the use of only single terms in the regression equation did not provide the highest possible predictive accuracy.

In order to assess the effects of interaction terms, regression analysis was performed by including one at a time each interaction term up to the maximum power of the underlying order of the polynomial, while simultaneously maintaining all the single terms in the equation. Table 4 presents the number of coefficients estimated for the 4th, 5th and 6th order polynomials along with the residual MSE values and the coefficient of determination. The designation INT3 in Table 4 indicates, for example, the polynomial equation obtained by adding the interaction terms up to the 3rd power. The data suggest that for polynomials greater than the fourth-order, decreasing the number of interaction terms, and thus the number of regression coefficients included in the polynomial equation, slightly lowered the values of the residual MSE. In particular, the lowest MSE value of 0.29 was obtained for the 6th order polynomial model obtained by adding interaction terms up to the 4th power (INT4).

[Insert here Table 4]

Figure 4 presents the equal sensation curves obtained for the 4th, 5th and 6th order polynomial regression models by including progressively the interaction terms. All curves suggest that increasing the order of the polynomial equation from 4th to 6th produces a more pronounced dip behaviour at approximately 10 and 100 Hz at low perceived intensities from 0.5 (just noticeable) to 2.0 (weak) Borg. As the perceived intensity increases towards the maximum value of 8.0 of the Borg scale, the equal sensation curves assume a flatter and more linear shape for frequencies between 40 and 400 Hz. The curves of Figure 4 suggest that the use of polynomial equations of order higher than the 4th produces equal sensation curves which closely resemble the frequency dependency of the human subjective response to hand-arm vibration as found in the existing scientific literature.

[Insert here Figure 4]

3.3 Choice of an optimal model

In order to identify an optimal model, a validation procedure was used which was based on a leave-one-out cross validation method (Bates et al., 2000). The method involves re-fitting a selected equation to a subset of data points consisting of all observed data expect one chosen as a validation data point, and then subsequently predicting the value of the validation data point which was left out when performing the regression fit. The measure of the accuracy of the fitted model was taken to be the root-mean-square-error (RMSE) which is defined for the leave-one-out method as:

$$RMSE = \sqrt{\frac{1}{s}\sum_{i=1}^{s}\left[\hat{v}_i - v_i\right]^2} \qquad (2)$$

where s is the number of data points chosen as a validation dataset, v_i is the observed Borg CR10 intensity value of the ith validation point, and $\hat{v}_i$ is the estimate of the Borg CR10 intensity value obtained when all the data points are used to perform the regression fit except the validation point v_i.

Table 5 presents the root-mean-square-error obtained for each type of polynomial equation when using a subset of eight validation data points. The validation points consisted of the eight frequency values of 4, 10, 31.5, 63, 160, 200, 250, 400 with the respective acceleration levels of 1.17, 3.52, 2.74, 1.27, 0.12, 0.46, 11.71, 2.68 m/s^2 r.m.s. The data suggest that a 6th order polynomial, which included interaction terms up to the 5th power in logarithmic co-ordinates for both frequency and acceleration, achieved the lowest root-mean-square-error value (0.37). The best-fit equation was found to be:

$$\begin{aligned} Z = {} & 23.014 - 48.602\log(X) + 1.525\log(Y) + 46.920\log(X)^2 + 0.667\log(X)\log(Y) + 0.177\log(Y)^2 - 21.702\log(X)^3 + \\ & - 0.025\log(X)\log(Y)^2 - 0.209\log(X)^2\log(Y) - 0.094\log(Y)^3 + 5.131\log(X)^4 + 0.038\log(X)\log(Y)^3 + \\ & + 0.028\log(X)^2\log(Y)^2 - 0.015\log(X)^3\log(Y) + 0.008\log(Y)^4 - 0.601\log(X)^5 - 0.004\log(X)\log(Y)^4 + \\ & - 0.005\log(X)^2\log(Y)^3 - 0.004\log(X)^3\log(Y)^2 + 0.005\log(X)^4\log(Y) + 0.006\log(Y)^5 + 0.026\log(X)^6 + 0.00001\log(Y)^6. \end{aligned} \tag{3}$$

Where Z is the estimate of perceived intensity of the steering wheel vibration, X is the vibration frequency and Y is the vibration amplitude.

[Insert here Table 5]

4 Discussion

Considering the effect of the independent parameter of the vibration frequency, the equal sensation curves suggested a decreased sensitivity to hand-arm vibration with increasing frequency from 10 to 400 Hz, but an increased sensitivity to hand-arm vibration with increasing frequency from 4 to 10 Hz. Considering instead the effect of the independent parameter of the vibration amplitude, the equal sensation curves were found to behave in a manner which is analogous to the behaviour of the well-known equal loudness contours for hearing (Zwicker and Fastl, 1990), with the curves becoming flatter and more linear with increases in the vibration amplitude.

The equal sensation curves of the current study suggest a nonlinear dependency on both the frequency and the amplitude of the test stimulus. At low perceived intensities from 0.5 (just noticeable) to 1.0 (very weak) of Borg CR10 scale, the equal sensation curves were found to resemble the general shape of the vibrotactile perception threshold curves of the hand (Gescheider et al., 2004). As the perceived intensity increased towards the maximum value of 8.0 found in the current study, the equal sensation curves assume a more uniform shape, resembling the annoyance threshold for the hand-arm system defined by Reynolds et al. (1977).

The higher human sensitivity to vibration indicated by the equal sensation curves at about 10 Hz may be explained in terms of the acceleration transmissibility properties of the human hand-arm system. At low frequencies from 6.3 to 20 Hz, studies by Pyykkö et al. (1976) have reported large resonances of the hand, which cause the hand-arm system to operate as an amplifier. Instead, for frequencies above 10 Hz, studies by Reynolds and Angevine (1977) have shown that acceleration transmissibility drops sharply above 10 Hz due to a mechanical decoupling of the upper arm and shoulder from the vibration source.

Figure 5 presents the best fit equal sensation regression curves determined in the current study using the 6th order polynomial with interaction terms up to the 5th power (INT5), the results of Miwa (1967) for hand-arm vertical direction, the results of Reynolds et al. (1977) for hand-arm axial direction and the results of Amman et al. (2005) for steering wheel rotational vibration. Comparison of the results of the various investigations suggests that while the curves of Miwa and of Amman et al. suggest relatively small dependencies on the vibration amplitude, the equal sensation curves of the current study and those of Reynolds et al. suggests a significant nonlinear response. A possible explanation of these differences may be the use of relatively low reference frequencies of 14 Hz and 20 Hz in the studies of Amman et al. and of Miwa, respectively. The use of a low reference frequency has been found to affect the shape of equal sensation curves, especially at frequencies above approximately 50 Hz (Giacomin et al., 2004).

[Insert here Figure 5]

Figure 6 presents the best fit equal sensation regression curves determined in the current study, the results of Giacomin et al. (2004) and Amman et al. (2005). All data in Figure 6 are therefore relative to the perception of rotational steering wheel vibration as might occur when driving an automobile. Figure 6 suggests that the equal sensation curves of the current study compare favorably with the curves for rotational vibration of Giacomin et al. and with the curves for the vertical and rotational steering wheel vibration obtained by Amman et al.

An important difference between the equal sensation curves of the current study and those obtained by Giacomin et al. in their 2004 study can be noted at low frequencies below 10 Hz and at high frequencies above 50 Hz. A possible explanation for the differences may lie in the artifacts caused by the regression analysis performed in the two studies. While Giacomin et al. used a regression analysis over three different segments in the frequency range from 3 to 6.3 Hz, from 6.3 to 50 Hz, and from 50 to 315 Hz, the current study used a global regression analysis over the entire frequency range from 3 to 400 Hz.

[Insert here Figure 6]

Finally, observation of the equal sensation curves obtained in this and previous research investigations suggests the possible usefulness of developing more than one frequency weighting for hand-arm vibration. Given the wide range of vibration amplitudes which occur in some work environments, it may prove useful to have a range of weightings available, in analogy to what routinely occurs in acoustic applications.

5 Conclusions

Equal sensation curves for steering wheel hand-arm rotational vibration were established using a multivariate regression analysis. Psychophysical response tests of 20 participants were performed in a steering wheel rotational vibration simulator using the category-ratio Borg CR10 scale procedure for direct estimation of perceived vibration intensity. The results suggested a nonlinear dependency of the subjective perceived intensity on both the steering wheel rotational vibration frequency and amplitude. The equal sensation curves were found to be characterised by a decreased sensitivity to hand-arm vibration with increasing frequency from 10 to 400 Hz, but by an increased sensitivity with increasing frequency from 4 to 10 Hz. A 6th order polynomial model expressed in logarithmic form for both vibration frequency and amplitude has been proposed as a best fit regression model from which the equal sensation curves for steering wheel rotational vibration were derived.

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Figure 1) Schematic representation of the steering wheel rotational vibration test rig and associated electronics.

Figure 2) Borg's category ratio CR-10 scale (adapted from Borg 1998).

Figure 3) Effects of variable type and of polynomial order used on the equal sensation curves. X denotes frequency variable, Y denotes r.m.s. acceleration variable. Each of the equal sensation curves represents a curve of equal subjective perceived Borg intensity values from 0.5 to 8.0.

Figure 4) Effects of interaction terms on the equal sensation curves for (a) 4th order, (b) 5th order and (c) 6th order polynomial regression model. Each of the equal sensation curves represents a curve of equal subjective perceived Borg intensity values from 0.5 to 8.0.

Figure 5) Comparisons between the equal sensation curves obtained in the current study and in previous studies of hand-arm translational or rotational vibration.

Figure 6) Comparisons between the equal sensation curves obtained in the current study and in previous studies of hand-arm rotational vibration.

Table 1) Geometric dimensions of the steering wheel rotational vibration test rig.

Table 2) Test stimuli used in the subjective rating test to establish the equal sensation curves using a combination of 22 third octave frequencies ranging from 3 to 400 Hz and 78 acceleration amplitudes ranging from 0.06 to 30 m/s^2 r.m.s.

Table 3) Global statistics of the goodness-of-fit in terms of the residual mean-square-error (MSE) and the coefficient of determination r^2 for the regression models fitted when using both linear and logarithmic variables.

Table 4) Global statistics of the goodness-of-fit in terms of the residual mean-square-error (MSE) and the coefficient of determination r^2 for the regression models fitted when including only interaction terms and using the logarithmic operator.

Table 5) Root-mean-square error values determined to measure the accuracy of the fitted models.

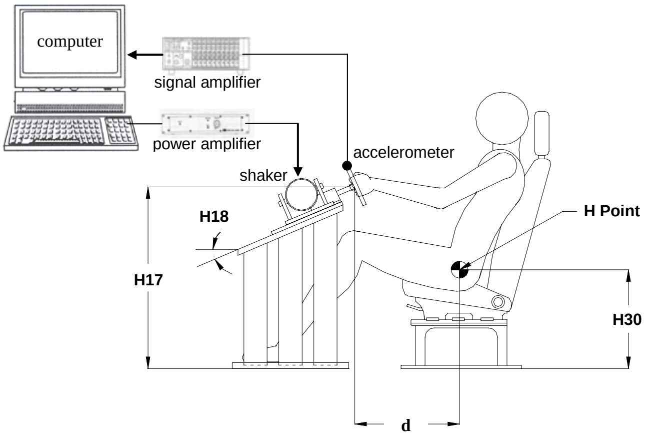
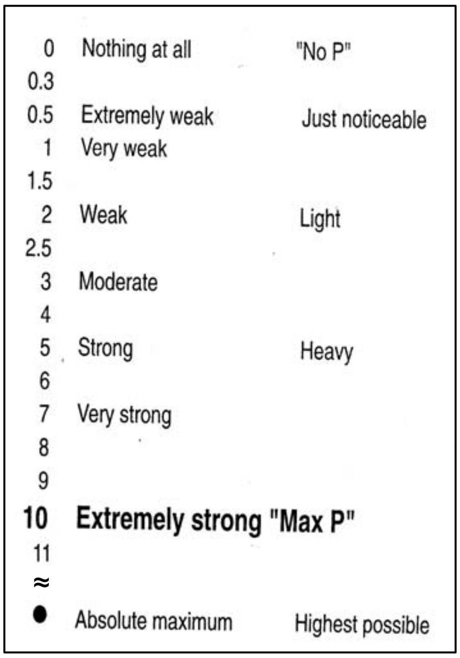


Figure 1) Schematic representation of the steering wheel rotational vibration test rig and associated electronics.



0	Nothing at all	"No P"
0.3		
0.5	Extremely weak	Just noticeable
1	Very weak	
1.5		
2	Weak	Light
2.5		
3	Moderate	
4		
5	Strong	Heavy
6		
7	Very strong	
8		
9		
10	**Extremely strong "Max P"**	
11		
≈		
●	Absolute maximum	Highest possible

Figure 2) Borg's category ratio CR-10 scale (adapted from Borg 1998).

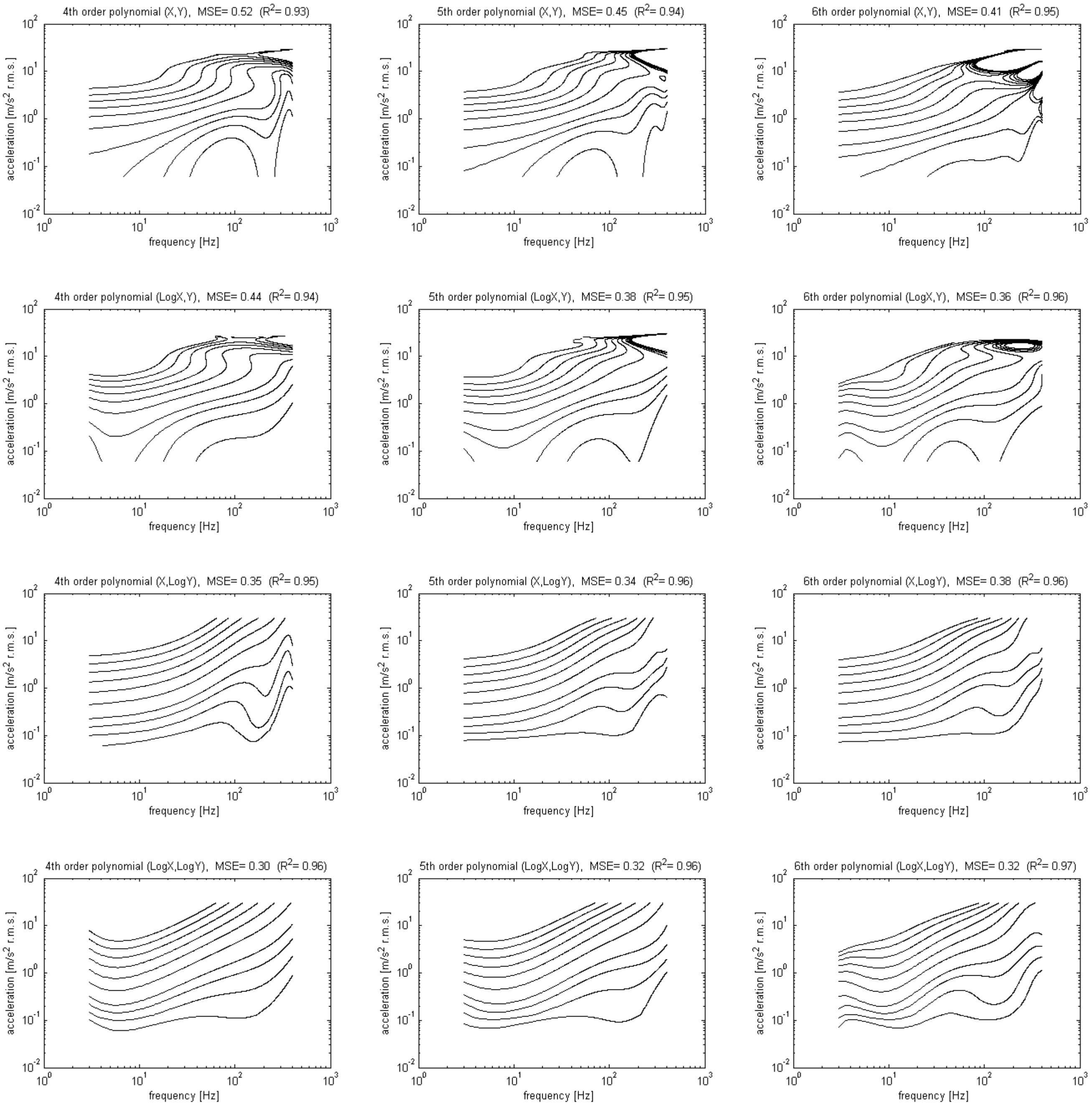


Figure 3) Effects of variable type and of polynomial order used on the equal sensation curves. X denotes frequency variable, Y denotes r.m.s. acceleration variable. Each of the equal sensation curves represents a curve of equal subjective perceived Borg intensity values from 0.5 to 8.0.

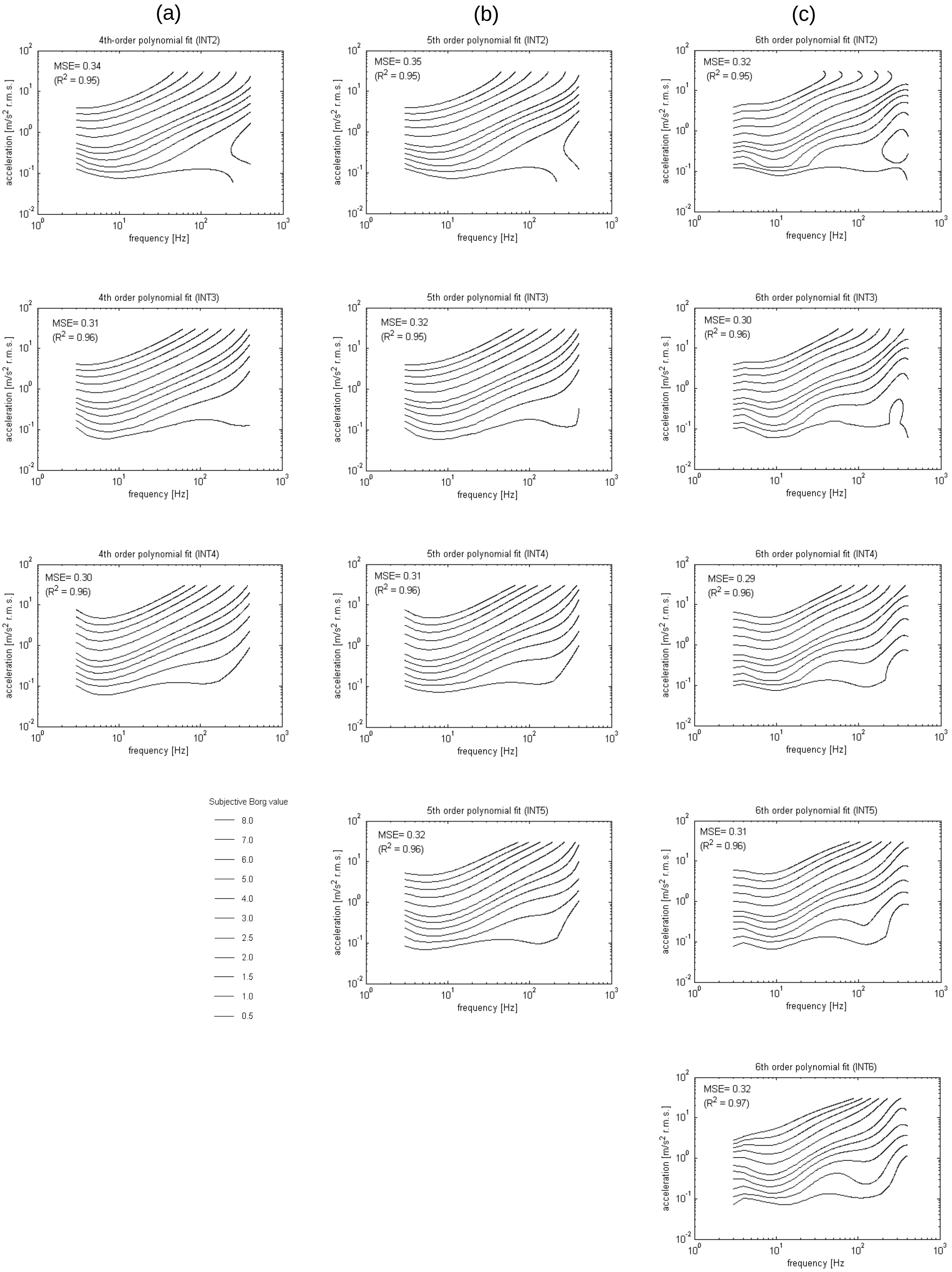


Figure 4) Effects of interaction terms on the equal sensation curves for (a) 4th order, (b) 5th order and (c) 6th order polynomial regression model. Each of the equal sensation curves represents a curve of equal subjective perceived Borg intensity values from 0.5 to 8.0.

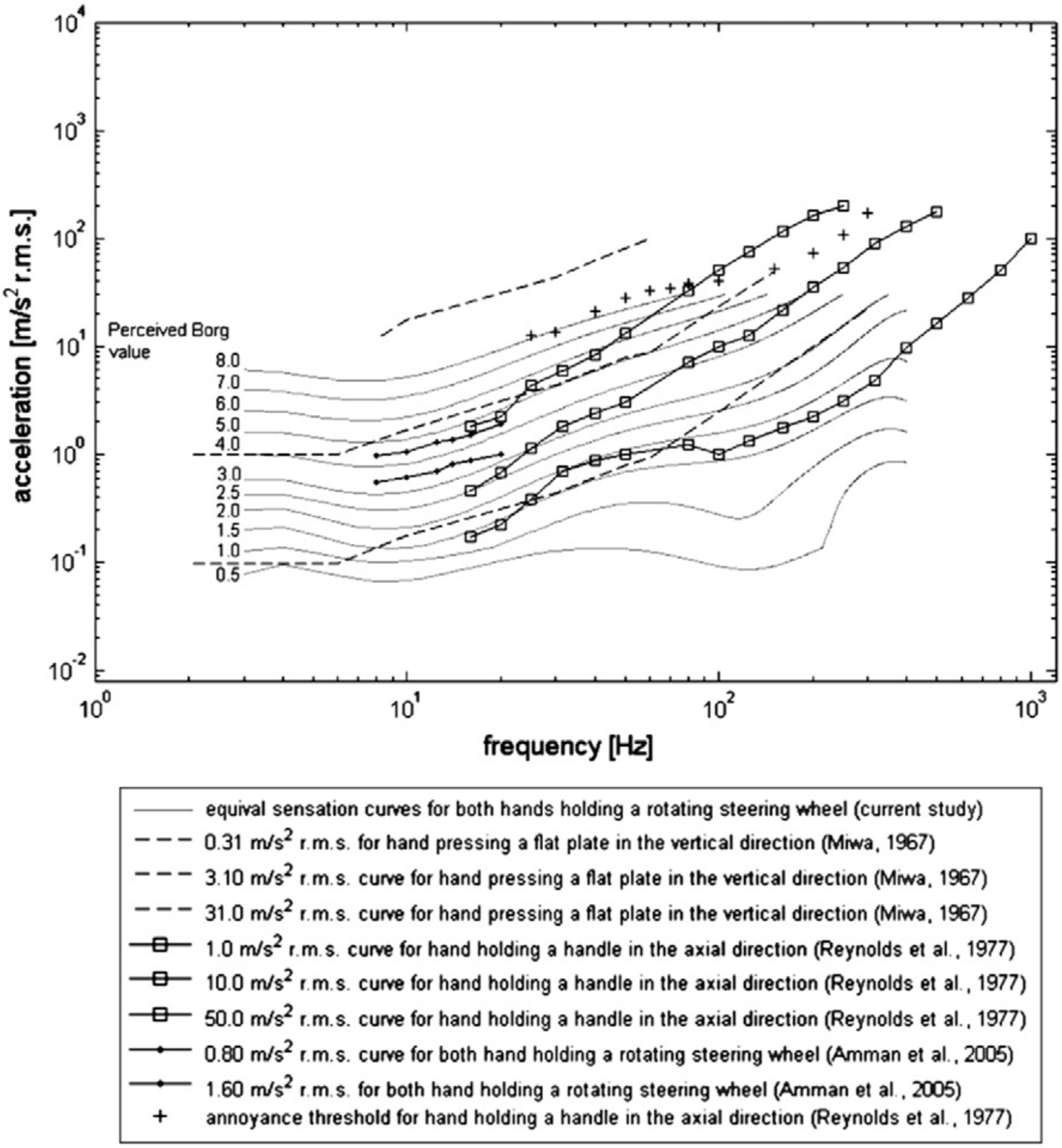


Figure 5) Comparisons between the equal sensation curves obtained in the current study and in previous studies of hand-arm translational or rotational vibration.

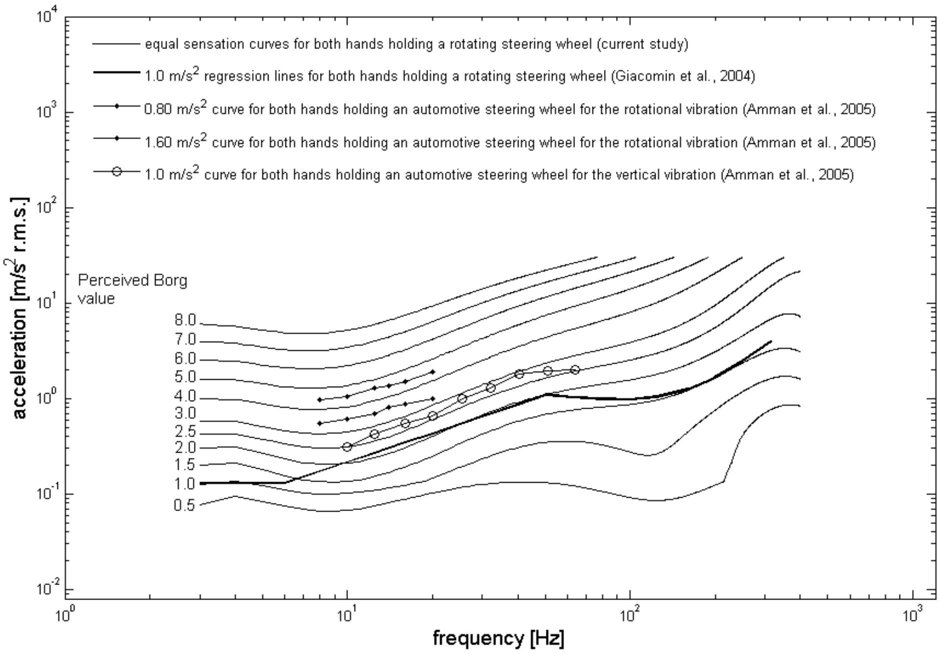


Figure 6) Comparisons between the equal sensation curves obtained in the current study and in previous studies of hand-arm rotational vibration.

Table 1) Geometric dimensions of the steering wheel rotational vibration test rig.

Geometric Parameter	Value
Steering column angle (H18)	23 °
Steering wheel hub centre height above floor (H17)	710 mm
Seat H point height from floor (H30)	275 mm
Horizontal distance adjustable from H point to steering wheel hub centre (d = L11-L51)	390-550 mm
Steering wheel handle diameter	25.0 mm
Steering wheel diameter	325 mm

Table 2) Test stimuli used in the subjective rating test to establish the equal sensation curves using a combination of 22 third octave frequencies ranging from 3 to 400 Hz and 78 acceleration amplitudes ranging from 0.06 to 30 m/s^2 r.m.s.

Frequency (Hz)	Acceleration r.m.s (m/s^2)	Frequency (Hz)	Acceleration r.m.s (m/s^2)	Frequency (Hz)	Acceleration r.m.s (m/s^2)	Frequency (Hz)	Acceleration r.m.s (m/s^2)	Frequency (Hz)	Acceleration r.m.s (m/s^2)	Frequency (Hz)	Acceleration r.m.s (m/s^2)
3	0.08	6.3	2.34	16	0.89	40	0.20	80	22.00	200	3.52
3	0.19	8	0.08	16	4.47	40	1.17	100	0.16	200	27.00
3	0.43	8	0.34	20	0.08	40	6.96	100	1.20	250	0.15
3	1.00	8	1.42	20	0.43	50	0.08	100	8.84	250	2.05
4	0.14	8	6.00	20	2.26	50	0.50	125	0.06	250	11.71
4	0.40	10	0.17	20	12.00	50	3.07	125	0.45	315	0.40
4	1.17	10	0.77	25	0.19	50	19.00	125	3.35	315	1.20
5	0.08	10	3.52	25	1.06	63	0.20	125	25.00	315	5.00
5	0.27	12.5	0.08	25	5.92	63	1.26	160	0.12	315	29.00
5	0.90	12.5	0.37	31.5	0.08	63	7.97	160	1.02	400	0.80
5	3.00	12.5	1.72	31.5	0.47	80	0.07	160	8.83	400	2.68
6.3	0.16	12.5	8.00	31.5	2.74	80	0.48	200	0.06	400	8.96
6.3	0.61	16	0.18	31.5	16.00	80	3.24	200	0.46	400	30.00

Table 3) Global statistics of the goodness-of-fit in terms of the residual mean-square-error (MSE) and the coefficient of determination r^2 for the regression models fitted when using both linear and logarithmic variables.

	Full polynomial in X, Y, Z		Full polynomial in LogX, Y, Z		Full polynomial in X, LogY, Z		Full polynomial in Log X, LogY, Z	
Order of polynomial fitted	Mean square error (MSE)	Coefficient of determination r^2	Mean square error (MSE)	Coefficient of determination r^2	Mean square error (MSE)	Coefficient of determination r^2	Mean square error (MSE)	Coefficient of determination r^2
1st order	1.10	0.60	1.03	0.62	0.97	0.63	0.90	0.65
2nd order	0.85	0.74	0.76	0.75	0.66	0.77	0.59	0.78
3rd order	0.74	0.88	0.64	0.90	0.41	0.94	0.34	0.94
4th order	0.52	0.93	0.44	0.94	0.35	0.95	0.30	0.96
5th order	0.45	0.94	0.39	0.95	0.34	0.96	0.32	0.96
6th order	0.41	0.95	0.37	0.96	0.38	0.96	0.32	0.97
7th order	0.37	0.97	0.35	0.97	0.37	0.96	0.36	0.97
8th order	0.38	0.97	0.36	0.97	0.38	0.96	0.37	0.97

Table 4) Global statistics of the goodness-of-fit in terms of the residual mean-square-error (MSE) and the coefficient of determination r^2 for the regression models fitted when including only interaction terms and using the logarithmic operator.

Polynomial order fitted	Interaction terms included / Estimated parametrs	up to 2nd power (INT2)	up to 3rd power (INT3)	up to 4th power (INT4)	up to 5th power (INT5)	up to 6th power (INT6)
4th order polynomial (LogX, LogY)	Number of regression coefficients	10	12	15	—	—
	Mean square error (MSE)	0.34	0.31	0.30	—	—
	Coefficient of determination r^2	0.95	0.95	0.96	—	—
5th order polynomial (LogX, LogY)	Number of regression coefficients	12	14	17	21	—
	Mean square error (MSE)	0.35	0.32	0.31	0.32	—
	Coefficient of determination r^2	0.95	0.95	0.96	0.96	—
6th order polynomial (LogX, LogY)	Number of regression coefficients	14	16	19	23	28
	Mean square error (MSE)	0.32	0.30	0.29	0.31	0.32
	Coefficient of determination r^2	0.95	0.96	0.96	0.96	0.97

Table 5) Root-mean-square error values determined to measure the accuracy of the fitted models.

Interaction terms included Polynomial order fitted	up to 2nd power (INT2)	up to 3rd power (INT3)	up to 4th power (INT4)	up to 5th power (INT5)	up to 6th power (INT6)
4th order polynomial (LogX, LogY)	0.55	0.50	0.47	——	——
5th order polynomial (LogX, LogY)	0.51	0.46	0.43	0.45	——
6th order polynomial (LogX, LogY)	0.53	0.44	0.41	0.37	0.43