Proc. Schl. Eng. Tokai Univ., Ser. E
40 (2015) 83-88

A Study on Ride Comfort Control Method Using Heart Rate Variability in Consideration of the Physiological State

by

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(Received on Mar. 30, 2015 and accepted on Jul. 9, 2015)

Abstract

In recent years, ultra-compact mobility vehicles have been being introduced in Japan. This ultra-compact mobility vehicle is an electric automobile for 1 or 2 passengers and is currently being sold by several automobile manufacturers. Unlike ordinary cars, ultra-compact electric vehicles can easily drive on a narrow or unpaved path. Being lightweight, however, they are subject to vibration from road irregularities and road surface steps, and it is necessary to develop a vibration control system for safe and comfortable driving. To improve ride comfort against up-and-down vibration, our research group has proposed an active seat suspension using a voice coil motor at the seat section of the vehicle. Our past research examined driver's heart rate variability, a type of biometric data, and found that different acceleration degrees of vibration resulted in significantly different driver's stress responses measured through the driver's heart rate variability. This paper proposes a vibration control system that first evaluates the psychological state of the driver from the biometric data continuously collected while driving, and then selects from the preconfigured ride comfort options the ride comfort experience that the driver prefers.

Keywords: Active seat suspension (ASS), Ride comfort, Ultra-compact electric vehicle, Heart rate variability

1. Introduction

Efforts have been made to date to improve automobile ride comfort through designing suspensions and seats that reduce and absorb vibration. As such passive controls may not be fully effective in achieving ride comfort at high driving speeds and when traveling on rough roads, active suspensions have also been used to reduce the vibration [1). However, vehicles that offer ride comfort options are rare, and the model of a vehicle mostly determines its ride comfort. The automobile manufacturing industry has thus far relied on expert test drivers and subjectively evaluated ride comfort [2). To objectively evaluate ride comfort; however, biometric data of a driver are now often analyzed to evaluate his/her psychological state and fatigue level [3-5). Our past research examined driver's heart rate variability, a type of biometric data, and found that different acceleration degrees of vibration resulted in significantly different driver's stress responses measured through the driver's heart rate variability [6). Although biometric data are used to evaluate automobile ride comfort, they have not yet been incorporated into the vibration control system, to our best knowledge, to provide the ride comfort experience that is customized for the driver.

Ultra-compact mobility vehicles are being introduced recently, because of their easy maneuverability, environmental friendliness, and good potential as a regional transportation means [7). This ultra-compact mobility vehicle is an electric automobile for 1 or 2 passengers and is currently being sold by several automobile manufacturers. Being lightweight, however, it is subject to vibration from road irregularities and road surface steps, and it is necessary to develop a vibration control system for safe and comfortable driving. To improve ride comfort against up-and-down vibration, our research group proposed an active seat suspension (hereafter ASS) using a voice coil motor at the seat section of the vehicle [8). ASS directly controls the seat section, which is independent of the vehicle

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body. Therefore, it is lower in cost, more compact, simpler to install, and more versatile than the active suspension of four-wheel vehicle. In the past, we proposed a vibration control system that first evaluates psychological state of the driver from the biometric data continuously collected while driving and then selects from the preconfigured ride comfort options the ride comfort experience that the driver prefers [9]. We note that fluctuations in heart rate occur even at rest [10]. As we previously proposed system is highly sensitive, these natural fluctuations must be taken into account. As the first step towards evaluating effectiveness of the proposed vibration control system, this paper conducts vibration-testing experiments using a stationary vehicle. In the experiments, ASS chooses a vibration frequency, based on the change in the driver's psychological state evaluated from the driver's heart beat variability, from two vibration frequencies for which the ride comfort experiences are generally different.

2. Evaluating the Driver's Psychological State from Heart Rate Variability

In this paper, we use an electrocardiogram (ECG) to simplify measurements and continuously collect data from a driver conducting driving maneuvers in order to evaluate driver's autonomic nervous system responses and his/her levels of stress and relaxation. The periodic peaks reflect the contraction of the left ventricle and are called R waves. We calculate the RR interval (hereafter RRI), i.e., the time from one R wave peak to the next one. By collating the RRIs as a time history, we may evaluate the continuously changing psychological state of the driver. Therefore, the RRI time history is able to draw by electrocardiogram. From this RRI time history, we may understand the activity of the autonomic nervous system and evaluate the stress/relaxation level of the driver. A decrease in the RRI value from the reference value indicates an increase in the heart rate and is evaluated as stress or tension since the sympathetic nervous system is dominant in such a case. An increase in the RRI value from the reference value indicates relaxation since the parasympathetic nervous system is dominant in such a case [11-12].

We calculate high frequency components (HF) of 0.15–0.4 Hz and low frequency components (LF) of 0.04–0.15 Hz through frequency analysis of the RRI time history obtained the previous subsection and use them as indices in evaluating the responses of the autonomic nervous system. LF and HF are widely used to distinguish and separately in evaluate the activities of the sympathetic nervous system and those of the parasympathetic nervous system. In this paper, we use an LF/HF ratio, an index that expresses activities of the sympathetic and parasympathetic nervous systems, to readily compare the collected data and to evaluate driver's autonomic nervous system responses while driving.

When the LF/HF ratio is high, the parasympathetic nervous system is dominant, and thus, it may be interpreted as stress; when it is low, the sympathetic nervous system is dominant, and it may be interpreted as relaxation.

3. Ride Comfort Control Using Heart Rate Variability

3.1 *RRI-SW vibration control*

To provide the ride comfort experience that is optimally suited for the individual driver, we proposed the RRI-switching vibration control system (hereafter RRI-SW vibration control system) that switches between the preconfigured vibration control types based on the RRI analysis of heart rate variability collected continuously while driving. Since the LF/HF ratio described in the previous section generally requires data collected for longer than 5 min for effective frequency analysis [13-14], it is not suitable for control to reflect the driver's psychological state at a finer time granularity. Therefore, we use RRIs that require fewer data points to analyze heart rate responses arising from a change in the driving environment and calculate for each minute, an average $\overline{\mathrm{RRI}}$ of the RRI values in the last minute, considering the time required for a vibration change to reflect in driver's heart rate variability. Switching of the vibration control type is also determined by the minute, and when the current $\overline{\mathrm{RRI}}$ value decreases from the previous $\overline{\mathrm{RRI}}$ value, namely, when ride comfort provided by the current vibration control type does not fit the driver's psychological state and when the driver is in stress, the vibration control type is switched.

In this paper, we only consider two vibration control types to switch between in order to verify the basic effectiveness of the proposed RRI-SW vibration control system. Figure 1 shows the RRI time history for eight minutes and the eight $\overline{\mathrm{RRI}}$ values calculated from when we started measuring the RRI time history. At 2 min, for example, the $\overline{\mathrm{RRI}}$ plot in Fig 1 shows an average value of the last minute, i.e., the 1 to 2 min time interval. As shown in Fig. 1, the vehicle first runs with vibration control type A (in the 1 to 2 min time interval), and when the $\overline{\mathrm{RRI}}$ value measured for this time interval decreases from the $\overline{\mathrm{RRI}}$ value measured for the previous time interval (the 0–1 min time interval), the proposed RRI-SW vibration control system determines that the driver feels stress with vibration control type A and switches to vibration control type B to use in the 2-3 min time interval. Similarly, the vehicle runs with vibration control type B in the 2-3 min time interval, and when the $\overline{\mathrm{RRI}}$

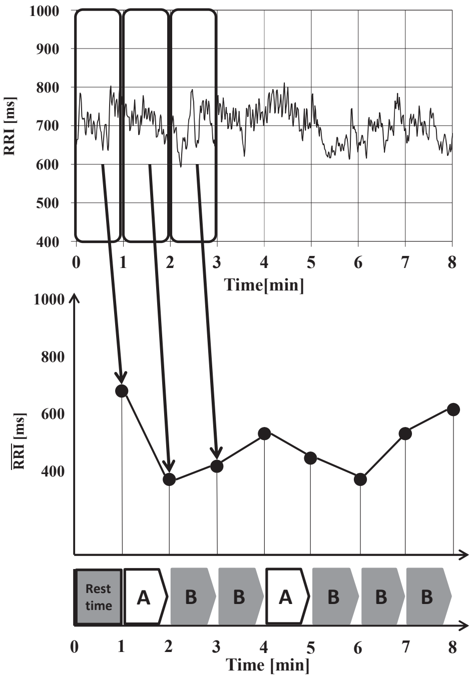


Fig. 1 Switching the control using heart rate variability

Fig. 2 Ultra-compact electric vehicle and active seat suspension

value for this time interval increases from the $\overline{\text{RRI}}$ value for the 1-2 min time interval, the proposed RRI-SW vibration control system determines that the driver is relaxed with vibration control type B and continues to use vibration control type B.

In measuring an RRI for a certain time interval and calculating RRI every minute since when the measurement begins, let $\overline{\text{RRI}}_i$ denote the $\overline{\text{RRI}}$ value for the i–1 to i minute time interval. Then, the evaluation criteria j_i is expressed as follows using a sign function:

$$j_i = \text{sign}(\overline{\text{RRI}}_{i-1} - \overline{\text{RRI}}_i) \tag{1}$$

When j_i = 0 or −1, the proposed RRI-SW vibration control system uses the same vibration control type that was used in the i−1 to i minute time interval for the i to i+1 minute interval, and when j_i = 1, the proposed RRI-SW vibration control system switches to the other vibration control type.

3.2 *The heart rate variability at rest*

By the past study, we noted that fluctuations in heart rate occur even at rest [15)]. As Equation (1) is highly sensitive, these natural fluctuations must be taken into account. Thus we acquired electrocardiograms from one test subject at sitting and rest positions for 10 minutes. We calculated the average of difference of RRI average for each one minute. In addition, we calculated the average of 5 test subjects' data and defined it as $\overline{\text{RRI}}_f$. The $\overline{\text{RRI}}_f$ applied for equation (1) as follows:

$$j_i = \text{sign}(\overline{\text{RRI}}_{i-1} - \overline{\text{RRI}}_i + \overline{\text{RRI}}_f) \tag{2}$$

We used this average fluctuation value to prevent unnecessary switching of the vibration control type due to the natural fluctuations in heart rate of a driver at rest.

4. Experimental Setup

In the experiments conducted in this paper, we used an ultra-compact one-seat electric vehicle. This vehicle is equipped with ASS in its seat section shown in Fig. 2. The aluminum-plate seat is supported by four coil springs that are constrained by linear sliders to up-and-down vibrations only. For a control actuator, we adopted a voice coil motor, a type of a linear motor. Unlike a conventional active suspension that controls vibration of the entire vehicle, the ASS controls the seat section and achieves ride comfort by responding to the psychological state of each passenger in a vehicle with two or more seats. We loaded onto the rear of the vehicle the peripheral equipment such as digital signal processors and batteries to drive the voice coil motor.

For electrocardiogram measurements, we used Bio Amp ML132, Power Lab ML825 2125, and MLA2503 shielded lead wires (manufactured by AD Instruments), and for the analysis, we used the analysis system, heart rate variability, by the same company. Figure 3 shows measuring device of electrocardiogram. When using the electrocardiogram, it is desirable to attach electrodes to the body to encircle the heart in a roughly equilateral triangle. In this paper, since the driver's arms moved frequently during steering operations, we adopted the NASA induction method to prevent noise and enable steady ECG measurements.

(a) Bio Amp

(b) Electrode and shielded lead wire

Fig. 3 Measuring device of electrocardiogram

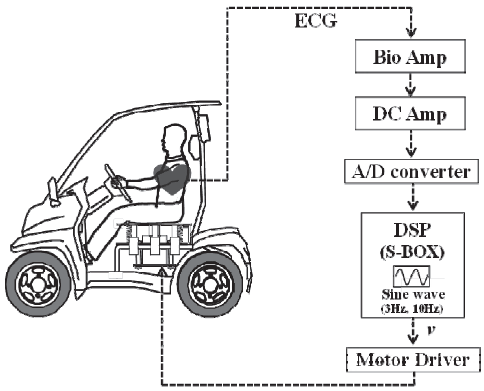
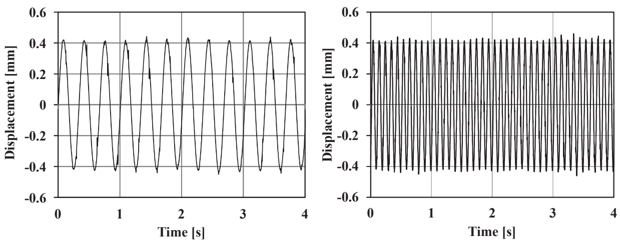


Fig. 4 System in vibration experiments of vehicle stop state



(a) 3Hz (b) 10Hz

Fig. 5 Time histories of seat displacement

5. Setting Vibration Frequencies in Vibration Experiments

To verify the effectiveness of the RRI-SW vibration control system, we conducted experiments in a stationary vehicle using ASS to generate driver vibration. A stationary vehicle was used in the experiments to eliminate driver's stress from maneuvering a vehicle as much as possible. In ISO2631's equal-feeling contours [16] and Janeway's limits of ride comfort [17], it is shown that a human body is sensitive to vibration at frequencies of 4–8 Hz and that, in order to reduce the degradation in ride comfort caused by up-and-down vibration, vehicle body vibration at this frequency range must be reduced. In general, when steady vibration occurs, a vibration frequency of between 0.2 Hz and 3 Hz is experienced as a "floating feeling" and that of between 8 Hz and 20 Hz is experienced as a "fluttering feeling" [18].In the vehicle used in the experiments, therefore, we set the RRI-SW vibration control system to switch between 3 Hz and 10 Hz to provide different two vibration control levels. Figure 4 shows a schematic of the experimental setups used in this paper. We used the algorithm described in Section 3 in the RRI-SW vibration control system. Figure 5 shows examples of seat responses when the ASS was vibrated at a frequency of 3 Hz and 10 Hz. For comparison purposes, we also conducted the experiments with vehicles having only these when the ASS was vibrated at a frequency of 3 Hz and 10 Hz. When a vehicle enters a rough road, the height differences of uneven road surfaces is typically confined to a certain range, and the acceleration amplitude is rarely constant at different vibration frequencies, as described in the ISO standards. Therefore, considering the impact of a change in vehicle speed while traveling on the same rough road, we set the vibration frequencies such that they provide the same displacement amplitude.

To understand the impact that up-and-down vibration frequency has on heart rate variability, we conducted vibration experiments on one test subject. Vibration frequencies used in the experiments were 3 Hz and 10 Hz chosen for the different ride comfort experiences, and the frequencies between 4 Hz and 8 Hz that require restraint to improve ride comfort. We set the maximum displacement amplitude to approximately 1 mm for all vibration conditions. The experiments involved sitting at rest for three minutes and vibration for ten minutes, a total of 13 minutes, while an electrocardiogram was taken. As a result, the LF/HF value was high at frequencies between 4 Hz and 8 Hz, confirming that the driver was in stress. The LF/HF value at 3 Hz (floating feeling) and that at 10 Hz (fluttering feeling) were lower than at 4–8 Hz and higher than at no vibration. The LF/HF values during vibration were approximately two to seven times higher than that at no vibration, showing a clear difference during up-and-down vibration. This confirms that it is possible to estimate the psychological state of a driver.

6. Experimental Method

We confirmed it was possible to estimate the psychological state of a driver to up-and-down vibration from the preceding section. Therefore, we conducted

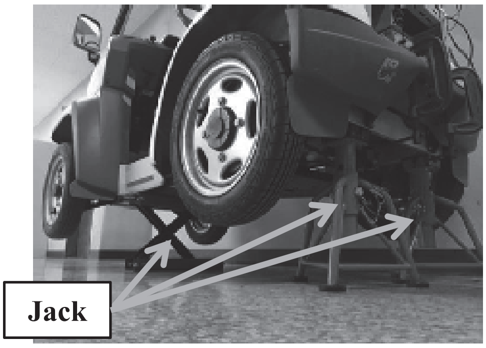


Fig. 6 A vehicle used in the experiments for a stationary vehicle

Table 1 List of experimental vehicles

Vehicle	Vibrating state
A	10 Hz
B	3 Hz
C	RRI-SW vibration control with $\overline{\mathrm{RRI}}_f$
D	RRI-SW vibration control without $\overline{\mathrm{RRI}}_f$

vibration-testing experiments using a stationary vehicle. In the vibration experiments with a stationary vehicle, we eliminated vehicle body resonance by jacking up the vehicle, as shown in Fig. 6. We conducted the experiments on the ASS seat of the four vehicle types described in the previous section. We also examined two kinds of vehicles as RRI-SW vibration control system. One is considered with $\overline{\mathrm{RRI}}_f$, another is not considered with $\overline{\mathrm{RRI}}_f$. Table 1 shows list of experimental vehicles. The flow of the experiment, it involved a driver taking three minutes of rest in a stationary vehicle, followed by ten minutes of vibration, and an electrocardiogram was acquired for the entire 13 minutes. The test subjects were not informed of the length of their stay in the vehicle prior to the experiments. In electrocardiogram monitoring, a change in the person's breathing rhythm makes it difficult to accurately evaluate the activities of the autonomic nervous system. Thus, test subjects were asked not to speak during the experiments. We conducted the vibration vehicle controlled by experiments in the following order: a vehicle vibrating at 10 Hz, a vehicle vibrating at 3 Hz, and the RRI-SW vibration control system. To take into account the fatigue of the test subjects and their physical burden from the vibration experiments, we provided sufficient rest time between experiments in each vehicle. Before starting the experiments in each vehicle, we checked that test subjects' blood pressure and heart rate were at a certain level. We also measured the salivary amylase activity as a simple and quantitative indicator of stress. When a test subject was identified stressed, we increased the rest time so that the psychological state of the test subject became approximately the same when each experiment started. Before starting the experiments, we acquired an electrocardiogram at no vibration (sitting at rest) for ten minutes for each test subject for comparison with the electrocardiogram acquired during the vibration experiments. Table 2 shows the height, weight, and age of the test subjects. The test subjects were three healthy male undergraduate and graduate students with a passenger vehicle driver license. (The average and standard deviations of height, weight, and age are 169.7 ± 2.9 cm, 57.5 ± 0.8 kg, and 21.7 ± 0.9 years old, respectively.) The experiments were approved by the Ethics Committee for "research on human beings" of Tokai University, and we explained test subjects their participation in the experiments. Test subjects who agreed to participate in the experiments signed the agreement approved by the Committee.

Table 2 List of height, weight and age of the test subjects

Subject	Height [cm]	Weight [kg]	Age
A	173.5	57.8	21
B	166.2	56.3	21
C	169.5	58.3	23

7. Experimental Results

Figure 7 shows LF/HF values at each vehicle when the 10 Hz vibrating vehicle was considered to be 100%. The two RRI-SW vibration control systems vehicle which take $\overline{\mathrm{RRI}}_f$ into consideration and not take $\overline{\mathrm{RRI}}_f$ into consideration are compared. In the case of the RRI-SW vibration control system vehicle which does not take $\overline{\mathrm{RRI}}_f$ into consideration, the subject felt stress.

All test subjects were found more relaxed in the 3 Hz-vibrating vehicle than in the 10 Hz-vibrating vehicle. In addition, all subjects were most relaxed when using $\overline{\mathrm{RRI}}_f$ applied to the RRI-SW vibration control system. From these, we conclude that, in the vibration experiments with a stationary vehicle, a driver was most relaxed when using the RRI-SW vibration control systems which take $\overline{\mathrm{RRI}}_f$ into consideration that switches between vibration control types in response to the driver's biometric data.

8. Conclusion

This paper proposed an RRI-SW vibration control system that evaluates the change in driver's psychological

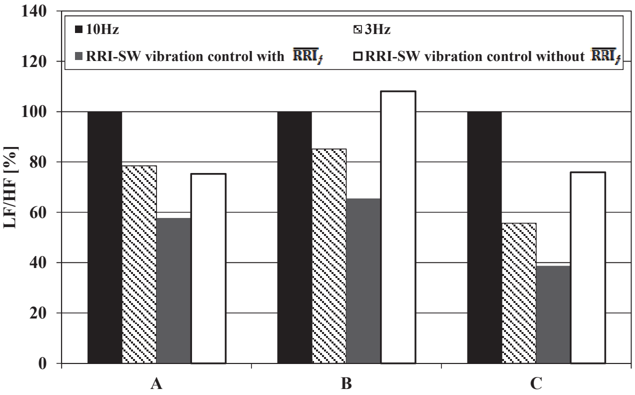


Fig. 7 LF/HF values at each vehicle when the 10 Hz vibrating vehicle was considered to be 100%

state in response to up-and-down vibration from continuously collected driver's heart rate variability and switches between vibration control types. We implemented the proposed RRI-SW vibration control system by loading ASS onto the seat of an ultra-compact electric vehicle that has become popular recently, and conducted a basic study on its effectiveness. We conclude that, in the vibration experiments with a stationary vehicle, a driver was most relaxed when using the RRI-SW vibration control systems which take $\overline{\mathrm{RRI}}_f$ into consideration that switches between vibration control types in response to the driver's biometric data.

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