EVALUATION OF RIDE COMFORT UNDER SINUSOIDAL VIBRATION

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Nomenclature

\[ x_i(t) : \text{signal from electrode } i \]
\[ x_j(t) : \text{signal from electrode } j \]
\[ C_{ij} : \text{Cross correlation coefficient between EEG signals from electrode } i \text{ and } j \]
\[ N1 : \text{Emotion spectrum for Anger/Stress} \]
\[ N2 : \text{Emotion spectrum for Sadness} \]
\[ P1 : \text{Emotion spectrum for Pleasure} \]
\[ R : \text{Emotion spectrum for Relax} \]
\[ S : \text{Score of ride comfort} \]
\[ C_{N1} : \text{partial regression coefficient for N1} \]
\[ C_{P1} : \text{partial regression coefficient for P1} \]
\[ C_{N2} : \text{partial regression coefficient for N2} \]
\[ C_R : \text{partial regression coefficient for R} \]

ABSTRACT

This paper presents an investigation on the behavior of the human body under sinusoidal vibration and the influence of vibration on mental state. In order to measure the transmissibility of the most sensitive parts of the body, excitation experiments with sinusoidal input were performed. Frequency responses of body parts and bioelectric signals were measured to discuss the influence of vibration on ride comfort, and the relation between vibration and mental state has been discussed.

1. INTRODUCTION

Recently, the request for better ride comfort has been raised and the clarification of influence of vehicle vibrations on passenger ride comfort is required to improve quality of the vehicles. Most of previous researches have taken into account only floor vibration and seat vibration for the evaluation of ride comfort\(^{(1)}\). However, ride comfort is the reaction of human body against the vibration sensed by their body such as head, shoulder, waist, and knees. Therefore, ride comfort should be discussed taking into account the response of body.

Fundamental research on the sensitivity against vibration has been made by many researchers for instance, using weighting functions that is regulated in BS6841\(^{(2)}\) based on equivalent discomfort curve\(^{(3)}\), or performing multiple-regression analysis with the result of questionnaires and acceleration of sensitive parts of body\(^{(4)}\). These are the attempt to evaluate comfort quantitatively.

The purpose of this research is to clarify the relation between ride comfort and response of the human body. For this purpose, excitation tests with sinusoidal vibration were conducted. Ride comfort is very subjective issue. Usually, these evaluation is performed by taking questionnaires. However, these methods are based on subjective comment of the subjects and they are based on the ambiguous memory and different value judgement of subjects. From the reason, the evaluation of ride comfort by taking questionnaire potentially includes error from the subjectivity.

One of the solution to this problem is to introduce bioelectric signal, and brain wave is one of major method. Because the comfort is the reaction of brain against the stimuli from sensory organs. Mind, consciousness, recognition, and sense is organized by brain so that there is a possibility that the change of the state of brain activity can be detected from brain wave\(^{(7)}\). There are several methods to measure brain activities such as (PET(POSITRON EMISSION TOMOGRAPHY), f-MRI(FUNCTIONAL MAGNETIC RESONANCE IMAGING), etc. However EEG has
an advantage to be non-invasive and is performed with very simple apparatus. From these reason, researches using EEG have been studied for many cases such as an evaluation of the design of driving wheel of wheel chairs[5], and usability of software [6]. Once, the relation between EEG signals and ride comfort has been established, evaluations of ride comfort can be performed without taking questionnaires. In this study, the method for the evaluation of ride comfort from EEG was introduced and the possibility has been validated.

2. EXCITATION EXPERIMENT AND ANALYSIS WITH SINUSOIDAL INPUT

2.1. Experimental Setup and Conditions

Fig.1 shows the setup for the excitation experiments. Subjects were seated on an iron seat attached to a hydraulic-driven two-dimensional shaking table. They were requested to sit up straight, put their palms on their knees, relax, not look down, and not speak.

The subjects are exposed to vertical excitation. And acceleration on the head, shoulder, waist, and knee are measured, and the frequency response is calculated. The measurement of the acceleration on the head was measured at the top of the head. An accelerometer was attached on the edge of the shoulder [8]. They are attached on the waist at the point of the 3rd or 4th corpus vertebrae[8]. The accelerometer on the knee was attached on the top of the knee.

The intensity of the sinusoidal vibration is set to 1.0m/s², and the frequency range is from 1.0 to 30Hz, where the increment of the frequency is 1.0 Hz. The duration of exposition is 30 seconds for each frequency, and the total duration of the experiment is less than 15 minutes in consideration of the fatigue of subjects.

2.2. The result of vertical excitation test

Fig.2(a)-(d) shows the frequency response of the 26 subjects. Fig.2(a) shows the result on the head, and the first resonance is observed around 4 Hz and the second resonance is between 9 and 19 Hz. Fig.2(b) shows the result on the shoulder and the first resonance is around 5 Hz and the first natural frequency is little bit higher than on the head for most of subjects. In this result, no big difference is observed between subjects. Fig.2(c) shows the result on the waist. The first resonance is observed around 5 Hz for several subjects, but it is not clear compared to that on the head and shoulder. The second (the first for several subjects) resonance is between 10 to 17 Hz. Fig.2(d) shows the result on the knee. The first resonance is observed between 9 and 16 Hz. If the first resonance is about 10 Hz, there is the second resonance around 20 Hz for some subjects.
The experimental setup was the same as the previously experiment. This time, the subjects are asked to wear electrodes on their head for the measurement of EEGs, and also asked to hold a controller to answer ride comfort during the excitation. The experiments were conducted with 12 male subjects.

The input is sinusoidal vibration within a range of 1 Hz to 15 Hz that includes the dominant frequency for vertical vibration and first and second resonance of apparent mass. The acceleration amplitude is set to 1.0 m/s². The excitation was performed for 1 minute and the sequence of the excitation was at random.

3. Evaluation of ride comfort

The subjects were requested to answer the ride comfort while they were under excitation. The range of comfort was set from –3 (Very uncomfortable) to 0 (feel no discomfort). The frequency which they felt the worst ride comfort had been investigated beforehand by shaking them with the 15 types of excitation. They were asked to answer the ride comfort by comparing the current frequency and the worst frequency. They were asked to answer the ride comfort after 55 second during 1 minute excitation.

A controller was used to answer the questionnaire. There are 7 buttons for ride comfort (-3, -2.5, -2, -1.5, -1, -0.5, 0). The signals from the controller were captured by AD board (PCI3177C, Interface.Co) installed on an IBM compatible PC and recorded by a program written in Visual Basic. The timings of excitation start and stop are detected by signals of accelerometer attached on the shaking table. After the vibration of the table converged, the recording of EEG was started.

Fig. 5 shows the average of the ride comfort result classified by patterns. There were three major patterns. Pattern A showed the drop of the score at 5 Hz, but the score recovers as frequency increases. In Pattern B, the score constantly decreases as frequency increases. In pattern C, the score drops at around 6 Hz, and it recovers around 10 Hz. However, the score decreases as the frequency approaches to 15 Hz. 5 Hz is the first natural frequency of the head and shoulder for many subjects. And 15 Hz is the natural frequency at waist and knee.
3.2. Measurement of EEG

In order to measure EEG, electrodes were put on the subjects’ head. The location of the electrodes were based on the 10-20 electrode system[10] and 12 points(Fp1, Fp2, F3, F4, T3, T4, P3, P4, O1, O2, the mid point of Fz and Cz as grounding, and A2 as reference[11]) were selected based on the researches made by Musha[7], The electrodes were fixed on the head skin by using a paste(GE Marquette Medical System Japan, Biotach)

EEG were recorded for 20 seconds after the table was completely stopped. The measurement of EEG should be carried out during excitation. However, the frequency range of the frequency analysis of EEG includes the frequency of excitation so that EEG signal can be contaminated by the artifact. From the reason, the measurement of EEG was performed after excitation.
3.3. Analytical Method for EEG

From the result of recent researches, the comprehension to the brain functionality has been changed. Not only the sequential pattern of a specific point but also the spatial pattern has meaning. This indicates that information is not propagated only by sequential codes but also by dynamic spatial patterns[7]. From this point of view, cross correlation coefficient is introduced to describe the spatial pattern.

The advantage of introducing cross correlation coefficient is that the value is normalized so that the difference of absolute value of EEG signal by subjects can be canceled, and the relation between different point on the head can be expressed. From the reason, cross correlation coefficient is applied to various researches that attempt to abstract the thought and emotion from EEG[11].

10 channels of EEG signals are acquired with 200Hz sampling frequency. The acquired data are separated into segments every two seconds, and cross correlation coefficient $C_{ij}$ was calculated with the following formula. The combination of 10 electrodes are $\binom{10}{2} = 45$.

$$C_{ij} = \frac{x_i(t) \cdot x_j(t)}{\sqrt{x_i(t)^2 x_j(t)^2}} \quad (1)$$

The frequency band that are essential to the analysis are the followings; theta band(4-8[Hz]), alpha band(8-14[Hz]), and beta band(14-20[Hz]). Cross correlation coefficient can not express the actual time historical wave pattern, so that the band are filtered with Butterworth filter and cross correlation coefficient is calculated in each band. The total number of cross correlation coefficient comes to 135 and these values are the input vector.

The vector is multiplied by a matrix called emotion matrix and transformed into a vector that have four rows. Each element represents the intensity of four spectrum, (N1:Anger/Stress, P1:Pleasure, N2:Sadness, and R:Relax) [7]. The calculation has been performed using Emotion Spectrum Analysis system(ESA-16, Brain Function Laboratory, Inc.).

3.4. Evaluation function for ride comfort

A multiple regression analysis was performed using the answer of the questionnaire as predictor variable and the result of ESAM as dependent variable assuming a linear equation between them as shown in Eq.(2).

$$S = C_{N1} \cdot N1 + C_{P1} \cdot P1 + C_{N2} \cdot N2 + C_R \cdot R + C \quad (2)$$

3.5. Explanation of ride comfort with brain wave.

The evaluation of ride comfort and the measurement of EEG is conducted with 12 male subjects. And analysis was performed with ESAM. After that, multiple-regression analysis was also performed and the determination of coefficient was calculated. Fig.6(a),(b) shows the results whose coefficient of determination was higher than 0.5 weve selected. The subject index are from A to F. In the figures, the coefficient of determination are 0.85 in Fig.6(a) and 0.55 in Fig.6(b). These coefficient varies in every set of experiment due to the condition of subjects and the measurement error. However, it is indicated that the explanation of ride comfort by EEG is possible from these results.

3.6. Prediction of the ride comfort of other persons

From the result of the previous section, the possibility of explanation of ride comfort by EEG is indicated. Therefore, once a good partial regression coefficient is found, it would be possible to predict the ride comfort only from EEG. In order to investigate the possibility, the cross correlation between partial regression coefficient are calculated. The result is shown in Table 1. From the result, the correlation are rather high except the result of subject E, and the existence of common partial regression coefficient is indicated.
(a) Subject E

Fig. 6 Comparison between the Questionnaire and the result of multiregression analysis

(b) Subject D

Table 1 Correlation between the partial regression coefficient

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Fig. 7(a),(b),(c) shows the result of predictions of the ride comfort of subject C, D, and F by the partial regression coefficient of other subjects. Fig. 7(a) shows good correlation except there are some error at 1 and 2 Hz. The tendency of the worst score at 5 Hz and 9 Hz is predicted. The result of questionnaire has rough point between 5 Hz and 10 Hz, but the prediction showed smooth transition. Beside, the questionnaire showed the same score from 12 Hz to 15 Hz, but prediction showed some changes between these frequencies. From these results, it is indicated that EEG has information that cannot be obtained by questionnaire. Fig. 7(b) showed good much, although some errors are observed at around 11 Hz. Fig. 7(c) showed good much at all frequency and the score at 1 to 3 Hz showed good much. This time, there are big error around 5 Hz, but the worse comfort is emphasized. From the results, the possibility of the prediction of others' ride comfort is indicated.

Fig. 7(a) Prediction of Ride Comfort of Subject C by using Multiregression coefficient of A

Fig. 7(b) Prediction of Ride Comfort of Subject D by using Multiregression coefficient of C
4. CONCLUSION

1. The first natural frequency was observed around 5 Hz only at the head and shoulder, and it was observed at around 12 Hz at waist and knee.
2. The average result of the questionnaire showed three patterns of ride comfort score.
3. The possibility of the evaluation of ride comfort by ESAM has been verified.

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REFERENCES