'94 KACC (1994. 10. 17 ~ 20)

Active control of an ambulance stretcher: Simulation study

K. Sagawa, H. Inooka and E. Ino-Oka
Department of Mechanical and Aeronautical Engineering,
Faculty of Engineering, Tohoku University,
Sendai, 980-77, JAPAN

Abstract:

In this paper, we discuss a method for design of an ambulance stretcher which can decrease blood pressure fluctuation caused by ambulance acceleration.

Recently, a lot of stretchers which can isolate the vertical vibration to reduce body resonances (4~10 Hz) have been used during ambulance transport. However, we have found that blood pressure of a patient laying in the stretcher fluctuates when the ambulance accelerates or decelerates. Since the enforced change of the blood pressure may deteriorate the patient's condition, a stretcher to cancel head-to-foot acceleration and to decrease the blood pressure variation (BPV) is expected for safe transport.

We propose a method to design a stretcher which is tilted according to an adequate angle to cancel head-to-foot acceleration by gravity when the ambulance accelerates or decelerates. A control method of the stretcher is constructed by means of simulation analysis using acceleration data measured during ambulance transport.

It is confirmed that the active controlled stretcher proposed has good performance for the BPV reduction.

1 Introduction

Recently, a great deal of attention has been paid to patient's death before arriving at a hospital during ambulance transport, named DOA (Dead On Arrival). The factors which deteriorate the patient's condition during transport are as follows; (1) lack of prehospital care for the patient [1], and (2) vibration, acceleration and deceleration of running ambulance with relatively poor ride characteristics compared with a private car. To overcome the problem (1), the ambulance with a doctor or emergency technician have been used recently. In addition, CPR (cardiopulmonary resuscitation) by ordinary citizens should be operated. The problem (2) is solved by using a vibration-absorbing stretcher that isolates the vibration frequency of body resonances (4~10Hz). Moreover, many researches have been made on the design of the stretcher based on the reduction of ambulance vibration [2] [3] [4].

We have found that the blood pressure of a human laying on the stretcher fluctuates due to head-to-foot acceleration caused when the ambulance accelerates or decelerates. As the enforced change of the blood pressure may lead to deterioration of patient's condition, it is necessary to design a stretcher to cancel head-to-foot acceleration and to decrease the blood pressure variation (BPV). However, no studies have ever tried to design the stretcher based on the BPV reduction. In order to design the stretcher, we have developed a 3rd order ARX (autoregressive exogenous) model which can quantitatively express the relation between the BPV of the patients and head-to-foot acceleration in an emergency brake. The model will be used to compare the BPV of the patients laying in a conventional stretcher and that laying in the stretcher we propose.

In this paper, we propose an active controlled stretcher that can cancel head-to-foot acceleration by changing a tilting angle of it according to ambulance acceleration. The effect of the stretcher on the BPV reduction is numerically compared by means of substituting head-to-foot acceleration data to the ARX model. In addition, the effect of chest-to-back acceleration caused by the motion of the stretcher on patient's body is evaluated. A control method of the stretcher is constructed to achieve the BPV reduction close to 100 % and chest-to-back acceleration with positive value and slight change.

2 Active Controlled Stretcher

2.1 Method for canceling head-to-foot acceleration

Principle for canceling head-to-foot acceleration of the active controlled stretcher proposed is shown in Fig.1. A patient is laid in supine position head backward and the stretcher is tilted around a fulcrum O. Here, acceleration α_{ZB} and α_{XB} are head-to-foot and chest-to-back

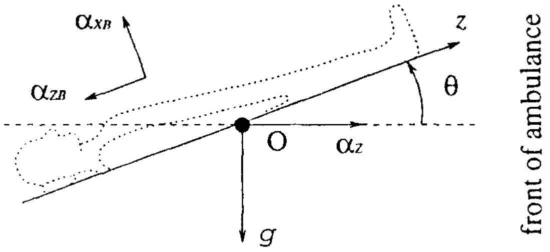

Fig 1: Active controlled stretcher

acceleration operated in the supine patient's portion at a distance of z from O on the stretcher, respectively, see Fig.1. Acceleration α_{ZB} and α_{XB} are given by

$$\alpha_{ZB} = -\alpha_Z \cos\theta - g\sin\theta + z\dot{\theta}^2, \qquad (1)$$

$$\alpha_{XB} = -\alpha_Z \sin\theta + g\cos\theta + z\ddot{\theta}, \qquad (2)$$

where θ is pitch angle of the stretcher, $\dot{\theta}$ is angular velocity, and $\ddot{\theta}$ is angular acceleration. θ is restricted with

$$-\theta_m \leq \theta \leq \theta_m. \qquad (3)$$

The effect of vertical acceleration of the ambulance is ignored because that shall be isolated by the stretcher suspensions used recently.

When the ambulance accelerates or decelerates, the stretcher is tilted to cancel head-to-foot acceleration α_{ZB} by counterbalancing head-to-foot component of α_Z with that of gravity g. It is important to keep chest-to-back acceleration α_{XB} larger than zero to prevent the patient's body from hitting against the stretcher surface. Moreover, α_{XB} must be smaller than human tolerable acceleration.

We derive a desired angle θ_d of the stretcher to cancel head-to-foot acceleration. Assuming $\alpha_{ZB} = 0$ and $\dot{\theta} = 0$, we rewrite Eqn.(1) as follows,

$$0 = -\alpha_Z \cos\theta_d - g\sin\theta_d.$$

The desired angle θ_d of the stretcher is given by,

$$\theta_d = -\tan^{-1}\frac{\alpha_Z}{g}. \qquad (4)$$

The relation between α_Z and θ_d is shown in Fig.2. This figure indicates that when α_Z decreases, the desired angle is expected to be increased. Because the tilting angle has a restriction as shown in Eqn.(3), the desired angle is limited as

$$\tilde{\theta}_d = \begin{cases} \theta_m & \theta_d > \theta_m \\ \theta_d & |\theta_d| \leq \theta_m \\ -\theta_m & \theta_d < -\theta_m \end{cases}. \qquad (5)$$

In this paper, we choose

$$\theta_m = 0.122 \text{ rad. (7 deg.)},$$

because this angle corresponds to relatively steep slopes in Japan.

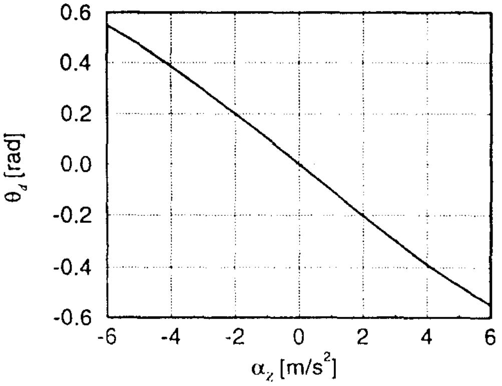

Fig 2: α_Z vs. θ_d

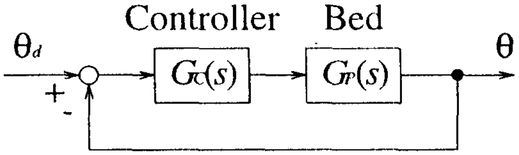

Fig 3: Block diagram of active controlled stretcher

2.2 Transfer function of the active controlled stretcher

For the simulation analysis of the active control of the stretcher, we need to construct a control system for it. The block diagram of the active controlled stretcher system is constructed as Fig.3, where $G_C(s)$ and $G_P(s)$ are the transfer functions of a controller and dynamics of the stretcher, respectively. The closed loop transfer function $G(s)$ of this system is given by

$$G(s) = \frac{G_C(s)G_P(s)}{1 + G_C(s)G_P(s)}.$$

We assume that the control system can be expressed by 2nd order transfer function like a servo one, and rewrite $G(s)$ as follows,

$$G(s) = \frac{\omega_B^2}{s^2 + 2\zeta_B\omega_B s + \omega_B^2}, \qquad (6)$$
$$\omega_B = 2\pi f_B,$$

where ζ_B and f_B are viscous damping ratio and natural frequency, respectively. As the tilting angle of the stretcher is limited, no overshoot in the step response of $G(s)$ is desirable. Therefore, we determine the damping ratio as,

$$\zeta_B = 1.0. \qquad (7)$$

The natural frequency f_B will be determined by the simulation analysis later. The controller $G_C(s)$ is constructed so that $G(s)$ will satisfy Eqn.(6).

3 Evaluation index

To evaluate the effect of the active controlled stretcher, we use following indices; reductive ratio of the BPV caused by using the active controlled stretcher, the sign of α_{XB} operating on the patient's head, and a limit of exposure for vibration (α_{XB}) transmitted from stretcher surface to the patient's body.

3.1 Reductive ratio of the BPV

We define ρ_{BP} to indicate a reductive ratio of the BPV of a patient transported by the active controlled stretcher compared with that transported by a fixed one. The reductive ratio ρ_{BP} is given by

$$\rho_{BP} = \frac{R_0 - R_1}{R_0} \times 100[\%], \tag{8}$$

(9)

where R_0 and R_1 are the root mean square value (RMS) of the BPV using the fixed stretcher and the active controlled one, respectively. The increase of ρ_{BP} means an improvement in the performance of the active controlled stretcher.

Note that R_0 and R_1 are numerically obtained using a 3rd order ARX model which indicates the relation between the BPV of the patients and head-to-foot acceleration during emergency brake [6]. Namely, R_0 and R_1 are generated by the use of head-to-foot acceleration of the stretcher in the fixed state and active controlled one. The ARX model is given by

$$\mathrm{BPV} = G_3(z^{-1})\overline{\alpha_{ZB}} \tag{10}$$

where $G_3(z^{-1})$ is a discrete time transfer function from head-to-foot acceleration to the BPV and is given by

$$G_3(z^{-1}) = \frac{2.610 - 4.043z^{-1} + 1.753z^{-2}}{1 - 1.698z^{-1} + 0.865z^{-2} - 0.092z^{-3}} \tag{11}$$

where $\overline{\alpha_{ZB}}$ is a discrete data sampled from a continuous α_{ZB} with the sampling period of 1 second [6].

3.2 Sign of α_{XB}

If the tilting angle makes rapid change, patient's body may heave and hit against the stretcher surface. Therefore, chest-to-back acceleration α_{XB} should be positive for safety, and is given by

$$\alpha_{XB} > 0. \tag{12}$$

3.3 Limit of exposure for vibration

To evaluate the effect of chest-to-back acceleration (α_{XB}) on the patient's body, we use ISO 2631 [5] (the International Organization for Standardization) as a criterion of exposure limit and compare it with the RMS of α_{XB} generated during the active control of the stretcher. ISO 2631 defines and gives numerical values for limits of exposure for vibrations transmitted from solid surfaces to the human body in the frequency range 1 to 80 Hz. These limits are given for use according to the three generally recognizable criterion of preserving comfort, working efficiency, and safety or health. The limits set according to these criterion are named in ISO 2631, the "reduced comfort boundary", "fatigue-decreased proficiency" and the "exposure limit", respectively. For example, in the design of passenger accommodations, the "reduced comfort boundary" should be considered. Therefore, we employ the "reduced comfort boundary" as a criterion of chest-to-back acceleration during transport. In addition, considering from transport interval, exposure time of 2.5 hours is employed for the criterion. Examples of chest-to-back acceleration limits as a function of frequency and exposure time is shown in Fig.4. Sensitivity of the supine patient to chest-to-back vibration is greatest at 2 Hz and below. For example, in the case of the exposure time of 2.5 hours, people in normal health can bear acceleration of 0.16 m/s^2 (RMS) in the frequency range from 1 to 2 Hz in preserving comfort.

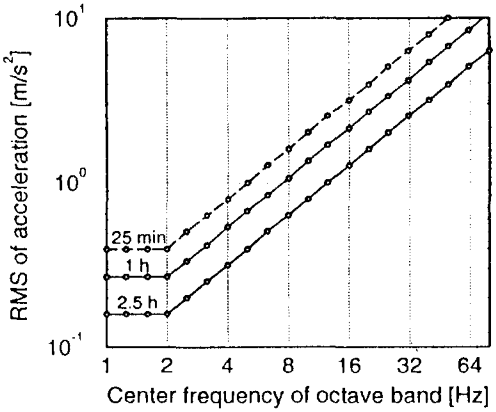

Fig 4: Chest-to-back acceleration limits

Fig.5 shows the way to get the RMS of α_{XB}. First, power spectral density of α_{XB} is obtained by FFT (fast fourier transform) method. Next, square root of the area in the power spectral density is obtained in the frequency range of one-third octave band. Finally, the RMS of α_{XB}, which is equivalent to square root of each area, is obtained for the center frequency of one-third octave band. According to ISO 2631, the RMS of α_{XB} must be smaller than the "reduced comfort boundary".

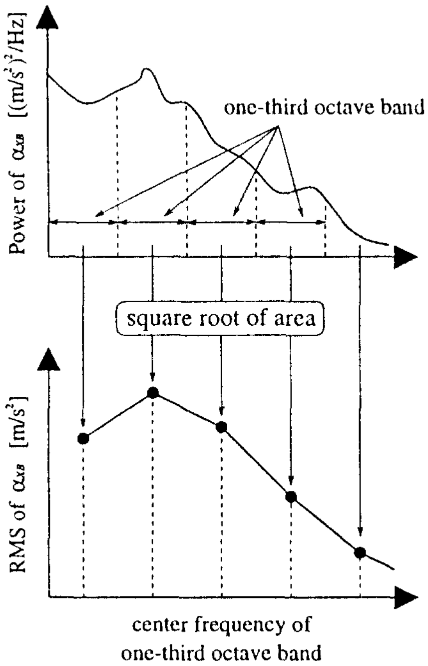

Fig 5: How to get RMS of α_{XB}

4 Simulation Analysis

We investigate the effect of the active controlled stretcher by the simulation analysis. The method of the simulation analysis is illustrated as follows; first, α_Z is converted into θ_d by Eqn.(4) and θ is obtained according to the parameter f_B from Eqn.(6). Next, α_{ZB} at $z = 0$ (a position to measure the blood pressure) and α_{XB} at $z = -1$ (patient's head) are derived from Eqn.(1) and (2) using α_Z, θ, $\dot{\theta}$ and $\ddot{\theta}$, where $\dot{\theta}$ and $\ddot{\theta}$ are derived by numerical differentiation of θ. Next, the BPV obtained by using the fixed stretcher and the active controlled one are derived from Eqn.(10). Finally, ρ_{BP} is obtained from Eqn.(9). In addition, the natural frequency f_B in Eqn.(6) must be determined so that ρ_{BP} is close to 100 %, $\alpha_{XB} > 0$, and the RMS of α_{XB} is smaller than the "reduced comfort boundary".

Two kinds of experimental acceleration data (α_Z) are used in the simulation analysis, and are shown in Fig.6(a) and Fig.6(b). They were taken during emergency brake tests when the ambulance had stopped within 5 seconds and 10 seconds from 50 km/h. We call these data α_Z(a) and α_Z(b), respectively. α_Z(a) and α_Z(b) are different in the minimum value of acceleration; the minimum value of α_Z(a) is about -5.43 m/s^2 and that of α_Z(b) is about -2.10 m/s^2. We consider that acceleration like α_Z(b) will be appeared during transport usually, while acceleration over -5 m/s^2 like α_Z(a) happens rarely.

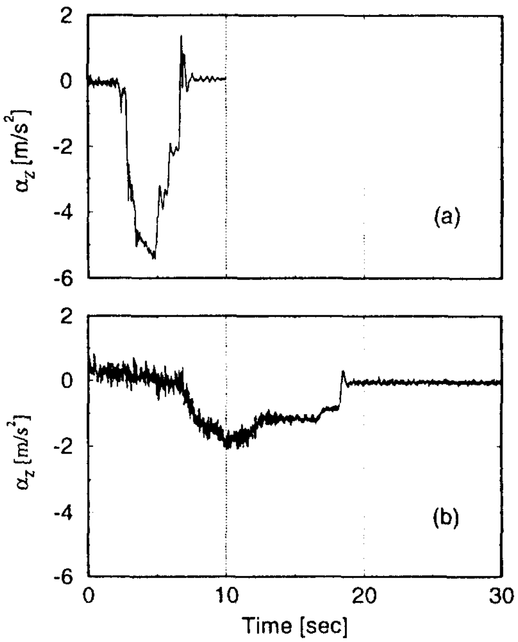

Fig 6: α_Z applied in simulation analysis

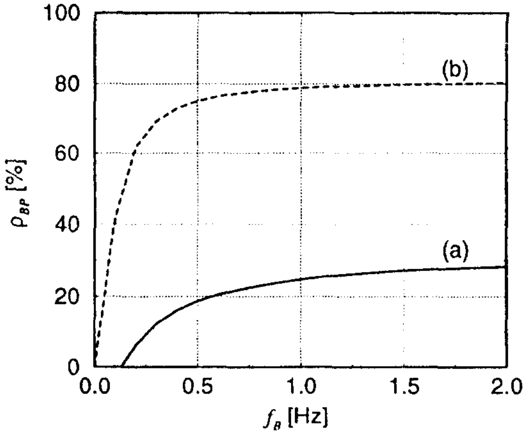

Fig 7: f_B vs. ρ_{BP}

5 Results

The relation between f_B and ρ_{BP} is shown in Fig.7. The curves of (a) and (b) indicate the simulation results using α_Z(a) and α_Z(b), respectively. There are steep rises both the curves (a) and (b) in $f_B < 0.5$ but slight increases in $f_B \geq 0.5$. In addition, the curve (b) is remarkably larger than that of (a). We have found that f_B should be large for the effect of the active controlled stretcher on the reduction of the BPV. However, ρ_{BP} derived from α_Z(a) is smaller than that from α_Z(b) throughout all the range of f_B. This is due to the re-

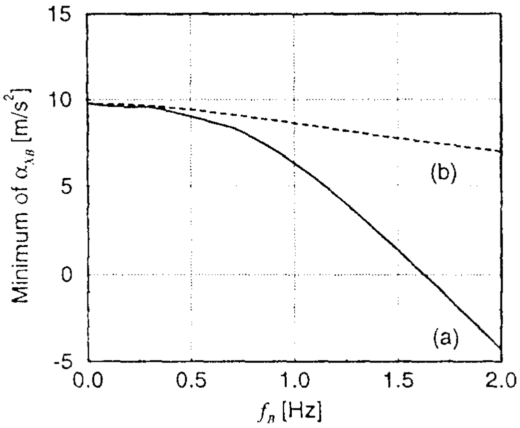

Fig 8: f_B vs. minimum α_{XB}

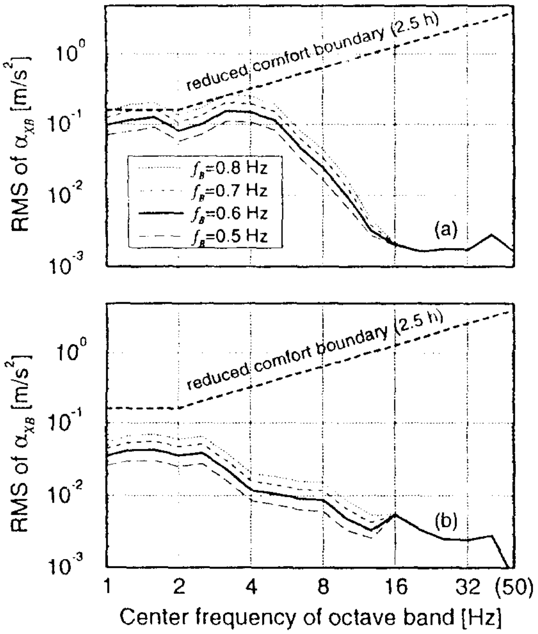

Fig 9: RMS of α_{XB}

striction of the tilting angle. Therefore, it is difficult to reduce the BPV when large acceleration have occurred.

The relation between f_B and the minimum of α_{XB} is shown in Fig.8. It is obvious that there are gradually decreases in both of them and the curve of (a) is smaller than that of (b). In addition, the curve (a) is negative when f_B is larger than 1.63 Hz. That is to say that f_B should be small for chest-to-back acceleration at patient's head. It is necessary for both of ρ_{BP} and the minimum of α_{XB} to achieve their desired conditions. In this case, we give weight to the result of the minimum of α_{XB} than that of ρ_{BP} because the hitting of the body against the stretcher surface may cause some injuries anew. Therefore, we decide $f_B < 1.6$ at present.

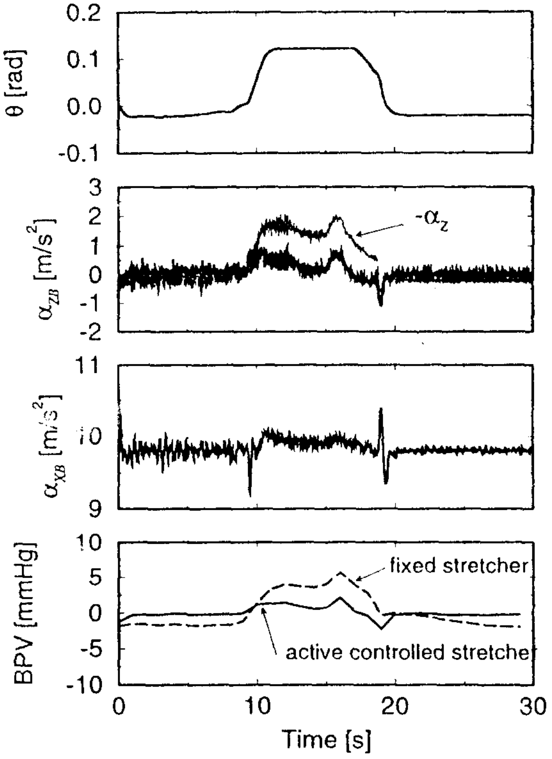

Fig 10: Example of θ, α_{ZB}, α_{XB} and BPV ($f_B = 0.6$)

Fig.9(a) and (b) show the RMS of α_{XB} generated from α_Z(a) and α_Z(b) at $f_B = 0.5, 0.6, 0.7$, and 0.8. The "reduced comfort boundary" with exposure time 2.5 hours is also shown. As Fig.9(a) indicates, the RMS of α_{XB} at $f_B = 0.7$ and 0.8 are greater than the criterion within 1 to 50 Hz band. In the case of $f_B \leq 0.6$, the RMS of α_{XB} are smaller than the criterion. Therefore, natural frequency of the closed loop transfer function Eqn.(6) is determined as

$$f_B = 0.6. \qquad (13)$$

An example of time trajectories for θ, α_{ZB}, α_{XB} and the BPV derived by the simulation is shown in Fig.10. In this case, ρ_{BP} is 67 %.

The relation between the minimum of α_Z and ρ_{BP} is shown in Fig.11. Acceleration α_Z were measured by the emergency brake tests implemented 11 times. Three ρ_{BP} rise up to 70 % when the minimum of α_Z is bigger than about -2.5 m/s^2 but one falls down to 20 % when the minimum of α_Z is about -5.5 m/s^2. This is due to the restriction in the tilting angle of the stretcher. Therefore head-to-foot acceleration is not canceled completely.

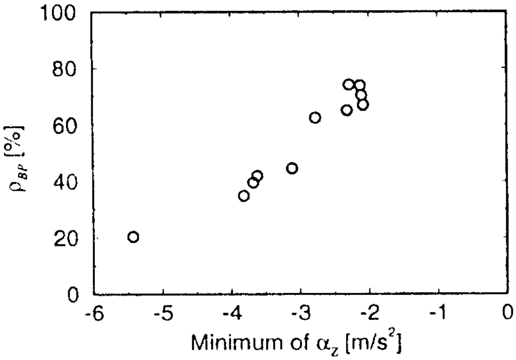

Fig 11: Relation between minimum value of α_Z during emergency brake and ρ_{BP} ($f_B = 0.6$)

The results of the simulation analysis show that the stretcher we propose is able to reduce the BPV during emergency brakes to less than half and to transport the patient with preserving comfort.

6 Discussion

The effect on the direction of patient's head in the ambulance is worth a mention. The subject had experienced the riding quality test of the ambulance laying in the stretcher head frontward before our experiment. After the experiment, the subject became motion sickness. However, the subject was in good health throughout our experiment that was implemented for two hours, and he had an opinion that it was more comfortable to be transported laying in the stretcher head backward than head frontward.

Moreover, head-to-foot acceleration occurred by the emergency brake causes the blood or body fluid to shift and pool in the upper limbs when the patient is laid in the stretcher head frontward. On the other hand, in the case of head backward, the fluid shifts and pools in the lower limb. In both head frontward and head backward, venous return decreases and then cardiac output decreases. Finally many kinds of accident will occur by the lack of the blood or by the enforced change of the blood pressure in the circulatory system of systemic portions. Especially, when the patient is laid head frontward, the blood is shifted and pooled in the head. For example, the pooling of the blood or body fluid into the brain, that is called cerebral edema, causes the expansion of the volume of the brain and causes hypoxic encephalopathy by the lack of the blood flow into the brain [7]. It is very dangerous for the patient to take no treatment when cerebral edema occurs.

From reasons mentioned above, the patient should be transported head backward in the ambulance. Therefore, we have proposed the stretcher in which the subject is laid head backward.

We can say that the active controlled stretcher proposed has the ability not only to reduce of the blood pressure variation and to support the patients in comfort but also to prevent the blood or body fluid from shifting and pooling into the systemic portions and to keep the patient from being motion sickness.

7 Conclusions

In this study, the simulation analysis of the active controlled stretcher is implemented and the effect of it is illustrated by the reduction of the BPV, the minimum of α_{XB}, and the RMS of α_{XB}. From these results we conclude that the control method of the stretcher we propose is able to achieve the favorable reductive ratio of the BPV (ρ_{BP} = 80 % max.), keep α_{XB} positive all the time, and α_{XB} within the limit of exposure for the human body.

We are planning to make an active controlled stretcher and to confirm the effect of it on the reduction of the BPV and chest-to-back acceleration experimentally.

References

[1] Emergency cardiac care comittee and subcomittes, American Heart Association: Guidelines for cardiopulmonary resuscitation and emergency cardiac care, JAMA, 268, 2171–2274, 1992

[2] R SNOOK, R PACIFICO, Ambulance ride: fixed or floating stretcher?, British Medical Journal, 2, 405–407, 1976

[3] D R Leyshon, C W Stammers, The development and performance of an ambulance stretcher suspension, IMechE, Vol 900, No D4, 249–257, 1986

[4] S BLOK, Improvement of vibration isolation in transports by bearing flats, Journal of the society of environmental engineers, 3 8, 1973

[5] Evaluation of human exposure to whole-body vibration - Part 1: General requirements, ISO 2631/1, 1985

[6] K. Sagawa, T. Takahashi, H. Inooka, E. Ino-Oka, Modeling of the Blood Pressure Variation at the Deceleration of an Ambulance, JJME, Vol.31, No.2, 35-42, 1993, Japan

[7] Nanzando's Medical Dictionary, pp.1513, Nanzando, 1990, Japan