Sleep-Inducing Factors in Mechanical Environments*

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Abstract
In running cars or trains, passengers are often getting sleepy. We focus on this physiological phenomenon. If a machine can reproduce this phenomenon, it is feasible to put insomnia patients or infants to sleep without any harmful effects. This will bring extreme benefit for insomnia patients or parents of babies. The purpose of this study is to elucidate the sleep-inducing factors of running cars or trains, and the final goal is to develop a sleep inducing machine which reproduces the mechanical environment for sleep. For the first step, this study investigated the relationship between sleepiness and vibrations on several trains. The sleepability of each train is discussed by the ratio of sleeping passengers (RSP). High RSP trains can be recognized as comfortable to sleep. The acceleration profile of trains is analyzed by FFT and jerks. The results suggest that the comfortable train has mainly low-frequency (under 2.0 Hz) vibrations with particular fluctuation. Small jerk also contributes the sleepability. A prototype sleep inducing machine is tested with several subjects. The questionnaire survey indicates that near 1.0 Hz excitation is the most comfortable vibration for sleep. This result supports our hypothesis.

Key words: Sleep Inducing, Mechanical Environment, Train Vibration, Low Frequency Vibration, Jerk.

1. Introduction
Sleep is important for health. Insomnia is one of major social problems. Babies who could hardly fall asleep are also seen as a headache for their parents, because there are a lot of nuclear families in Japan. In terms of insomnia patients, drug therapy is a common treatment, however, there is a problem of adverse effect. In addition, drug therapy is not appropriate for babies. If a machine can put people to sleep without drugs, it is a very effective treatment. Other practical applications are also expected, for example a quick sleep inducing machine for long distance truck drivers at a resting place. In order to realize such sleep inducing machine, this study focuses on a phenomenon that passengers often fall asleep in running cars or trains.

Conceivable sleep inducing factors in mechanical environments are light, temperature, sound, vibration, oxygen density and so on. Light condition is an important factor of sleep, however, light may not be a conclusive factor because passengers often sleep in well lighted trains. Even though suitable temperature is necessary to sleep, people do not always get sleepy in comfortable temperature. The oxygen density control requires high cost, and also has physiological risk. Then, this study focuses the vibration because sleeping children often wake up when the car or the train is stop. This phenomenon suggests that the vibration is one of special factors of sleep induction. Although there are a lot of studies about sleep disturbance [1] and comfortableness with vibration [2][3], there are few studies about the vibration which induces sleep. Then, this study investigated the relationship between sleep induction phenomenon and the vibration. A prototype machine for sleep inducing is also discussed.
2. Vibration measurement of running trains

Vibration measurement is an important point of this study. With regard to the research object, trains and cars are possible. In this study, trains are more applicable than cars considering repeatability of measurement, safety, and costs. This study adopts acceleration sensors which are Analog Devices products, ADXL103 (1-axis) and ADXL203 (2-axes). The two sensors are fixed on the surfaces of a metal cube cut by NC machine and the assembled sensors are used as a three axes acceleration sensor for the vibration measurement. The sensor is set on a window frame of the running trains. Considering design of a sleep inducing machine such as a mechanical bed, the vibration pattern at stiff position will be required rather than at soft position. Object trains of vibration measurement are 9 railway lines (from 'A' to 'I') in Tokyo and its environs. As illustrated in Fig.1, in this measurement, sensor axes are set as mentioned below; x-axis is the direction of movement, y-axis is the crosswise direction, z-axis is the vertical direction.

Fig. 1 Direction of Acceleration Sensors

Fig.2 and Fig.3 show the vibration patterns of railway line 'D' and 'F'. In the direction of the train movement (x-axis), almost all components are low frequency vibrations. The reason of this result is guessed that the x-axis vibration pattern mainly includes the acceleration of start and stop, and no acceleration with uniform motion. X-axis vibration is important to discuss the jerk of trains. Discussion about the jerk is described later. With respect to the crosswise direction (y-axis), rapid acceleration changes are observed when the train approaches a tunnel or two trains pass each other. However, vibration of y-axis does not impact to sleep because such rapid changes do not observed frequently. In Fig.2 and Fig.3, there are offsets of $-1 \text{ m/s}^2$ in each axis. This might probably be caused by the inclination of the sensor position and/or the offset of the sensor.

In the vertical direction (z-axis), the measurement results considerably correspond with the sensible vibrations. For instance, the z-axis acceleration indicates large change when the measurer feels large shock. This tendency is also true for small shock. Moreover, the overall tendency of the vibration intensity of railway 'F' is larger than that of 'D'. This result corresponds to sensible vibration of the measurers. Consequently, the sensible vibration of the passengers is greatly affected by the z-axis vibration. In this paper, subsequent discussion of the vibration deals with z-axis vibration, unless otherwise noted. In Tokyo and its environs, distances between two adjacent stations are often short, and the acceleration data are divided into short time vibrations. This study adopts 20 seconds data for FFT analyses. Fig.4 displays two FFT results calculated from 20 seconds data and 40 seconds data in the railway line 'B'. As indicated in Fig.4, the overall tendency of FFT result scarcely changes if using the data of 20 seconds or more.
Fig. 2  Vibration Data of Railway Line 'D'

Fig. 3  Vibration Data of Railway Line 'F'
2.2. Relationship between Vibration and the Ratio of Sleeping Passengers (RSP)

Considering usual experience in running cars or trains, these conveyances can be classified into easy or difficult to sleep. This study defines the ratio of sleeping passengers to all passengers as RSP (Ratio of Sleeping Passengers). This index will show the sleepability of each train. It is no secret that human beings have a biological clock called circadian rhythm. Desirable RSP measurement style is that all passengers are measured in all periods of time because the drowsiness depends on the passengers and times. However, such style requires too much cost. For feasible measurement, this study surveys in a certain period of time for all target trains. This style also aims to coordinate the measurement conditions as much as possible except the mechanical environments.

The period of time for the measurement is from 2:00 PM to 4:00 PM to avoid the drowsiness peak at around noon after. Sleeping passengers are judged only by visual evaluation. Only for measuring the sleepability of trains, this method is enough though the detail of sleeping condition is not clear [10]. For data reliability, RSP was measured in from 2 to 7 cars per a boarding. The numbers of measured passengers are from 161 to 1114. The result of RSP measurement is listed in Table 1. This result suggests that railway line ‘A’ and ‘B’ are easy to sleep, whereas ‘H’ and ‘I’ are difficult.

To elucidate the relationship between RSP and the mechanical environment of a train, this report discusses the characteristics of train vibrations. The FFT result of each train is shown in Fig.6. The graphs on the left side show overall result (0-50 Hz) and the right side is magnified view (0-5 Hz). As overall tendency, high RSP trains almost only include low frequencies. On the other hand, low RSP trains include both low and high frequencies as shown in Fig.6. Especially, railway line ‘I’, the minimum RSP train, indicates large peaks in the range of 10-25 Hz. In this measurement, acceleration intensity seems to have no relationship with RSP.
Fig. 6 FFT Results of Railway Line 'A-I'
Table 1  Ratio of Sleeping Passengers

<table>
<thead>
<tr>
<th>Line</th>
<th>Num. of Sleeping Passengers</th>
<th>Num. of Passengers</th>
<th>Ratio of Sleeping Passengers</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>298</td>
<td>931</td>
<td>0.32</td>
</tr>
<tr>
<td>B</td>
<td>266</td>
<td>933</td>
<td>0.29</td>
</tr>
<tr>
<td>C</td>
<td>224</td>
<td>852</td>
<td>0.26</td>
</tr>
<tr>
<td>D</td>
<td>267</td>
<td>1114</td>
<td>0.24</td>
</tr>
<tr>
<td>E</td>
<td>173</td>
<td>970</td>
<td>0.18</td>
</tr>
<tr>
<td>F</td>
<td>148</td>
<td>845</td>
<td>0.18</td>
</tr>
<tr>
<td>G</td>
<td>145</td>
<td>857</td>
<td>0.17</td>
</tr>
<tr>
<td>H</td>
<td>25</td>
<td>289</td>
<td>0.09</td>
</tr>
<tr>
<td>I</td>
<td>4</td>
<td>161</td>
<td>0.02</td>
</tr>
</tbody>
</table>

From this result, we assume that low frequency vibration (0-2 Hz) has positive effect on sleepiness whereas high frequency (10-20 Hz) disturbs to sleep. Ride quality of a train has correlation with the sleepiness. Japan National Railway defined ride quality of trains. With this standard, vibrations from 5 to 10 Hz descent ride quality [4]. This standard also supports our assumption. At the present stage, measurement results are not in contradiction. To verify the assumption, large numbers of additional measurements and physiological approaches are necessary. It is one of future work.

Based on the assumption, we define a ratio ‘Plfmax_/Phfmax_’ as RPI (Ratio of Peak Intensity); where Plfmax is the maximum peak intensity in the range of low frequency (0-2 Hz), and Phfmax is the maximum peak intensity in high frequency range(10-20Hz) as shown in Fig.7.

Fig. 7  Definition of RPI

Fig.8 represents the relationship between RSP and RPI. There is positive correlation between RSP and RPI in the graph. Pearson’s product-moment correlation coefficient is 0.783 with p-value of 0.013. Moreover, if excepting the data of line 'A', the correlation coefficient is 0.91 with p-value of 0.002.
This result suggests that a high RPI vibration induces passengers to sleep. However, several trains indicate different RSP with almost the same RPI such as 'A' and 'G'. In addition, the RSP of 'A' (RPI=3.7) is higher than that of 'C' (RPI=7.2). This result suggests that there are other sleep inducing factors in the mechanical environments.

2.3. Sleep Inducing and Jerk

With the most intuitive forecasting, the candidates of sleep inducing factors are vibration and sound. With respect to the sound, quantitative difference between all measured trains could not be found at the present stage. Then, this study focuses the jerk of trains. Jerk is the temporal differentiation of the acceleration. Jerk is often used as the indicator of an abrupt change of target motion. Hogan et al. proposed a trajectory with minimized jerk represents the smooth motion of human's arm [5]. Hogan’s theory is also used to improve ride quality [6]. Fig.9 displays the acceleration and jerk in a car with repeating hard braking.

In terms of running train, the jerk is quite smaller than hard braking car as shown in Fig.10. With ordinal data treatment, the difference between all trains cannot be found because the S/N ratio of jerk is too small. Thus, this study adopts Savitzky-Golay filter to calculate the jerk of trains. Fig.11 indicates filtered data of the jerk.

![Fig. 9 Acceleration and Jerk of a Car with Hard Braking](image1)

![Fig. 10 Acceleration and Jerk of a Train (Line 'B')](image2)

![Fig. 11 Filtered Jerks (Car and Train)](image3)

We calculated the jerk profile of 300 seconds in the train movement direction (x-axis). The filtered jerk profile of each train is shown in Fig.12. Especially, the trains which have comparable RPI indicate different profile of jerks. In general, the motion of conveyance is evaluated by numerically integrated jerk, however, our data do not have high S/N ratio. This means the numerically integrated value includes considerable noises. In addition, only a certain magnitude of jerk probably disturbs passengers to sleep. Based on these viewpoints, the
frequency of a certain magnitude of jerk (over 0.2 m/s³) is counted in each train. Table 2 lists the relationship between RSP, RPI and the frequency of the certain jerks, and Fig.13 is the restatement of the Fig.8 with additional jerk data.

In Fig.13, trains which are out of RPI-RSP correlation show particular frequency of jerk. For instance, the line ‘C’ has large jerk frequency of 15. Although the line ‘C’ has high RPI of 7.2, it only indicates 0.26 RSP while the line ‘D’ performs 0.24 RSP with 4.7 RPI. On the other hand, the line ‘A’ indicates extremely high RSP of 0.32 and it has extremely small jerk frequency of 2. These results strongly suggest that there is a correlation between RSP and jerk.

![Fig. 12 Filtered Jerks of the Trains](image)

![Fig. 13 RSP-RPI and Frequency of Particular Jerk](image)

<table>
<thead>
<tr>
<th>Railway Line</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
</tr>
</thead>
<tbody>
<tr>
<td>RSP(%)</td>
<td>20</td>
<td>30</td>
<td>26</td>
<td>24</td>
<td>18</td>
<td>18</td>
<td>17</td>
<td>9</td>
<td>2</td>
</tr>
<tr>
<td>RPI</td>
<td>3.7</td>
<td>6.3</td>
<td>7.2</td>
<td>4.7</td>
<td>2.3</td>
<td>2.8</td>
<td>3.6</td>
<td>1.0</td>
<td>1.1</td>
</tr>
<tr>
<td>Jerk Freq.</td>
<td>2</td>
<td>11</td>
<td>15</td>
<td>12</td>
<td>5</td>
<td>5</td>
<td>7</td>
<td>7</td>
<td>17</td>
</tr>
</tbody>
</table>
As explained about Fig. 5, the overall tendency of train vibration is almost constant. However, there must be fluctuation of vibration. At first, $1/f$ fluctuation was prospected in train vibrations [7], however, there was not comparable result to $1/f$ fluctuation with our analyses. Fig. 14 shows the frequency distribution dependency on time using FFT. In this figure, each FFT is calculated per 0.64 seconds with following 10.24 seconds data. Although there is not $1/f$ fluctuation, FFT results show changes depending on time. Longitudinal white stripes in the figure represent the standing time at stations. Dark color area means frequently measured vibration. In this figure, the dark color area near 1.5 Hz is the peak frequency. The peak frequency slightly changes with time. This means that the train vibration has a fluctuation. Moreover, this tendency is also found in the other trains.

![Fig. 14 Time Dependency of Frequency Distribution in the Line 'B'](image)

Then, we anticipated that trains have different fluctuations depending on RSP. Fig. 15 shows the peak frequency changes and the occurrence rates in the line 'A-H'. The calculation method is the same with Fig. 14. The left side graphs display the frequency with the maximum occurrence rate. The right side bar graphs indicate the occurrence rate of the maximum peak.

With this analysis, a tendency was found. High RSP trains indicate mound shape in bar graphs, while low RSP trains have irregular pattern. In addition, high RSP trains perform the large peak of mound. This suggests that the peak frequency of high RSP trains is concentrated on a particular low frequency (under 2.0 Hz). The peak frequency has a fluctuation represented by the mound shape. Considering the characteristics of high RSP train vibration, the main frequency transits near 0-2 Hz. In addition, vibrations around 5-20 Hz and large jerks are suppressed.
Fig. 15  Peak Frequency Transition and Occurrence Rate of Peak Frequency
3. Prototype machine of sleep inducing

This study proposes a prototype machine for reproducing the mechanical environment for sleep inducing. The prototype is a reclining chair equipped with vibration exciter using eccentric rotator as shown in Fig.16. The mode of vibration is simulated with the numerical dynamic model. The parameters are determined for low frequency vibrations. As the first step of the machine test, comfortable excitation frequencies are researched by sensory evaluation with 10 subjects. The result of questionnaire survey is shown in Fig.17. Almost all subjects answered near 1.0 Hz excitation is the most comfortable. This result supports the hypothesis of the relationship between sleep inducing and low frequency vibration.

![Prototype of Sleep Inducing Machine](image)

Fig. 16 Prototype of Sleep Inducing Machine

![Questionnaire Result of Comfortable Vibration Frequency](image)

Fig. 17 Questionnaire Result of Comfortable Vibration Frequency

4. Conclusion

This study investigated sleep inducing vibration in running trains with RSP (Ratio of Sleeping Passengers) evaluation. We found several suggestions in terms of correlation between vibrations and RSP. Low frequency vibrations (under 2.0 Hz) contribute high RSP whereas high frequency (10-20 Hz) vibrations disturb passengers sleeping. Frequent large jerks over 0.2 m/s² also decrease RSP. With a prototype sleep inducing machine, near 1.0 Hz vibration is comfortable for 10 subjects. This result also supports our hypothesis about the relation between vibration and sleeping. Remaining works about sleep induction are as follows: The discussion of vibration amplitude, Physiological investigation [8] treating with biological organs. In addition, brainwave or other relevant sleep state judgment is necessary to keep the rigor. However, considering the cost of brainwave measurement in running trains, other durable and reasonable method is desirable for sleep measurement. This study also tries to develop such sleep judgment method [9]. After these discussions, we aim to develop a machine of sleep inducing.
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References