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CLASSIFICATION	SYSTEM NUMBER
UNCLASSIFIED	511941

TITLE

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System Number:

Patron Number:

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Notes:

DSIS Use only:

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98-P-89

Modeling of the Physiological Responses to Non-linear G-suit and Positive Pressure Breathing Schedules

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1. SUMMARY

Heart level blood pressure responses to G-suit pressures (2~8 psi) with and without Positive Pressure Breathing (5~60 mm Hg) at +1Gz were investigated in this paper for six test subjects. Various models were developed and tested to simulate these responses. The results show that a single-zero, two-pole, output-error model is suitable for characterizing the blood pressure responses to G-suit and Positive Pressure Breathing (PPB) pressures. A single-input model is used for the case of G-suit pressure with and without synchronized PPB, whereas a double-input model is used for the case of G-suit pressure with asynchronic PPB. The suitability of the models developed to high +Gz environment is investigated based on the data from a prior centrifuge test of one subject. Special dynamic indices are used to quantify the characteristics of the blood pressure responses. Significant variations in the dynamic indices of individual subjects and the same subject observed at different time instances are seen. These variations indicate that a fixed standard G-suit pressure schedule might not necessarily be capable of providing adequate Anti-G protection for all subjects and even for the same subject at different time instances. The models developed in this paper can be used in an adaptive feedback control system for real-time identification and update of subjects' Anti-G protection requirements. Consequently, the G-suit pressures can be adjusted based on these models to provide most adequate Anti-G protections and compensate the variations in subject's physiological state.

LIST OF SYMBOLS

Gs	static gain
PO	percentage of overshoot
Tr	rise time
Tp	peak time
Ts	settling time
Fn	resonant frequency
Fc	cut off frequency
Fq	Nyquist frequency

2. INTRODUCTION

Due to large differences and irregularities in physiological responses to +Gz stress and G-suit pressure, the protection provided by a standard pressure schedule could be sub-optimal and even unsuitable for some pilots. An effective way to solve this problem is to adjust G-suit pressure schedules based on the physiological status of each individual subject. Modern computer and sensor technologies enable us to consider the development of a real-time controller aimed at enhancing the performance of existing standard Anti-G systems.

To design a real-time G-suit pressure controller based on biofeedback, a model of the system controlled is typically required. As shown in Figure 1, such a model would reflect the relationship between system inputs (G-suit and PPB pressures) and system outputs (physiological variables). For instance, eye-level blood pressure can be regarded as a controlled physiological variable, and G-suit and PPB pressures adjusted so that eye-level blood pressure is maintained around the required values at different levels of Gz. In such a case, knowledge regarding the eye-level blood pressure response to G-suit pressure is essential for designing a suitable Anti-G controller. Unfortunately, very little work has been done on modeling of blood pressure responses to G-suit and PPB pressures.

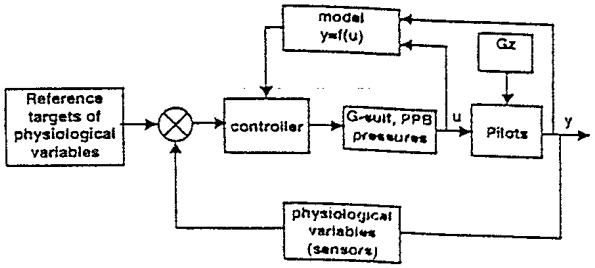

Figure 1. Schematic diagram of a biofeedback based G-suit pressure control system

There exist two general approaches to deriving a mathematical model of a dynamic system. Both methods are valid for the design of a real-time Anti-G controller. The major effort in the first approach is to identify fundamental physical laws that govern the dynamic behavior of a system in question. These laws are usually expressed through a set of differential equations. The models derived using this approach are easy to understand and provide an insight into the dynamic behavior of the systems. However, since the human body is a very complicated biological system, it is extremely difficult to

same resonant frequency of 0.06 Hz, which is also similar to the resonant frequency found in the responses of eye-level blood pressure to +Gz in [3].

5.2 Blood Pressure Response to G-suit Pressure with PPB

Two different types of electronic Anti-G valves were used in this set of experiments: (i) an NGL valve designed by Normalair Garrett Ltd., and ii) a SAMCAV valve designed by ESI. The NGL valve initiates PPB after G-suit pressure reaches 4 psi. The ratio of PPB to G-suit pressure is fixed. Therefore, one NGL valve can only produce a nearly synchronized PPB that is strongly correlated with G-suit pressure. To generate asynchronic PPB, two electronic SAMCAV valves were used to control G-suit and PPB pressures independently. In the following two subsections we discuss the responses to synchronized and asynchronic PPB schedules.

5.2.1 Model for synchronized PPB

In general, the model of Equation (2) for a two-input system can be written as follows:

$$y(k) = \frac{B_1(q^{-1})}{A_1(q^{-1})}u_1(k-1) + \frac{B_2(q^{-1})}{A_2(q^{-1})}u_2(k-1) + e(k) \qquad (3)$$

where u_1 is G-suit pressure, u_2 is PPB pressure. B_1, A_1, B_2, and A_2 are coefficient vectors and have the same structure as in Equation (2). Since synchronized PPB pressure can be expressed as a linear function of G-suit pressure, such as $u_2 = k * u_1$, Equation (3) can be re-written as follows:

$$y(k) = \left\{\frac{B_1(q^{-1})}{A_1(q^{-1})} + k\frac{B_2(q^{-1})}{A_2(q^{-1})}\right\}u_1(k-1) + e(k)$$

$$= \frac{B_e(q^{-1})}{A_e(q^{-1})}u_1(k-1) + e(k). \qquad (4)$$

Since the system (4) has only one independent input (G-suit pressure), a single-input model defined by $B_e(q^{-1})$ and $A_e(q^{-1})$ can be used to simulate the blood pressure responses. In such a case, the model maps the total protection input (generated by G-suit and PPB pressures) into one output (blood pressure). Figure 6 presents systolic blood pressure responses (for the same subject; similar to in Figure 3) to step inputs of G-suit pressure with PPB using NGL valve.

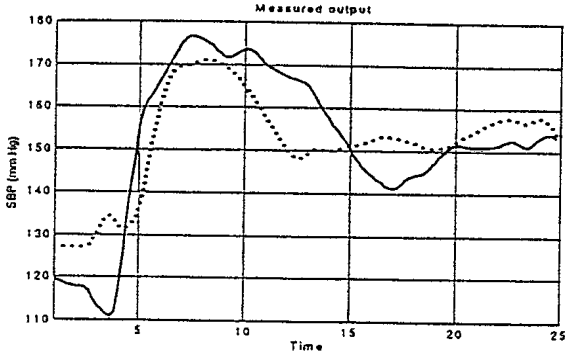

Figure 6. Two responses of systolic blood pressure at heart level to step inputs of G-suit pressure of 8 psi with PPB of 38 mmHg

Table 3. Model parameters (with synchronized PPB)

subject	number of inputs, G-suit pressures, PPB pressures	mean square fit (mm Hg)	model coefficients: b_1, b_2, a_1, a_2
1	18, 5~8 psi, 15~38 mm Hg	7.7	0.5159, -0.4807, -1.8916, 0.9028
3	9, 5~8 psi, 15~38 mm Hg	8.5	1.2524, -1.2152, -1.6847, 0.7086
4	6, 5~7 psi, 15~29 mm Hg	6.9	1.7082, -1.6714, -1.7004, 0.7092
5	17, 5~6 psi, 15~25 mm Hg	8.8	1.8016 -1.7557 -1.5463 0.5545

Table 4. Dynamic indices of the model (with synchronized PPB)

subject	Gs	PO (%)	Tr sec	Tp sec	Ts sec	Fn Hz	Fc Hz	Fq Hz
1	3.3	50	1.7	3.4	25	0.08	0.18	2.5
3	1.8	100	0.5	1.5	15	0.12	0.65	2.5
4	4.3	35	0.7	2.1	12	0.08	0.5	2.5
5	5	0	1.		10		0.2	2.5

The model parameters and dynamic indices for each subject are summarized in Tables 3 and 4. With PPB, the blood pressure responses for all the subjects have higher static gain and faster response speed than without PPB (refer to Table 2). These two features are clearly shown in Figure 7. Since the PPB pressure is directly applied to the chest to raise heart-level blood pressure, higher and faster responses are anticipated.

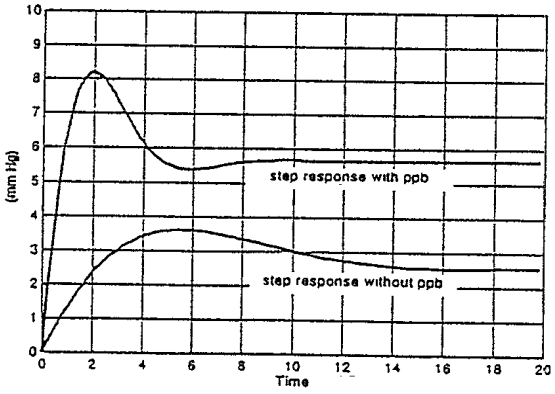

Figure 7. Step responses of the models with and without PPB

5.2.2 Model for asynchronic G-suit Pressure and PPB

A single-input model (4) cannot predict a subject's physiological response if the inputs are not correlated. In general, a separate model for each input is required to predict the total response to the independent inputs. To accomplish this task, the inputs should be generated in

such a way that they are not correlated with each other. For this purpose, two SAMCAV valves were used to control G-suit and PPB pressures independently. In this set of experiments, the profile of G-suit pressure consisted of a series of square waves with periods changing randomly from 2 to 5 seconds. The amplitude of the square waves varied from 1 to 4 psi. The profile of PPB was a step input with a plateau level of 25 mmHg.

A two-input model given by Equation (3) was used. Typical responses to each independent input are presented in Figures 8 and 9. The model parameters for each subject are presented in Table 5. Figure 8 shows that the response to the G-suit pressure raises slowly, and there exists no overshoot. As described in subsection 5.1, the displacement of blood volume to the chest by G-suit pressure might be the main factor contributing to the initial increase and overshoot in blood pressure. However, the displacement would be greatly reduced by the counteracting pressure in the lungs produced by PPB. A comparison of Figures 4 and 8 shows that the static gain of the model with PPB is much higher than that without PPB. This affirms the well-known fact that the protective effect of G-suit pressure is expected to be a function of PPB; it increases as PPB increases.

On the other hand, Figure 9 shows that PPB causes a rapid increase in the blood pressure only in the first few seconds following its application, and then its effect gradually vanishes. Overall, the net gain in the blood pressure will depend on a subject's physiological responses to both G-suit and PPB pressures. Because of the counteracting functions of G-suit and PPB, it can be anticipated that for a certain level of G-suit pressure, there exists an optimal level of PPB such that the gain in blood pressure is maximized.

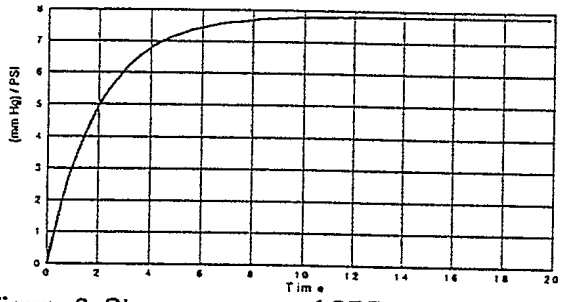

Figure 8. Step response of SBP model to G-suit pressure input with constant PPB of 25 mmHg

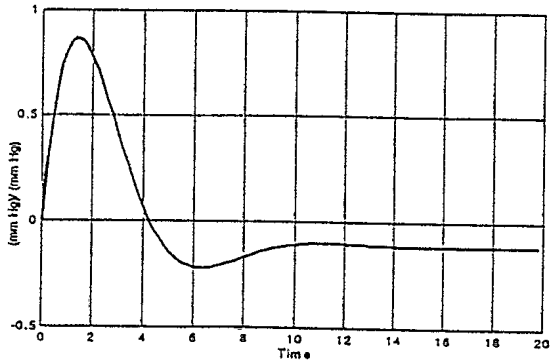

Figure 9. Step response of SBP model to PPB pressure input without G-suit pressure

Table 5. Model parameters (asynchronic PPB)

subject	Number of inputs, G-suit pressure, PPB pressure	mean square fit (mm Hg)	model parameters: $b_{11}, b_{21}, a_{11}, a_{21}$ for input 1 (G-suit) $b_{11}, b_{21}, a_{11}, a_{21}$ for input 2 (PPB)
1	1, 1~4 psi, 25 mm Hg	7.3	2.06, -0.61, 0.01, -0.82 0.26 -0.26, -1.81 0.83
4	1, 1~4 psi, 25 mm Hg	5.4	5.45, -4.49, -0.18, -0.67 0.34, -0.32, 1.66, 0.71
5	1, 1~4 psi, 25 mm Hg	7.1	3.09, -1.70, -0.26, 0.12 0.34, -0.31, -1.72, 0.77
6	1, 1~4 psi, 25 mm Hg	5.0	2.56, -1.41, -0.72, 0.32 0.35, -0.33, -1.71, 0.75

The responses to the G-suit pressure with a constant PPB were quite different from those to G-suit pressure without PPB (refer to Figure 4). As concluded from the previous work (e.g., [4]), the influence of G-suit and PPB pressures on the heart function are coupled and not additive. We can express blood pressure responses in a general form as a function of G-suit and PPB pressures:

$$bp = f(G\_suit, PPB) \tag{4}$$

$$\Delta bp = \left.\frac{\partial f}{\partial G\_suit}\right|_{\substack{PPB= \\ const}} \times \Delta G\_suit + \left.\frac{\partial f}{\partial PPB}\right|_{\substack{G\_suit= \\ const}} \times \Delta PPB \tag{5}$$

Considering the input profiles in the experiments, where PPB is constant and G-suit pressure varies, we can see that the model response shown in Figure 8 only represents a linearized relationship of the first term on the right-hand side of Equation (5) about the point $PPB = 25\ mmHg$. To establish the entire model (3), we have to conduct more experiments with different input profiles, such as varying G-suit pressure at different level of PPB and varying PPB at different level of G-suit pressure.

5.3 Comparison of Responses at +1Gz and High +Gz

The experiments described above were conducted at +1 Gz. It is important to investigate whether the similar models can be applied to the physiological responses exhibited in high Gz environment. Since one subject (subject 1) participated in a centrifuge experiment with the same G-suit (STING), we used the data from that experiment to estimate his model parameters. These parameters are shown in Table 6 to 9. The values of mean square fit (Tables 6 and 8) are quite small, which implies that the same model structure can be used to predict the blood pressure responses in high +Gz environment. By comparing the results in Tables 6-9 with the results in Table 1-4, we can see that the changes in the model parameters and dynamic indices are small. Hence, for this subject, the same model with minor revision in the parameters can be applied in a high +Gz environment.

Table 6. Model parameters (no PPB)

Subject	number of inputs, G-suit pressure, Gz	mean square fit (mm Hg)	model coefficients: b_1, b_2, a_1, a_2
1	5, 3.4~5 psi, 4.3~5 Gz	3.5	0.1312, -0.1139, -1.9554, 0.9632

A set of model parameters can be estimated for each particular value of κ. The sets of model parameters can be used to describe the overall model relationship. The model can be used in, for instance, a so-called 'gain scheduling controller' [6]. According to the operating conditions, such as subjects' physiological status and Gz intensity, a proper optimal κ, and the corresponding model parameters could be chosen by the controller automatically.

Large discrepancies in the subjects' blood pressure responses have been encountered in our modeling work. Some subjects (1 and 2) have significant response to Anti-G protections (Gs ≥ 2.5), whereas some others (subjects 3 to 6) have much less profound response (Gs ≤ 1.3; refer to Table 1). For some subjects, the PPB pressure has a crucial influence on the blood pressure responses, such as for subjects 4 and 5. Without PPB, their static gains (and, correspondingly, G tolerance) are very low, much lower than those for subjects 1 and 2. With PPB, however, the gains increase significantly and become higher than those for subject 1 (refer to Table 4). Since G-suit pressure alone provides little protection for those subjects, PPB pressure should be initiated earlier than suggested by a standard pressure schedule. For subject 3, protection gains with and without PPB are very low. It can be expected that an optimal pressure schedule for this subject would be higher than the standard one.

It is also noted that significant changes in dynamic physiological behavior of the same subject could occur over a short time period. This atypical behavior can be compensated if a real-time Anti-G controller based on physiological sensory feedback is used. The controller would monitor changes in a subject's status online and regulate G-suit pressure and PPB to achieve the required responses. This approach has been successfully tested in our recent centrifuge experiments.

7. CONCLUSIONS

An OE model with a single-zero and two-poles has been found adequate to model the response of a subject's blood pressure to G-suit pressure with and without PPB at +1Gz. A single-input model is adequate for the case of G-suit pressure with synchronized PPB. The same model structure may also be used to simulate the responses to G-suit pressure at high Gz levels. This has been validated based on the data collected in centrifuge experiments performed on one of our test subjects. Significant variations in blood pressure responses have been found from subject to subject and for the same subject observed at different time instances.

8. REFERENCES

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