HAND-ARM EQUAL SENSATION CURVES FOR 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 using the category-ratio Borg CR10 scale procedure. The test stimuli used were sinusoidal vibrations at 22 third octave band centre frequencies in the range from 3 to 400 Hz, with amplitudes in the range from 0.06 to 30 m/s^2 r.m.s. A multivariate regression analysis was performed on the mean Borg CR10 intensity values as a function of the two independent parameters of the vibration frequency and amplitude. The results suggested a nonlinear dependency of the perceived intensity on both the steering wheel rotational vibration frequency and amplitude. A sixth-order polynomial model has been proposed as a best fit regression model.

1 Introduction

Most psychophysical hand-arm vibration research has been previously 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 [1] performed equal sensation and annoyance threshold tests using a paired comparison method for ten 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.* [2] 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. Reynolds *et al.* 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.* [3] established equal sensation curves using the method of adjustment for fifteen 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 315 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.* [4] have recently established equal sensation curves for hand-arm vibration using the method of adjustment for twenty-eight 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 [5] have determined perception thresholds and equal sensation curves using the psychophysical method of magnitude estimation for twelve 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.

The equal sensation curves developed by Miwa and other researchers have contributed to the definition of the Wh frequency weighting for measuring hand-arm vibration exposure over the frequency range from 8 to 1000 Hz which is currently used in both International Organisation for Standardization 5349-1 [6] and British Standards Institution 6842 [7]. Studies on the subjective response to hand-arm vibration [8] have suggested, however, 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.* [3] 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.

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 Experiment

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. Table 1 presents the main geometric dimensions of the test rig which were based on average data taken from a small European automobile. The construction details of the test rig and its stimuli reproduction accuracy are described in detail in [3]. Rotational vibration was applied by means of a G&W V20 electrodynamic shaker which was driven by a PA100 amplifier. The steering wheel acceleration was measured in the tangential direction 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. 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 [9].

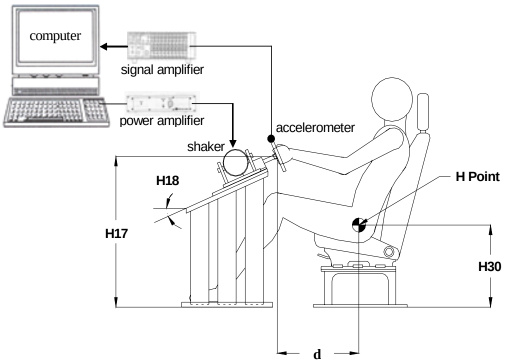

Figure 1- Schematic representation of the steering wheel rotational vibration test rig and associated electronics.

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	12.5 mm
Steering wheel diameter	325 mm

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 [3], 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 with acceleration magnitudes in the range from 0.06 to 30 m/s^2 r.m.s. A total of 78 vibration stimuli were used.

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. All declared themselves to be in good physical and mental health. The psychophysical method of the category-ratio Borg CR10 scale [10] 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 [10] for the scale’s administration. 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 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.

3 Results

3.1 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 [11] was then used to establish a mathematical model to express the Borg CR10 subjective intensity as a function of the two independent variables of vibration frequency and magnitude. The regression coefficients of the model were determined using the MATLAB software environment 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 [11] 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 [11]. 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 [8]. 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).

3.2 Effects 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. 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 sixth-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.

3.3 Effects of single terms, interaction terms and number of 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. From the results of this analysis, 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 sixth-order polynomial model obtained by adding interaction terms up to the 4th power.

3.4 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 [12]. 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) between the estimated and the observed Borg intensity values. The RMSE was calculated for each type of polynomial equation fitted for a subset of eight validation data points which consisted of the 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 sixth-order polynomial, which included interaction terms up to the fifth 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:

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

4 Discussion

Figure 2(a) presents the best fit equal sensation regression curves determined in the current study using the sixth-order polynomial with interaction terms up to the fifth power, the results of Miwa [1] for hand-arm vertical direction, the results of Reynolds *et al.* [2] for hand-arm axial direction and the results of Amman *et al.* [4] for steering wheel rotational vibration. 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. 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.* [2].

Considering the effect of the independent parameter of the vibration frequency, the equal sensation curves of the current study 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 with the curves becoming flatter and more linear with increases in the vibration amplitude. 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 [3]. Figure 2(b) presents, instead, the best fit equal sensation regression curves determined in the current study, the results of Giacomin *et al.* [3] and Amman *et al.* [4] which are relative to the perception of rotational steering wheel vibration as might occur when driving an automobile. Figure 2(b) 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.*

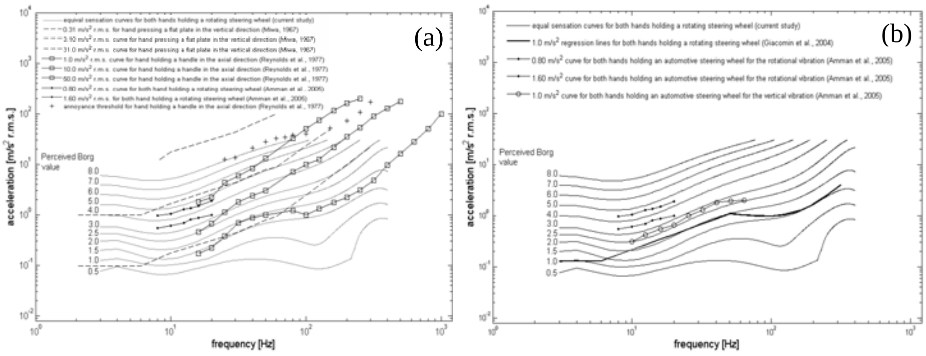

Figure 2 - Comparison between the equal sensation curves obtained in the current study and in previous studies of (a) translational or rotational vibration and of (b) rotational vibration only.

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. The 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. The results suggested a nonlinear dependency of the perceived intensity on both the vibration frequency and amplitude. A sixth-order polynomial model expressed in logarithmic form for both frequency and amplitude was found to produce a better fit than either the linear or semi-logarithmic forms.

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