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In-vehicle comfort assessment during fore-and-aft random vibrations based on artificial neural networks (ANN)

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Abstract. Driving comfort is one of the important factors for vehicle users. There is a lot of research related to comfort or discomfort in a vehicle but there is still no well-defined way to assess it accurately. In this paper, an assessment of vehicle comfort during fore-and-aft random vibrations was made based on measured and predicted r.m.s. acceleration values. Measured values of r.m.s. accelerations were obtained by laboratory testing while the predicted values of r.m.s. accelerations obtained based on the ANN (Artifical Neural Network) model. 20 male subjects participated in the study. Their different anthropometric characteristics of the body were taken into account. Based on the measured r.m.s. values of acceleration formed ANN model which has ability to predict r.m.s. acceleration values based on measured values. The obtained results showed high accuracy of the model.

1. Introduction

During driving, certain forces are transmitted from the road to the vehicle in the form of vibrations. The appearance of these vibrations is felt by the driver and passengers and can lead to a feeling of discomfort. The definition of comfort is difficult to define, it changed during the research. Thus, for the definition of comfort based on the Cambridge dictionary [1], it can be said that it is a pleasant and satisfying feeling when a person is mentally and physically free from pain and suffering. Assessment of the oscillatory comfort of the human body can be achieved in two ways: subjective and objective methods. Subjective assessment of comfort is performed on the basis of experiments where subjective ratings are collected through a series of statements given in relation to a predefined scale. Standardized methods are used for the objective assessment of comfort. These include the ISO 2631 standards and the British standard BS 6841. In this work, the ISO 2631 standard was used, on the basis of which the comfort criteria were defined.

The role of vibration measurement is to record the movement of the body as a reaction to some kind of stimulus. The discomfort caused by vibrations varies depending on the frequencies present. In addition to the frequency, the duration of the vibration, the amplitude and the direction of the vibration (x, y and z axis) also have an impact on the appearance of discomfort. A review of the literature found that a significant number of studies dealt with the impact of vibrations, both on individual parts of the body and on the entire human body, in different environments. Exposure of the human body to the action of excitation in the direction of one axis is carried out in the fore-and-aft and vertical directions. Uniaxial vibrations along the vertical and fore-and-aft axis caused significant movements in the sagittal plane (vertically, fore-and-aft and laterally) of the upper body, suggesting a strong coupling effect [2], [3]. Whole body vibration is particularly significant in the frequency range from 1 Hz to 80 Hz. In this frequency range are also the main resonance points of certain organs and parts of the human body (e.g., head, eyes, stomach and spine) [4], [5]. Undesirable effects of these vibrations refer to the occurrence of a number of health problems, among which the most characteristic are back (lumbar region) and neck pains. Vibrations of the whole body in the area of extremely low frequencies (below 0.5 Hz) cause "seasickness" [6]. Table 1 shows the observations of the comfort of passengers of public urban transport for different intensities of vibrations according to the standard ISO 2631 (1997), based on laboratory tests. It is obvious that with an increase in the strength of vibrations, passenger comfort decreases [7].

Table 1. Passenger comfort perception according to ISO 2631 (1997).

Less than 0.315 m/s^2	Not uncomfortable
0.315 m/s^2 to 0.63 m/s^2	A little uncomfortable
0.5 m/s^2 to 1 m/s^2	Fairly uncomfortable
0.8 m/s^2 to 1.6 m/s^2	Uncomfortable
1.25 m/s^2 to 2.5 m/s^2	Very uncomfortable
Greater than 2 m/s^2	Extremely uncomfortable

A group of authors [8] showed that professional drivers are less sensitive to vibration levels. There are two reasons. First, drivers perceive obstacles on the road and are prepared for disturbances that reach their bodies (movements of internal organs are suppressed by increasing muscle tone). Second, the steering wheel allows the driver to moderate angular movements around the transverse axis and translational movements (fore-and-aft) of the body. The author [9] concludes that the perception of passenger comfort in real driving conditions corresponds to higher vibration intensities compared to the perception of the same level of comfort in laboratory tests. This is explained by the presence of numerous stimuli that affect the passenger's attention in real driving conditions.

Standard ISO 2631 (1997) [10] prescribes the total value of mean effective weighted accelerations, on the basis of which the impact on discomfort is assessed according to the formula:

$$a_v = \sqrt{\left(k_x \cdot \ddot{x}_{rms,w}\right)^2 + \left(k_y \cdot \ddot{y}_{rms,w}\right)^2 + \left(k_z \cdot \ddot{z}_{rms,w}\right)^2} \quad (1)$$

where:

k_x, k_y, k_z – are correction factors for r.m.s. values of weighted accelerations in the direction of the x, y and z axis,

$\ddot{x}_{rms,w}$, $\ddot{y}_{rms,w}$, $\ddot{z}_{rms,w}$ – are mean effective value of the weighted acceleration for the directions x, y and z, which are determined according to the formulas:

$$\ddot{x}_{rms,w} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} \ddot{x}^2{}_{w_i}} \quad (2)$$

$$\ddot{y}_{rms,w} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} \ddot{y}^2{}_{w_i}} \quad (3)$$

$$\ddot{z}_{rms,w} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} \ddot{z}^2{}_{w_i}} \quad (4)$$

where:

$\ddot{x}_{w_i}$, $\ddot{y}_{w_i}$, $\ddot{z}_{w_i}$ – are i-th sample of weighted accelerations of the user for the directions of the x, y and z axis (m/s^2),

N – is number of signal samples of weighted accelerations.

Machine learning is the process of finding hidden laws and connections between data. It represents a new approach and modern problem solving in engineering. The task of machine learning is to focus on developing human-like learning algorithms. A set of such methods that mimic the work of the human brain in learning, and have bases in biology, are collectively called neural networks. This approach is adapted to well predict the nonlinear responses of the human body in a seated position. Artificial neural network schemes have been widely used in a wide range of applications [11-13] because they can model complex nonlinear systems by learning from the input and output signals of the system.

In this paper, based on the obtained experimental results, an ANN model was created in order to evaluate the oscillatory comfort of the human body.

2. Materials and methods

2.1. Laboratory experiment

Causing excitation of different amplitudes and frequencies was achieved using an electro-hydraulic pulsator HP-2007. This pulsator is designed to provide excitation in the frequency range 0.1-31 Hz and amplitude 0-50 mm. A portable vibration analyzer NetdB1 was used to measure the transmission of vibrations from the seat through the human body. AC102-1A acceleration transducers, weighing 90 g, sensitivity 100 mV/g, frequency range 0.5-15000 Hz, which can work in the temperature range of -50-121°C, were used to record the vibration response. Twenty male healthy subjects, with mean age 30.7±6.15 years, height 183.25±4.43 cm, weight 89.4±11.72 kg, BMI (BMI Body Mass Index) 26.57±2.96, seating height 88.35±4.79 cm, were exposed to random vibrations of the whole body for three excitation values 0.45, 0.8 and 1.1 m/s2 r.m.s., in the frequency range 0.1-20 Hz. The angle of inclination of the backrest was 90°. The duration of each experiment was 60 s, and the number of repetitions was 2. The parameters of the experiment are: sampling rate 51.2 kHz, block duration 80 ms, number of samples 4,096, where the number of averaging is 2, sampling step Δt = 0.0195 ms. Signal overlap is 75%. The frequency step Δf=0.390625 Hz, and the bandwidth is B = 39 Hz, where the Nyquist frequency criterion was satisfied, because the sample frequency is higher than twice the sampling rate. The measurement scheme is shown in figure 1.

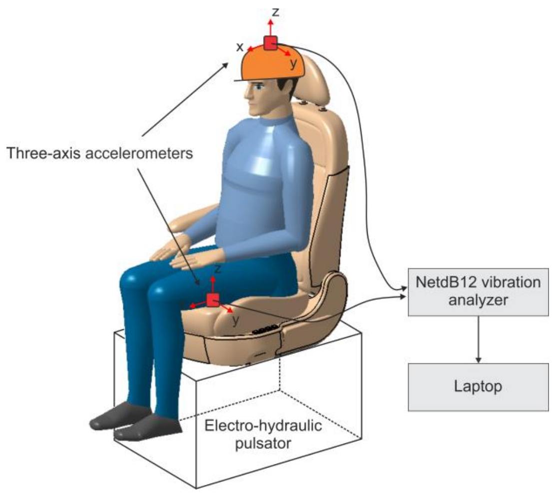

Figure 1. A scheme of the laboratory setup of the experiment.

2.2. Artificial neural network

Recurrent Neural Networks (RNN) were used in this work. Neural networks are formed in which the outputs of the neuronal elements of the following layers have synaptic connections with the neurons of the previous layers. This leads to the possibility of taking into account the results of information transformation by the neural network in the previous stage for processing the input vector in the next stage of the network operation. A recurrent network with a memory cell LSTM (Long-Short Term Memory) was used to determine the oscillatory comfort.

The data for training the neural network were data obtained from experimental measurements of 20 subjects exposed to random fore-and-aft vibration for three excitation amplitudes. Each subject was characterized by BMI, height, weight, sitting height and age. Figure 2 shows the scheme of the used neural network.

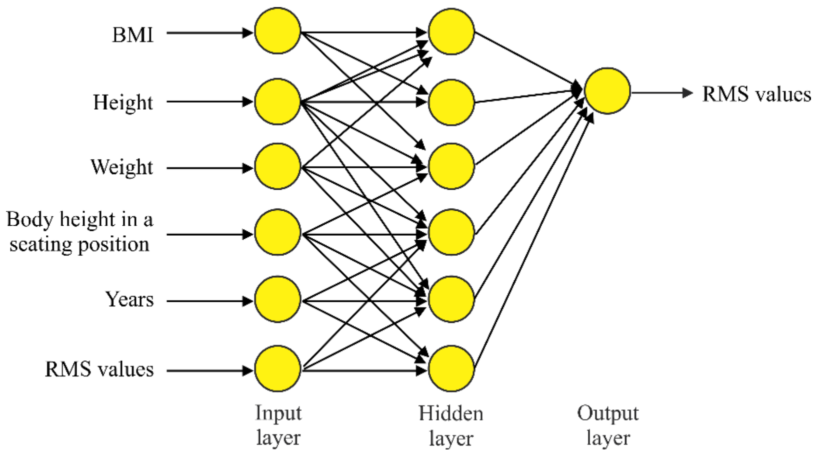

Figure 2. A scheme of a LSTM recurrent neural network.

The mean absolute error was used as the loss function in a training phase, while the effective Adam optimization algorithm was used to search for the minimum of the loss function.

3. Results

In this research, based on the ISO 2631 standard, an assessment of oscillatory comfort was performed based on the total mean effective value of the weighted acceleration. The ISO 2631 standard prescribes checking the value of the crest factor. The measured peak factor values were in the range of 1.391-2.784, which meets the requirements of the standard (peak factor < 9), so the weighting was done according to the ISO 2631 standard. Table 2 shows the total r.m.s. weighted acceleration values and oscillatory comfort ratings under the influence of fore-and-aft excitation for 20 male subjects. The lowest value of r.m.s. it was recorded in the subject number 3 (BMI = 34; the highest value) and is 0.213 m/s^2 for an excitation of 0.45 m/s^2 r.m.s. What characterizes the obtained results of all excitation directions is that with an increase in BMI, there is a decrease in the total r.m.s. acceleration values.

Table 2. R.m.s. weighted acceleration values and oscillatory comfort ratings under the influence of fore-and-aft excitation for twenty male subjects.

ID	0.45 m/s^2 r.m.s.		0.8 m/s^2 r.m.s.		1.1 m/s^2 r.m.s.	
1	0.381	A little uncomfortable	0.723	Fairly uncomfortable	0.984	Fairly uncomfortable
2	0.379	A little uncomfortable	0.714	Fairly uncomfortable	1.024	Uncomfortable

3	0.213	Not uncomfortable	0.603	A little uncomfortable	0.888	Fairly uncomfortable
4	0.227	Not uncomfortable	0.609	A little uncomfortable	0.896	Fairly uncomfortable
5	0.342	A little uncomfortable	0.679	Fairly uncomfortable	0.964	Fairly uncomfortable
6	0.355	A little uncomfortable	0.699	Fairly uncomfortable	0.988	Fairly uncomfortable
7	0.354	A little uncomfortable	0.714	Fairly uncomfortable	1.004	Uncomfortable
8	0.351	A little uncomfortable	0.683	Fairly uncomfortable	0.978	Fairly uncomfortable
9	0.282	Not uncomfortable	0.544	A little uncomfortable	0.928	Fairly uncomfortable
10	0.314	Not uncomfortable	0.606	A little uncomfortable	0.945	Fairly uncomfortable
11	0.322	A little uncomfortable	0.676	Fairly uncomfortable	0.964	Fairly uncomfortable
12	0.296	Not uncomfortable	0.653	Fairly uncomfortable	0.938	Fairly uncomfortable
13	0.236	Not uncomfortable	0.616	A little uncomfortable	0.908	Fairly uncomfortable
14	0.248	Not uncomfortable	0.624	A little uncomfortable	0.927	Fairly uncomfortable
15	0.382	A little uncomfortable	0.738	Fairly uncomfortable	1.045	Uncomfortable
16	0.374	A little uncomfortable	0.704	Fairly uncomfortable	0.996	Fairly uncomfortable
17	0.271	Not uncomfortable	0.634	Fairly uncomfortable	0.915	Fairly uncomfortable
18	0.334	A little uncomfortable	0.667	Fairly uncomfortable	0.954	Fairly uncomfortable
19	0.369	A little uncomfortable	0.701	Fairly uncomfortable	1.014	Uncomfortable
20	0.362	A little uncomfortable	0.705	Fairly uncomfortable	0.967	Fairly uncomfortable

Using an artificial neural network, it is possible to train the neural network based on the obtained experimental results and perform a comfort assessment based on ISO 2631 standard. The ANN model was trained with 100 training epochs, while the data series size was 20. The coefficient in training, validation and testing was over 98% for all types of stimuli. The root means square error of the predicted r.m.s. value was 0.024. R.m.s. the values of the original and the values after the process of training the network, for the fore-and-aft excitation, of the male subject under ID number 20, are shown in table 3.

Table 3. Prediction results of r.m.s. values of the male subject under serial number 20 for excitation in the fore-and-aft direction.

	0.45 m/s^2 r.m.s.		0.8 m/s^2 r.m.s.		1.1 m/s^2 r.m.s.	
	Original	Predicted	Original	Predicted	Original	Predicted
R.m.s.	0.362	0.347	0.705	0.682	0.967	0.974
Comfort rating (ISO 2631)	A little uncomfortable	A little uncomfortable	Fairly uncomfortable	Fairly uncomfortable	Uncomfortable	Uncomfortable

The developed model of artificial neural network shows that it has adequate precision of biodynamic modeling. The main feature of the ANN model is to consider height, weight, sitting height, BMI and age during whole body vibration exposure.

4. Conclusions

In this work, an assessment of oscillatory comfort was performed based on the ISO 2631 standard. Twenty male subjects were exposed to random uniaxial vibrations in the fore-and-aft direction. The R.m.s values obtained from these measurements were the input of the neural network, which had the task of evaluating the oscillatory comfort based on the input data. By using the weighted acceleration and the mentioned standard, it is possible to evaluate the comfort of a particular position of the subject. The neural network model was trained with 100 training epochs, while the size of the data series was 20. For all types of stimuli, the correlation factor in the training, validation and testing phase was over 98%. The root means square error of the predicted r.m.s. value of weighted acceleration was 0.024. The complexity of the model, which takes into account different anthropometric characteristics of the subjects, as well as different vibration amplitudes, is not a problem, but highlights the ability of the model to predict oscillatory comfort via r.m.s. values, in the time domain, defined by the ISO 2631 standard.

Future research will go in the direction of investigating the influence of the change in the angle of inclination of the seat back on the r.m.s. values, as well as determining the most influential factor on the response of the human body to the vibrations of the whole body.

Acknowledgments

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