THE INVESTIGATION OF THE DUAL-PATHWAY VESTIBULO-OCULAR REFLEX MODEL

by

HUINIAN XIAO

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MASTER OF SCIENCE

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ABSTRACT

Vestibulo-ocular reflex(VOR) generates eye movements which compensate for head movements in order to maintain the line of sight constant in the visual environment. The dynamic transfer characteristics of the semicircular canals and the eye plant are known. However, the signal processing done by neural networks are not well known presently. This thesis describes the investigation, evaluation and refinement of existing dual-pathway VOR models in order to obtain an improved model.

Through collecting and analyzing human VOR response data and comparing these to model output, modifications on the system parameters were made to obtain a improved comparison of the output of the model with human VOR response. Qualitative and quantitative comparisons were done in this work. In addition, the human VOR responses under different experimental conditions were studied in order to determine a procedure for obtaining reliable data.

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Chapter I

INTRODUCTION

It is well known that head movements (especially head rotation) elicit eye movements, that is, the eyes tend to move to compensate for head motion in order to fixate on a target. The nonvisual component of this response to rotational stimulation is known as the vestibulo-ocular reflex(VOR).

The reflex starts with the semicircular canals in the ears and ends with the oculomotor plant(eyeball, suspensory tissues, muscles and motoneurons). The transfer function of these devices is known, but the signal processing done by neural circuits is not well known presently. Present research in this area is concentrating more on the investigation of the signal processing that must take place in the central pathways.

Neurophysiological findings provide advances in tracing nerve cell processes and recordings from cells in alert animals, coupling this with certain simplifying features of the eye movement control system the use of quantitative analytic methods for organizing data into circuits and systems became possible. Increasingly complex models of oculomotor organization are established and more sophisticated methods are used for analyzing their responses and comparing them to experimental results. As a tool, control systems analysis is being used more and more in the study of the oculomotor system.

An attempt is made to develop an improved model by modifying previous models in order to explain as many characteristics of the nystagmic responses as possible. A new or revised model gives a challenge for programming oriented experiments and providing additional experimental data for further modelling efforts. In the end, it will be the models, not the data, that will tell us how the oculomotor system works. This is the objective in this study.

Format of the thesis

This thesis describes the research on a dual-pathway VOR model, which is based on the model described in Arbez's B.Sc. thesis[11]. However, as indicated in Arbez's thesis, the model was based partly on physiological facts and partly on physiological hypotheses which resulted from nystagmus observation. Little experimental verification was made to support the various assumptions and parameter values for the model. These should be verified using experimental methods[11]. Thus, the primary objectives of this research are to investigate, evaluate and refine the dual-pathway VOR model by comparing the model responses with the human responses. A computer-controlled vestibular examination chair system in the biomedical laboratory in the Electrical Engineering Department at the University of Manitoba was used for collecting the VOR data. Some programs were developed to get a variety of chair angular velocity profiles and to process the recorded VOR data. In addition, a study was made to compare the VOR data from human subjects with that of the simulated dual-pathway VOR model. This resulted in several modifications to the model in order to obtain more satisfactory comparisons.

This thesis consists of three major sections. The first, in Chapter 2, reviews different mathematical models for VOR in existence, and in Chapter 3, the basic theoretical introduction for dual-pathway VOR model is provided with major emphasis on its structure. The second section is in Chapter 4 and Chapter 5. In Chapter 4, the parameters of dual-pathway VOR model are discussed in detail. Some possible improvements are illustrated here. In Chapter 5, the performance of dual-pathway VOR model in different situations is compared with the behavior of the human VOR data. The evaluation is done on this model. The last section of the thesis, in Chapter 6, is concerned with collecting VOR data, since the correct collection of EOG data is fundamental and important. Possible undesirable EOG data under different conditions are demonstrated. Other error sources are discussed.

Chapter 7 concludes this thesis by proposing possible improvements to the dual-pathway VOR model, and by suggesting areas for future research.

Finally, in Appendix A EOG and dipole theory are described briefly. Appendix B includes all the computer programs, and Appendix C includes the circuit diagram for calibrating the EOG data.

Chapter II

BACKGROUND OF VOR MODELS

2.1 INTRODUCTION

The VOR system of man and higher order animals can be conveniently subdivided into three main components: the semicircular canals(the sensory endorgans), the neural network consisting of the slow phase pathways and a saccadic generator, and finally the oculomotor system, which consists of the ocular muscles and the eye (the motor endorgan). This open-loop system is illustrated in block diagram form in Fig.2-1[32].

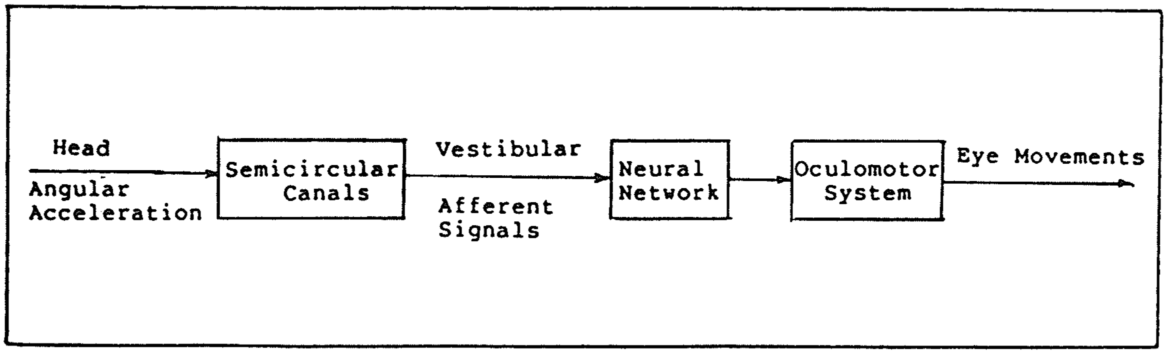


Fig.2-1 Representation of vestibular role in the control of eye movements.

Many mathematical models of the VOR system have been proposed in the literature[1,2,3,4,5]. There is general consensus in modelling the dynamic transfer characteristics of the semicircular canals and modelling the dynamic characteristics of the eye plant. It is also generally accepted that the canal may be approximated as an overdamped angular accelerometer in its linear range of operation, and the eye plant is considered as a simple first-order, low-pass filter. But the modelling of neural networks still is an controversial problem. The key point is whether an internal feedback loop exists between two sides of vestibular output In more detail, this should be relevant to arguments on cerebellar versus brain stem sites for vestibular adaption, currently a highly controversial issue. Based on this the models can be divided into two groups.

Robinson's model is representative of the first group. This group of models assumes that a simple neural integrator exists between vestibular output and oculomotor neuron. Without the benefit of immediate feedback the VOR is said to operate as an open-loop control system.

A bilateral model for the central neural system proposed by Galiana belongs to the second group. In this model it is suggested that one of the most important aspects is the central processing which assumes the existence of strong coupling between the two sides of the brainstem, provided by vestibular internuclear commissural pathways. Here an internal positive-feedback loop is assumed.

Some VOR models are introduced next which may be useful in the course of future research.

2.2 REVIEW OF THE MATHEMATICAL VOR MODELS

2.2.1 The Simplest Model

N.Sugie and M.Jones[1] presented the simplest mathematical model from experimental data. The experimental results were mainly from cats under controlled ether anesthesia. By appropriately controlling ether anesthesia one can selectively suppress the quick phase of nystagmus.

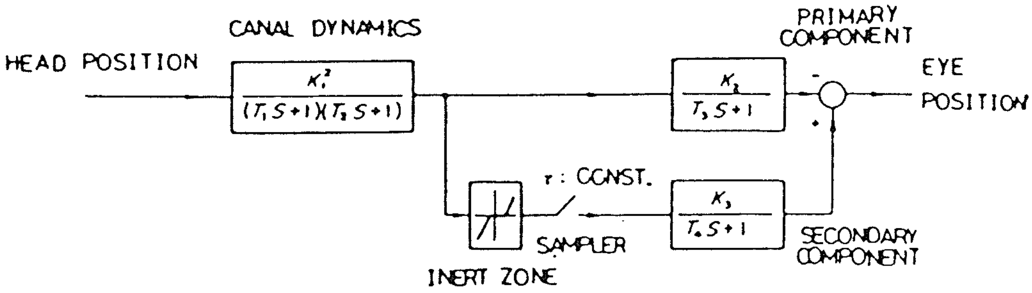


Fig.2-2 Improved mathematical model[1].

In this model (Fig.2-2) the eye movement is induced by two components. The eye movement with absent quick phase will be termed the primary component and the secondary component of oculomotor response is introduced when quick saccades are superimposed on the response to produce nystagmus. It is assumed that the overall rotational nystagmus is an algebraic sum of the primary and secondary components.

2.2.2 Three Similar Models

Three similar models of VOR system were proposed by Schmid and Lardini[2], Barnes[3] and Chun and Robinson[4]. Fig.2-3, Fig.2-4 and Fig.2-5 show these mathematical models, respectively.

These three models appear to be different but they all contain the same essential mode of operation. This is: (1) derive some desired eye position from the vestibular signal; (2) measure the error between this eye position and some internal state variable that behaves like this eye position; (3) finally, when the error reaches a threshold, the eye is rapidly reset to the desired eye position.

All three models differ only in minor ways as far as the slow phase path is concerned. The model of Schmid and Lardini uses two neural integrators, one for the fast phase, and one for the slow phase. In the other two models, the slow phase and the fast phase share the same integrator. According to Robinson[4], the evidence that the slow and fast phases share the same neural integrator is circumstantial but fairly compelling. However, E.Mile Godaux's experiments[7] in the cats indicate that the saccadic system and the vestibulo-ocular reflex do not share the same integrator. So it appears that this problem should be studied further.

The second main difference in these three models is that in the Robinson's model, rather than a linear relationship between the vestibular signal, $\dot{H}'(t)$, and desired eye position, C(t), a saturation in C exists. From the experimental data in the present study this saturation is necessary. This will be discussed in more detail later.

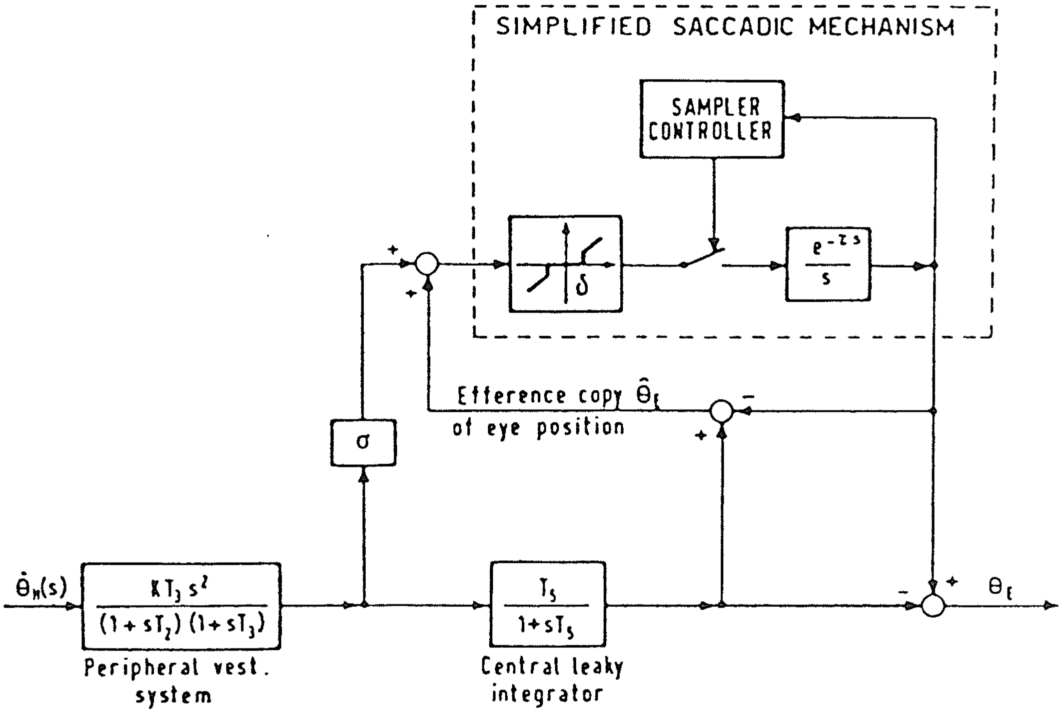


Fig.2-3 Simplified model of the vestibulo-ocular system[2].

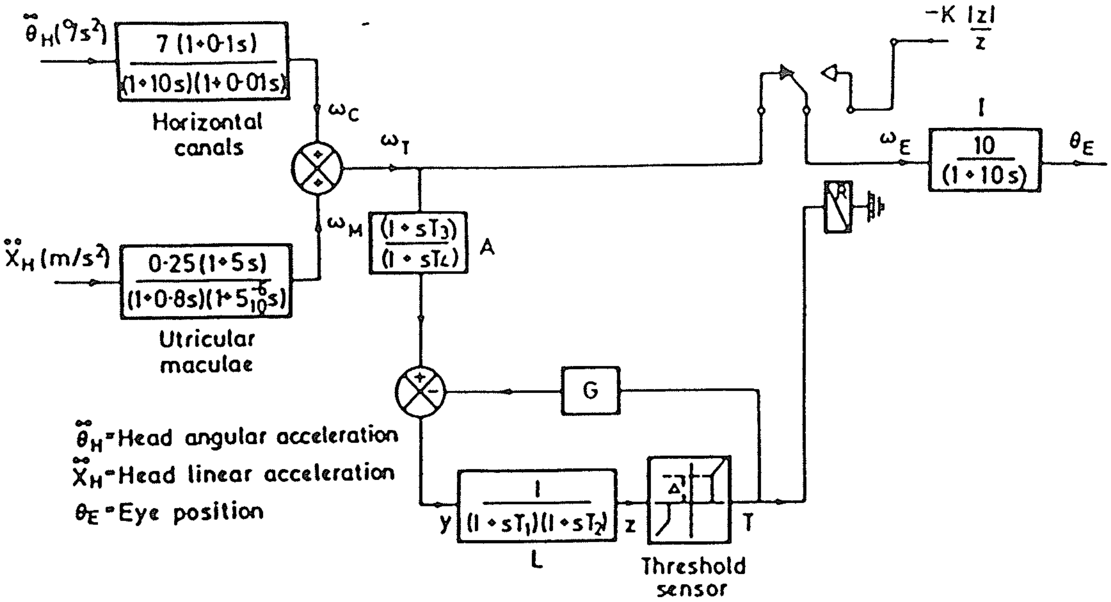


Fig.2-4 A mathematical model of the vestibulo-ocular system for the control of lateral eye movements[3].

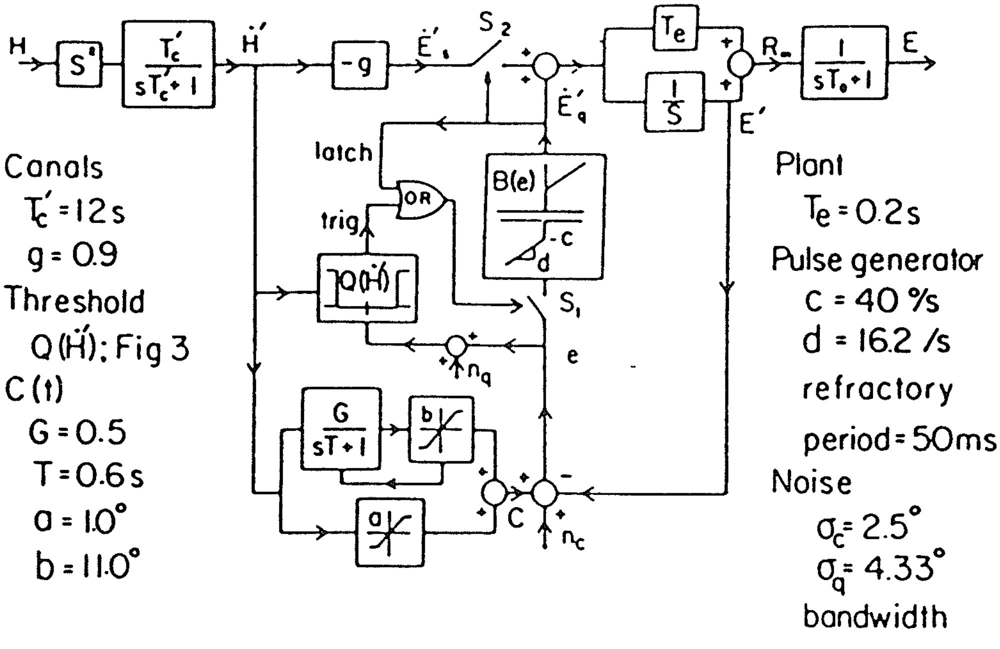


Fig.2-5 The complete model of the vestibulo-ocular reflex.The neural integrater has been replaced by a perfect integrater for simplicity[4].

Furthermore, statistical studies of C and Q(see Fig.2-5) signals have been carried out by Chun and Robinson[4], who have actually included noise generators in their model of the VOR.

Robinson's model is based on the physiological observations described below. The motoneurons can be divided into three categories. The tonic cells carry a signal component proportional to eye position, but do not burst during saccades. The burst cells discharge vigorously during saccades or quick phases with components in some particular direction but are otherwise silent. The pause cells(P-cells) in the flocculus fire at a fairly constant rate but pause during all rapid eye movements. According to the motoneurons' behavior neural circuits are proposed containing these cells that carry the above signals. Also, these neural circuits explain the overall organization of eye movements[6].

2.2.3 The Bilateral Model

In contrast to the first group of models, Galiana's bilateral model is more concerned with the neural signal processing that takes place between the vestibular sensors and the ocular motor nuclei.

The terminology used in discussing the responses of central cells is the same as that in Robinson's model. That is, motoneurons are divided into three categories. However, in addition, three postulates are assumed[5]: (1) neural filters on each side of the brain stem, each linked to tonic cells in the ipsilateral vestibular nuclei in negative feedback loops, (2) strong coupling between these bilateral loops by reciprocal commissaral connections that significantly affect response dynamics; and (3) modulation of this coupling by inhibitory burst neurons during fast phases. These postulates are based on the new hypothesis about adaptive gain control in the primate VOR proposed by Miles and Lisberger[8]. That is, modifiable elements mediating adaptive gain control are located in the brainstem pathway and regulated by error signals generated at least in part by the flocculus P-cells. In this way, there are reciprocal connections between the P-cells and the vestibular relay cells in the brainstem, and they are organized in essence as an internal feedback loop.

In Galiana's model the time constant of the neural integrator might even be as small as that of the eye plant, because during slow phase operation commissaral pathways provide a positive feedback effect that improves the effective integration function of the bilateral system beyond that of the neuron in each side. Fig.2-6 shows the slow-phase block diagram of the model. However, a realistic strategy for generating fast phases has not been worked out in the context of the model.

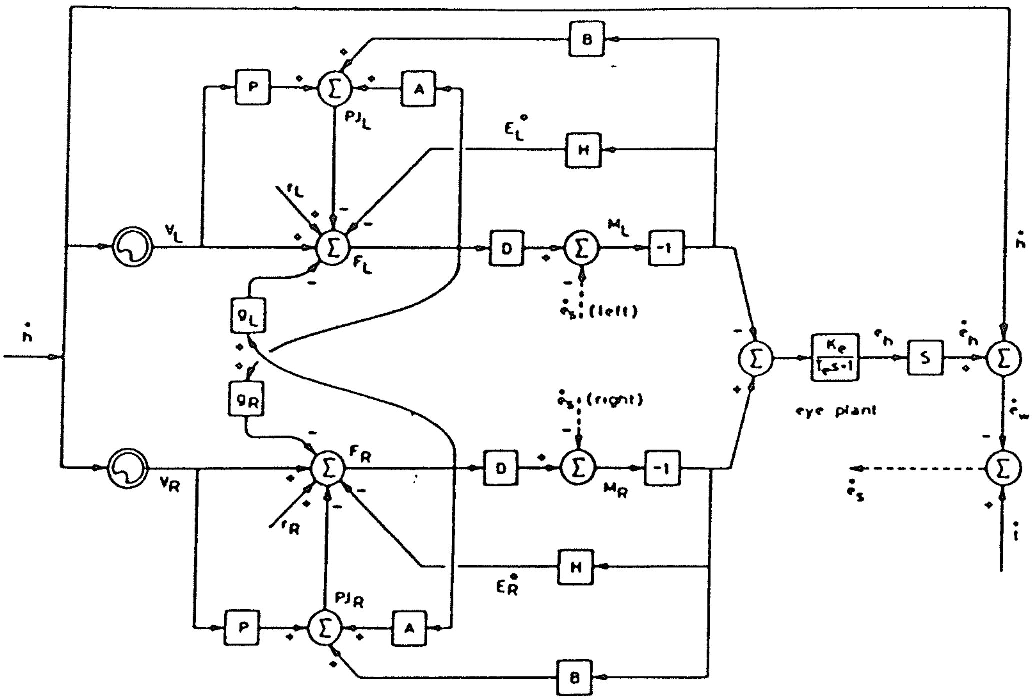


Fig.2-6 A bilateral representation of the VOR, relates head velocity, $\dot{h}$, to eye velocity in the head, $\dot{e}_h$, and includes the commissaral loop[10].

Chapter III

THE DUAL-PATHWAY VOR MODEL

The dual-pathway model, a complex control system developed in Arbez's thesis belongs to the first type of the models. The model is meant to be homomorphic to the extent of existing knowledge. That is, there is, as much as possible, a one-to-one correspondence between physiological functions and mathematical descriptions. The main difference from the Robinson's model is that two pathways are used in the dual-pathway VOR model, one for each set of canals. Thus, each canal selectively excites one muscle from each eye, resulting in muscle dynamics and eye dynamics to be considered separately.

3.1 DESCRIPTION OF SYSTEM

As mentioned before, there are three components in the dual-pathway model. The semicircular canals act as angular rate sensors transducing head rotation into afferent nerve impulses. The mathematical model describing canal dynamics has been developed by many authors[12,4], and the results are quite similar. The response of the horizontal canals to head rotation is modelled using the damped torsion pendulum analogy to the cupula-endolymph system. Adaptive effects due to a long duration stimulus are accounted for by the introduction of an adaptation filter.

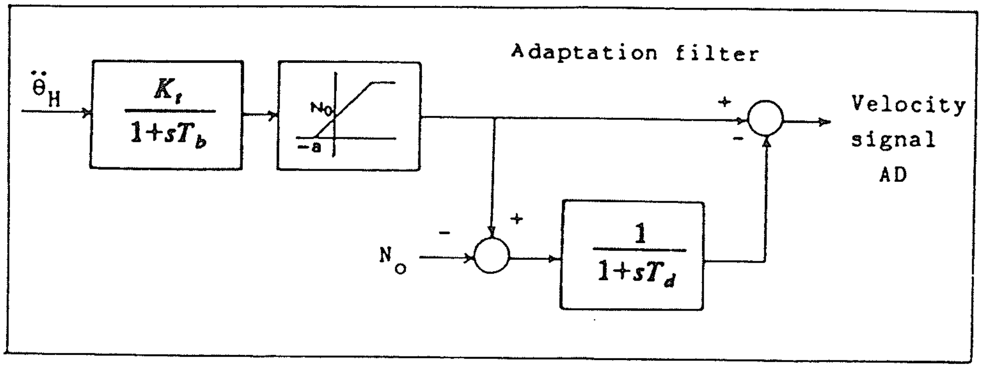


Fig.3-1 Block diagram of the semicircular canals including the adaptation filter.

The neural network is divided into two sections: the slow phase pathways and the saccadic generator. The slow phase pathways process the output signal from the canals dynamics to produce the slow phase component of nystagmus. A leaky integrator is used here(see Fig.3-2). There is evidence[6,32] that the neural integrator(NI) is a leaky integrator with a leak factor under control of the cerebellum. There is also evidence [4,6] that the signal fed to the ocular muscles is proportional to both eye position and eye velocity. Chun and Robinson[4] have done the research on actual neural pathway and have established that motoneurons of the ocular muscles do receive an eye velocity signal.

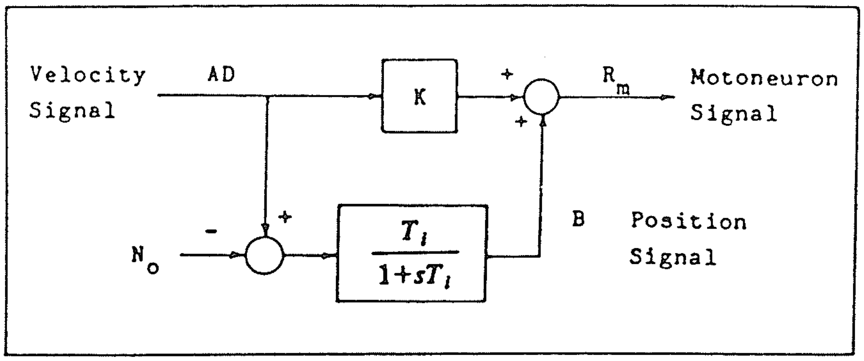


Fig.3-2 Block diagram of the neural integrator used in the dual-pathway model.

The saccadic generator, consisting of threshold and position dynamics and pulse generator, acts to produce the fast phase component of nystagmus. A model of the saccadic generator developed by Chun[4] and modified by Arbez is presented in Fig.3-3. The generator is based on a feedback system which monitors an eye position signal and generates a signal C proportional to the head velocity. The eye position is compared to the signal C, and when the difference between C and eye position exceeds a threshold Q, also dependent on head velocity, a saccade is generated to minimize the difference between E and C. Thus, the eye will be driven to a position determined by the signal C. This assumption is based on body image theory which dictates that a signal is produced to direct the eyes to view an object in a certain position with respect to the body no matter what the eyes'

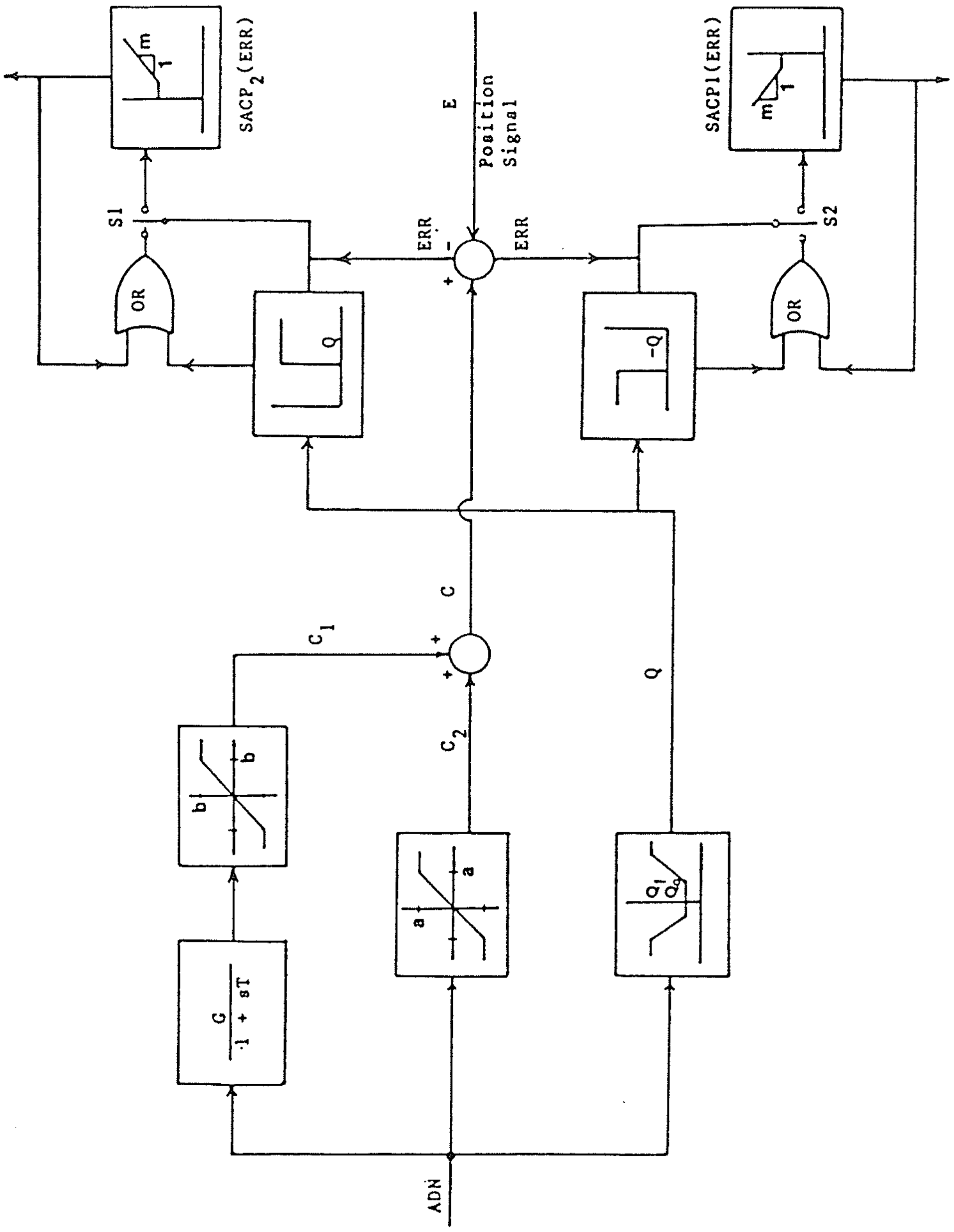


Fig.3-3 The model of the saccadic generator.

initial positions were. This theory is also applicable to movement of limbs, head and body[4].

Once the saccade is initiated, it must not end until the error ERR is zero. The OR gates perform this function. When Q has reached the threshold, the saccade is initiated by closing the switch S1, the latch signal from the output of the saccadic non-linearity, SACP(ERR), will assure that the switch will remain closed until ERR goes to zero.

The final component of the vestibulo-ocular system, the oculomotor apparatus, is comprised of the eye and ocular muscles. The relationships between muscle force and motoneuron signal and between net muscle force and eye position is used to provide a basis for modelling the oculomotor system.

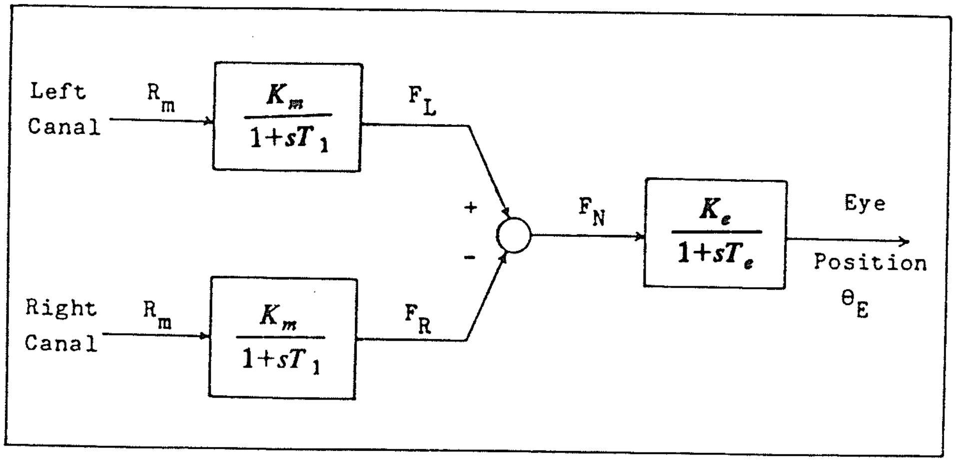


Fig.3-4 Block diagram of the ocular muscles and eye dynamics.

The whole VOR model is shown in Fig.3-5. Angular eye displacement is measured relative to the head, with the positive direction defined to be counterclockwise. As indicated previously, each slow phase pathway excites one muscle from each eye. When one canal is excited, the other canal is inhibited[11].

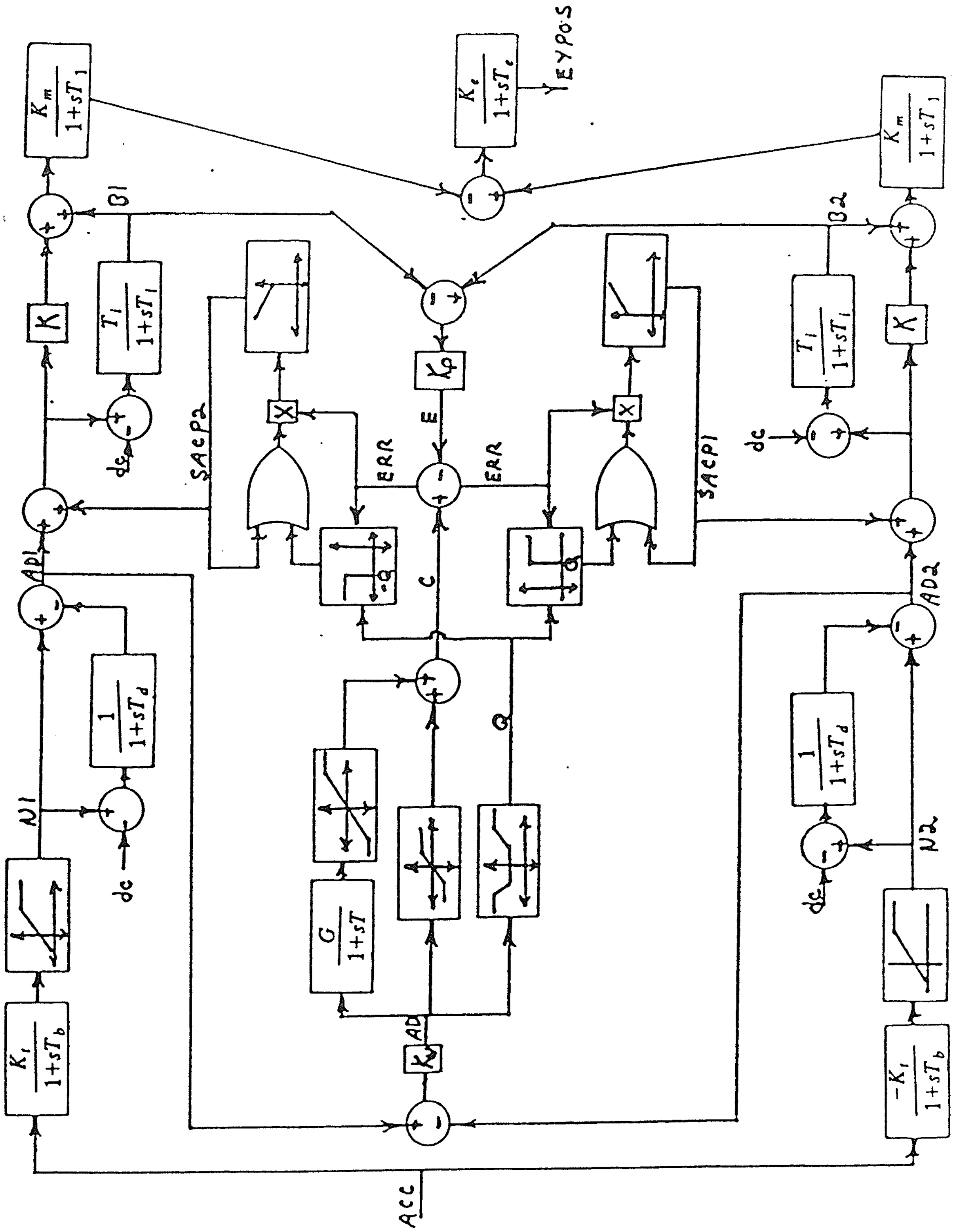


Fig.3-5 The dual pathway VOR model.

3.2 OPERATION OF DUAL-PATHWAY VOR MODEL

In Fig.3-5, assume the top slow phase pathway corresponds to the left horizontal canal, while the bottom slow phase pathway corresponds to the right. The two slow phase pathways produce the slow components of nystagmus. The difference in the force output of the muscle dynamics is fed to the eye dynamics to generate eye position. The left canal is primarily excited by positive angular velocities of the head which creates a negative slow phase eye velocity. The right canal is primarily sensitive to negative velocities producing right-beating nystagmus. Saccades are produced by introducing high amplitude pulses into the inhibited pathway. This function is performed by the saccadic generator.

The saccadic generator requires a head velocity signal and an eye position signal from the slow phase pathways. Slow phase eye velocity is assumed proportional to head velocity in magnitude, but opposite in sign. AD1 and AD2 are considered as slow phase velocity signals from their respective slow phase pathways. Eye movement depends on the difference between the signals in each slow phase pathway, that is, on (AD1 - AD2). The proportionality constant, Kv, is included to obtain a signal equal to head velocity.

The signals C and Q are obtained by operating on AD. The eye position signal, E, is obtained from the difference between the position signals B1 and B2. The constant of proportionality, Kp, is required to obtain actual eye position.

The signs of E and C will depend on which canal is excited. Exciting the left canal results in AD1>AD2, and thus a positive signal, C. Thus, B1>B2 and E will be negative. The error signal, ERR, will be positive and will initiate saccadic pulses in the right canal pathway, producing left-beating nystagmus.

Operation of the system is similar when the right canal is excited. Then C is negative, while E is positive. The resulting signal ERR is negative and saccadic pulses are introduced into the left canal pathway, resulting in right beating nystagmus[11,32].

Chapter IV

CHOICE OF MODEL PARAMETERS

4.1 DIGITAL SIMULATION OF THE DUAL-PATHWAY MODEL

The computer simulations are performed on the Data General computer system in the Electrical Engineering Department using Manitoba Hydro's electromagnetic transients(EMTDC) program[33]. The EMTDC program originally was developed at Manitoba Hydro by Dennis Woodford for simulating the dynamic interaction between control systems and electric network components including DC and AC systems. The control system building block functions(CSMF) in EMTDC are similar to those in CSMP(Continuous System Modeling Program), which is the desirable software to use, but not as available. Thus, EMTDC can be used for simulating control systems.

There are two advantages using EMTDC. One is that the software of EMTDC is more up-to-date than that of CSMP. Also, CSMP is not supported by the University of Manitoba Computer Centre. In addition, EMTDC is convenient for processing the generated data, for storing all data, and for generating fully documented graphs of variables of the model as function of time.

4.2 SELECTION AND ANALYSIS OF PARAMETERS

The dual-pathway model contains a total of 25 parameters (see Fig.3-5). These include eight constants, eleven physiological parameters and six time constants. A list of these parameters is shown in Table 4-1.

Table 4-1: Parameters of Dual Pathway Model

Time Constants	Physiological Parameters	Gain Constants
Tb=15sec	Qo=1.0deg	Kl=85impulses/s.d
Td=80sec	Q1=10.0deg	Kt=0.06sec
Ti=25sec	ADN1=5.0deg	Km=1N/deg
T1=0.1sec	ADN2=20.0deg	G=0.5sec
Te=0.0604sec	SACPo=130	K=0.2sec
T=1sec	ERRo=1.5deg	Kv=1
	m=20	Kp=1
	No=90impulses/sec	Ke=1deg/N
	Nm=500impulses/sec	
	A=1.0deg	
	B=10.0deg	

Where there is general agreement, the values of the time constants used are based on research by other authors.

The value for Tb is chosen to be 15.0 seconds, which is the median of its range of 10.0 to 20.0 seconds[4]. The time constant Td ranging from 80 to 120 seconds[12] is set to 80 seconds. The integration time constant is chosen to be 25 seconds as suggested by Chun and Robinson. As well a value for K of 0.2 is adopted from Chun and Robinson's model. Skeletal muscle dynamics suggest time constants for T1 from 0.1 to 0.2 second. The value of 0.1 is chosen since it seems logical to assume eyes muscles with quick reaction. The time constant Te is set to 0.0604 second, which is the result obtained by Robinson's study on eye dynamics[32].

Research has led to certain values of gain constants for various blocks and other parameters, especially for that of the saccadic generator. Of the parameters used in the model, based on the Arbez's thesis, some were adopted from Chun and Robinson's model which were based on the study of cat's VOR data, and some were established by assumption. Therefore, modifications have been introduced in this chapter in an attempt to alter the parameters to suit the human VOR system. Four such modifications are discussed next.

1) Gain constant:

There is no need to adjust signals AD(see Fig.3-5), so Kv is set to 1. Otherwise, the nature of the response would be changed, because the relative relationship between the actual variable (B1-B2) and the 'center of interest variable' C would be altered. In addition, Kp is set to 1 too. The gain constant Kt and Kl mainly determine the slow phase velocity and the values used originally are shown to be reasonable in the computer simulations compared to human EOG data.

The value of K(see Fig.4-1) is set to 0.2. This is based on Robinson's model and estimated in the following analysis.

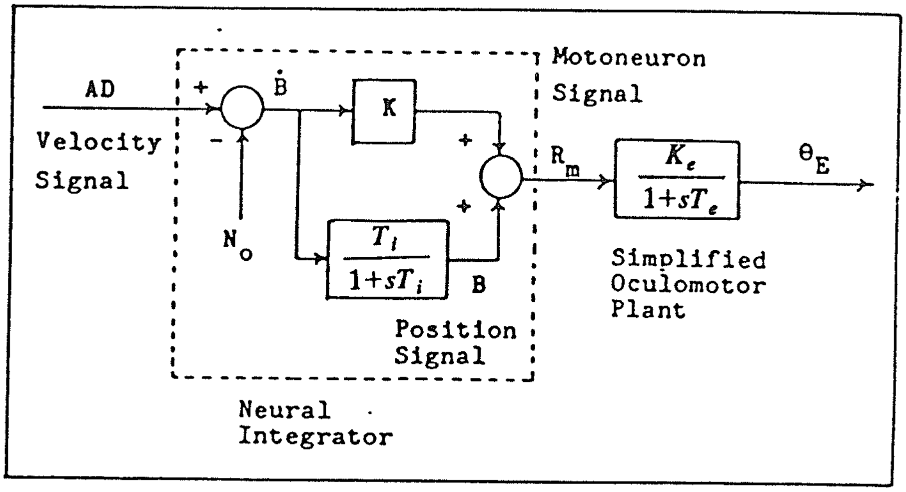


Fig.4-1 Block diagram illustrating a model of the neural integrator supplying eye velocity and eye position signals to(a simplified version of) the oculomotor plant.

The relationship between the eye position ?e and firing rate of motoneurons is given by:

$$\frac{\theta_E(s)}{R_m(s)} = \frac{1}{1+sT_e} \qquad (4.1)$$

Where Te is a time constant of about 0.2 second.

From Fig.4-1 Rm can be calculated to be:

$$\frac{R_m(s)}{\dot{B}(s)} = K + \frac{T_i}{1+sT_i} \approx (1+sK)(\frac{T_i}{1+sT_i}) \qquad \text{if } K << T_i \qquad (4.2)$$

$$\dot{B} = A_D - N_0$$

= desired eye velocity.

Combining Equations(4.1) and (4.2) results in:

$$\frac{\theta_E(s)}{\dot{B}(s)} = \frac{(1+sK)}{(1+sT_e)}(\frac{T_i}{1+sT_i}) = \frac{T_i}{1+sT_i} \approx \frac{1}{s} \qquad \text{if } K = T_e \qquad (4.3)$$

Thus, for B(t) to faithfully represent eye position $\theta_E(t)$, K is required to be Te. In the present model, K should be equal to 0.06, since Te is set to 0.06 second.

However, if K is chosen to be 0.06, no matter how the magnitude and shape of the saccadic pulse(SACP) are changed, the fast phase velocities of the simulated results are too small to match that of human EOG data. Furthermore, it was found that increasing K causes eye velocity, especially the fast phase velocity, to increase, thus, based on the simulation results, K is set to 0.2.

The choice of gain constant G will be discussed later.

2) Signal C(t) (see Fig.4-2):

Arbez adopted Robinson's scheme(Fig.4-2) to generate C(t) for all $\dot{H}$. The theoretical basis is the concept of a 'center of interest', which is the point in space C, measured with respect to the head at which the eyes should be pointed next. With no other stimuli(e.g., visual, auditory) C(t) is determined entirely by the vestibular signal. When the head turns to the left, the vestibular signal shifts C(t) to the left and the function of the quick phase is to drive the eyes promptly to the point C. A slow phase then compensates for head movement. As the head continues to turn, it carries C with it; when the eyes fall too far behind C, the desirability for a new rapid eye movement increases until some threshold is reached which triggers the next quick phase and returns the eyes to C.

With this interpretation the step responses of C(t) are determined in Fig.4-2A by drawing a curve that connects the end points of all quick phases. Averaging an ensemble of such responses gives the shape shown in Fig.4-2B. When $\dot{H}$ is zero, C is zero; however, when a step in $\dot{H}$ occurs, there seems to be an immediate step displacement of C by the amount A, followed by a rising phase to a steady level Cs. However, this is the response of a cat. Experiments to record the human eye position in response to a step of head velocity $\dot{H}$ from 13 to 65 deg/sec were done in this study.

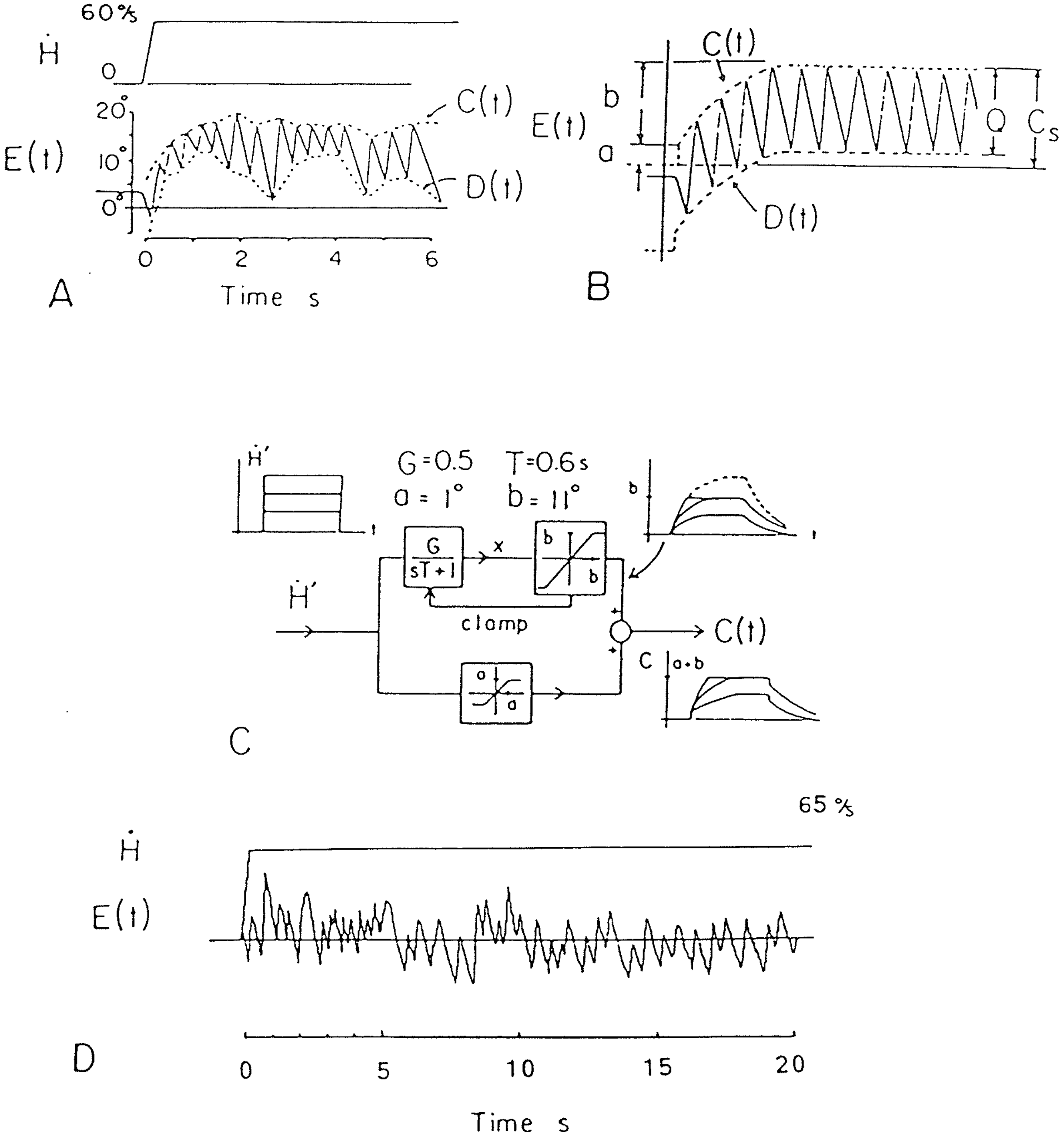


Fig.4-2A-D (A) A recording of the cat's eye position E in response to a step of head velocity Ḣ of 60deg/sec. C(t) is a line connecting the ends of all quick phases. D(t) connects their beginnings. (B) An idealized response as in (A) with fluctuations averaged out. (C) A model for generating C(t) from the vestibular signal Ḣ [4]. (D) A recording of the subject's eye position E in response to a step of head velocity Ḣ of 65deg/sec.

An ideal step velocity cannot be realized in the research vestibular examination chair system. Instead a trapezoidal velocity profile with the maximum acceleration of 300 deg/sec/sec was used. The outcome of the VOR is not affected very much since the saccade frequency of VOR is less than 10 pulses per sec. Even the time delay for a signal to get from the vestibular system to the eye is about 12 msec.

It was found that there is an immediate step displacement of C by the amount A (about 1 degree) the same as in the cat's responses. The value B of C(t) is about 16 degrees for man. Thus A is chosen to be 1 degree and B is chosen to be 16 degrees. One noticeable point is that even for a step head velocity, the eyes jump up and down with respect to the center position. This is different from the cat's response.

Analyzing the velocity steps from 13 to 65 deg/sec confirms that the time constant T(Fig.4-2) is 0.6 second. This was obtained by analyzing the results from human subjects. Table 4-2 lists the result of these experiments with four different step head velocities.

Varying G alters the magnitude of signal C and thus changes the final position of the eye after the occurrence of saccades. Comparing model data to human EOG data, it is suggested that G is considered to be a function of the frequency of the sinusoidal head velocity. When the sinusoidal frequency of the head velocity is 0.05, G is chosen to be

0.05Hz. With this selection the simulated results are best matched to the data of human subjects. This agrees with the data of all 10 subjects tested.

Table 4-2: Step Velocity Responses

H(deg/sec)	Cs(deg)	T(sec)	A(deg)
13	12.9	0.66	1.02
25	15.4	0.57	1.01
45	16.3	0.63	1.1
65	16.1	0.59	1.0

3) Threshold signal Q and saccadic pulse strength SACP(ERR).

The non-linearity defining Q in the present model is shown in Fig.4-3. Here the basic idea is that whenever the eye position differs from C(t) by about 16 degrees, a quick phase returns the eye to C(t). This is the result of analysis of the human EOG data. The value of Q is dependent on the head velocity ADN, as shown in Fig.4-3A. The analytical equation is:

$$Q(ADN) = \begin{cases} Q_1 & ADN = 0 \\ \dfrac{(Q_2 - Q_1) ADN}{ADN2} + Q_1 & 0 < ADN \le ADN2 \\ Q_2 & ADN2 < ADN \end{cases}$$

$$Q(-ADN) = Q(ADN)$$

$$\text{where: } Q_1 = 4, \quad Q_2 = 9, \quad ADN2 = 20$$

It is noticed (see Fig.3-5) that ERR is the difference between C(t) and B(t). Because the value of gain constant K was set to 0.2, B(t) does not faithfully represent eye position $\theta_E(t)$ (discussed before). B(t) is proportional to the signal of actual eye position. According to numerical analysis on the simulated results, the better choice of Q2 is equal to 9 degree to satisfy the assumption that whenever the actual eye position differs from C(t) by about 16 degrees, a quick phase take place. In addition, it was found that the fast phase velocities of the simulated results are close to that of the human responses.

The behavior of Q for small head velocities was determined by the effect on human responses to sinusoidal head velocities during the period when $\dot{H}$ crosses through zero. There is a null duration, i.e., the period free of quick phase when $\dot{H}$ passes through zero.

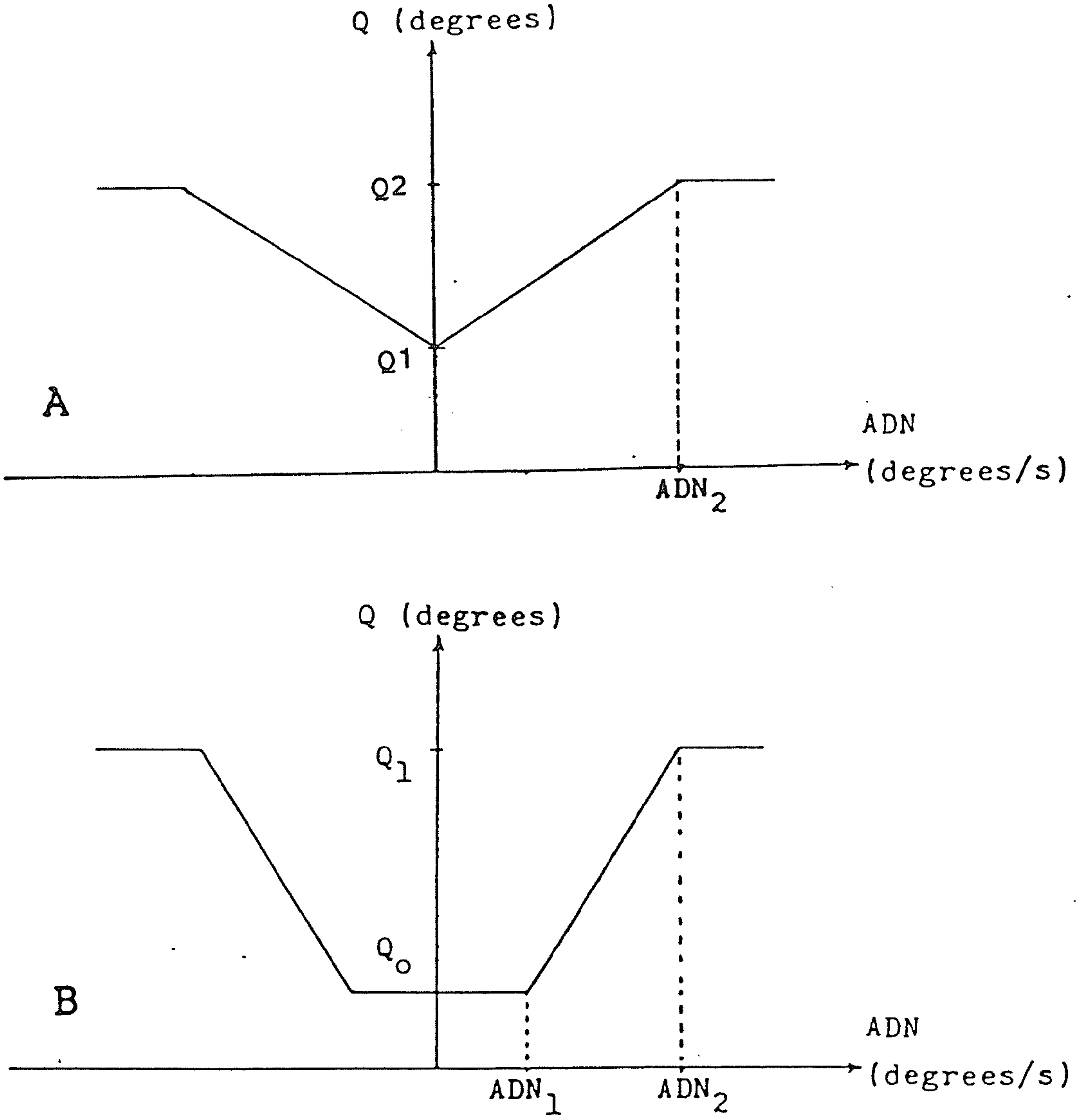


Fig.4-3 The dependence of threshold level, Q, on the net velocity signal, ADN.

From the theoretical view, increasing the value of Q1 will increase the duration of the null period. Based on this idea, the different values of Q1 were tested on the computer simulation of the model. As a result, Q1 is chosen to be 4 degrees. It was found when Q1 is smaller there is an increase in saccadic frequency when the head velocity passes through zero.

There is another non-linearity determining Q as shown in Fig.4-3B which resembles in shape the non-linearity used by Chun and Robinson[4] and used by Nakka in the dual-pathway VOR model[32]. According to the present investigation, the main point is the selection of Q1. The change of the value of ADN1 from 0 to 10 degree did not cause a big difference in the simulated results. In the present model, the non-linearity defining Q shown in Fig.4-3A is adopted.

The other non-linearity determining saccadic pulse strength SACP in the present model is shown in Fig.4-4D.

The saccadic pulse strength is a function of the error between the instantaneous eye position and the desired eye position C(t). Also, it is a function of the head velocity and the sinusoidal frequency of the head velocity, since the saccade eye velocity in the head is increased by the head velocity and the sinusoidal frequency of the head velocity. The saccadic pulse SACP, which is supposed to be fired by burst cells, B, has a very high gain initially and then saturates. It drives the eye position signal through the integrator and through the direct path of gain K until the error reaches zero at which time SACP is reset to zero[4,13].

The selection of SACP in Fig.4-4D is based on the above concept and on the simulated results from the model. Many schemes were tested. The scheme shown in Fig.4-4A is from the Arbez thesis[11]:

$$SACP(ERR) = \begin{cases} 0 & ERR < 0 \\ SACP_0 & 0 \le ERR < ERR_0 \\ SACP_0 + m(ERR - ERR_0) & ERR_0 \le ERR \end{cases}$$

$$\text{where: } SACP_0 = 130, \quad ERR_0 = 1.5, \quad m = 20$$

When using the scheme given in Fig.4-4A in the computer simulation it was found that saccades overshoot and cause a saccadic pulse to be initiated in the opposite direction. Furthermore, the saccadic frequency is too high.

Decreasing the values of the slope of m and SACPo would solve the problem. In order to produce physiologically acceptable saccades, m was chosen to be 13.5 and SACPo was chosen to be 100 deg/s. The reason for such a dc value is that the saccadic pulse must be larger than the 90 dc resting firing rate of the slow phase pathway. Inhibition of the pathway can totally remove this dc component and since the integrator pathway subtracts 90 deg/s before integration, the saccadic pulse must always be larger than 90 deg/s.

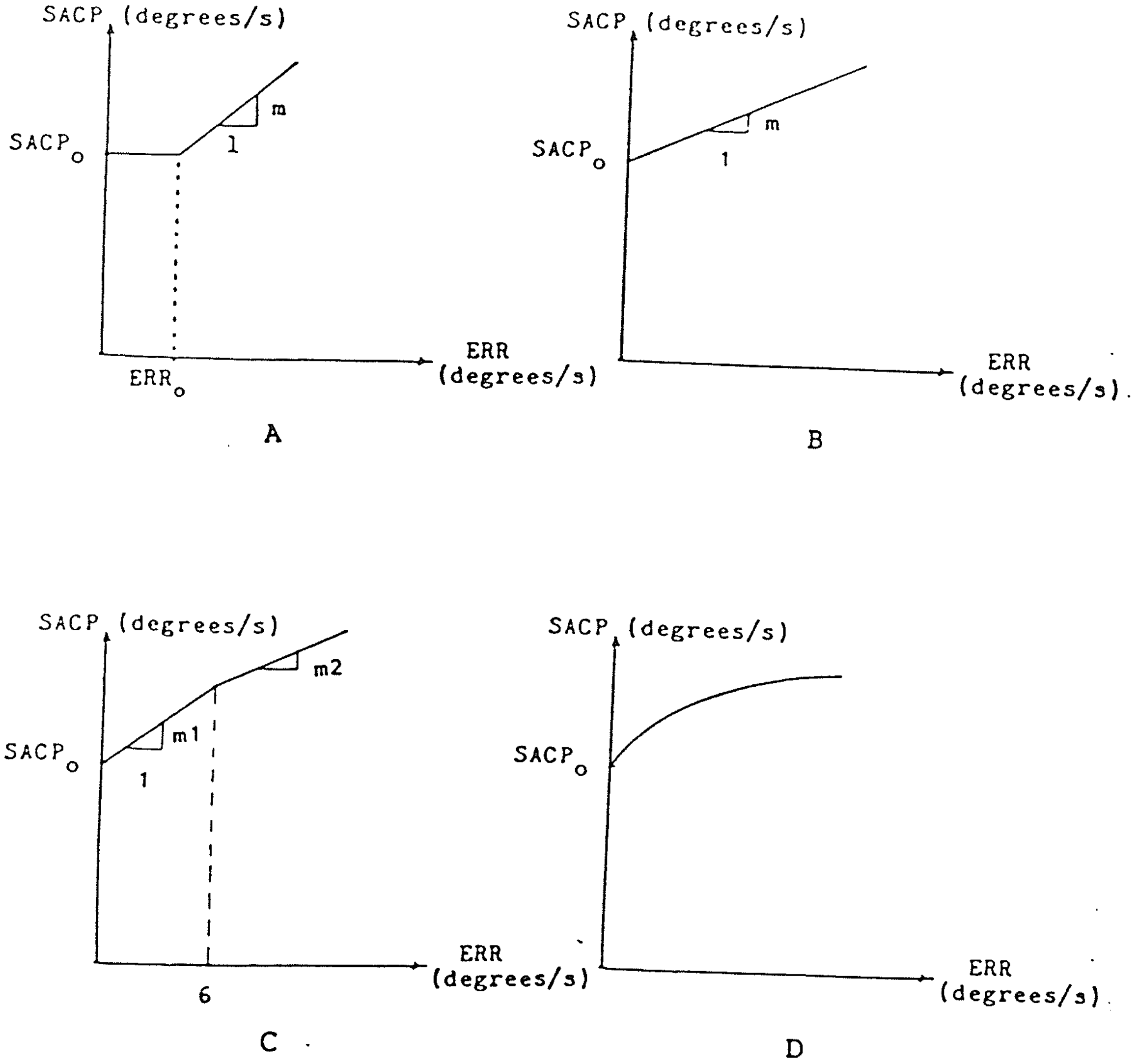


Fig.4-4 The dependence of saccadic pulse strength, SACP, on the error, ERR.

However, when considering the quantitative comparison of the behavior of the model with that of the human responses, a problem arises, in that, using scheme A, the fast phase velocity of the simulated result is too small to match that of the human responses. As the name SACP(strength of the saccadic pulse) suggests, SACP is the main factor determining the value of the eye fast phase velocity of the model. From this standpoint, the scheme shown in Fig.4-4B was tested. As a result, there is an increase in the eye fast phase velocity of the simulated results. However, comparing it with the human responses it is not satisfactory either.

Thus, the scheme for SACP shown in Fig.4-4C was tried. In Fig 4-4C the SACP curve consists the two straight lines with different slopes (m1=15.5, m2=13.6). The slope, when the error is less than 6 degrees, is slightly larger than that when the error is bigger than 6 degrees. If the second slope is too large, saccades would overshoot. SACPo is chosen to be $(90+0.1(\dot{H}-100)+50(F-0.05))$. This scheme works and can be used in the model.

To further investigate whether or not the smooth change of the slope of SACP curve brings about a better result, the scheme for SACP shown in Fig.4-4D was tried(analytically given in equation below).

$$SACP(ERR) = \begin{cases} 0 & ERR < 0 \\ M1(1-e^{\frac{-ERR}{M2}})+SACP_0 & ERR \geq 0 \end{cases}$$

$$SACP_0 = 90+0.1(\dot{H}-100)+50(F-0.05)$$

$$where: \quad M1=250$$
$$M2=11$$

Comparing the tested results using scheme Fig.4-4D with that using scheme Fig.4-4C, it appears that the scheme in Fig.4-4D is more suited to the model input for a wide range of sinusoidal frequencies and magnitudes. Thus, it is adopted in the present model.

4) Connection of $\dot{H}$ signal during rapid eye movement:

Finally, consider whether or not $\dot{H}$ is disconnected during a rapid eye movement. According to some neurophysiological results, the P-cells and tonic cells pause during saccades, thus, it would appear that the answer is 'yes'. In addition, Robinson's experiment[4] showed that the quick phase eye velocity actually increases when cats are rotated. It is different from Bizzietal's finding[34] that during a head-eye movement in monkeys, the saccadic eye velocity is decreased by the velocity of the head. There seems to be a significant species difference between cat and primate. Observing human EOG data, the results of the present study agree with Robinson's results, so a switch S3 is added(Fig.4-5). This observation was based on the EOG data of all subjects tested. Comparing the model response without

S3 to those with S3, the latter results in improved behavior when head velocity is small.

The results of the above discussion are summarized in Table 4-3 where the parameters of the present model are listed. These can be compared to those in Table 4-1.

Table 4-3: The Parameters of The Model

Time Constants	Physiological Parameters	Gain Constants
Tb=15sec	Q1=4deg	K1=85impulses/sec
Td=80sec	Q2=9deg	Kt=0.06sec
Ti=25sec	ADN1=0	Km=1N/deg
T1=0.1sec	ADN2=20deg	G=0.05sec
Tc=0.0604sec	SACPo=90+($\dot{H}$-50)x0.1	K=0.2sec
T=0.6sec	+(F-0.05)x50	Ke=1deg/N
	No=90impulses/sec	Kv=1
	Nm=500impulses/sec	Kp=1
	A=1deg	
	B=16deg	
	M1=250	
	M2=11	

Comparing the values in Table 4-3 to those in Table 4-1, it can be seen that none of the 'Time Constants' were changed. However, most of the 'Physiological Parameters' have been modified and two of the 'Gain Constants' have been changed.

Fig.4-5 shows the complete model.

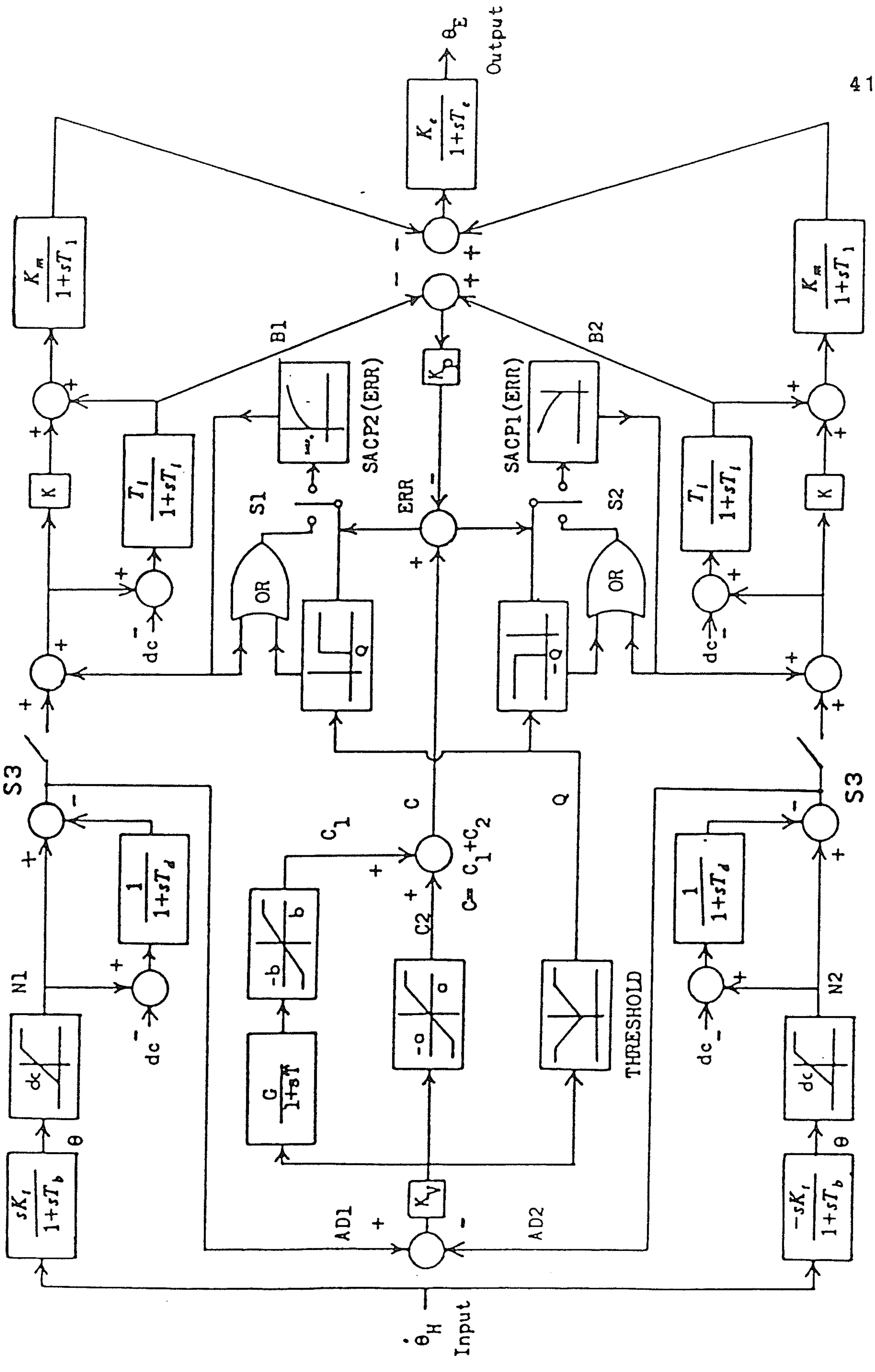


Fig.4-5 The dual-pathway VOR model.

Chapter V

PERFORMANCE OF THE MODEL

In order to assess the efficacy of the dual-pathway VOR model, the mathematical model results have been compared with human subject EOG data qualitatively and quantitatively in this chapter.

5.1 THE QUALITATIVE COMPARISON

1. Sinusoidal Responses

Fig.5-1 and Fig.5-2 illustrate the behavior of a subject and the model, respectively, at the frequency of 0.05Hz with the four different peak head velocities, 200deg/sec, 150deg/sec, 100deg/sec and 50deg/sec. Fig.5-3 and Fig.5-4 show the behavior of the subject and the model at the four main frequencies tested; 0.05, 0.125, 0.25 and 0.5Hz. The peak head velocity is 90deg/sec in all these cases.

2. Trapezoidal Responses

Fig. 5-5 shows the results of the subject and the model. The input consists of a ramp velocity of acceleration equal to 6deg/sec/sec for 15 seconds, followed by a constant velocity of 90deg/sec and finally a deceleration of 90deg/sec/sec to zero velocity.

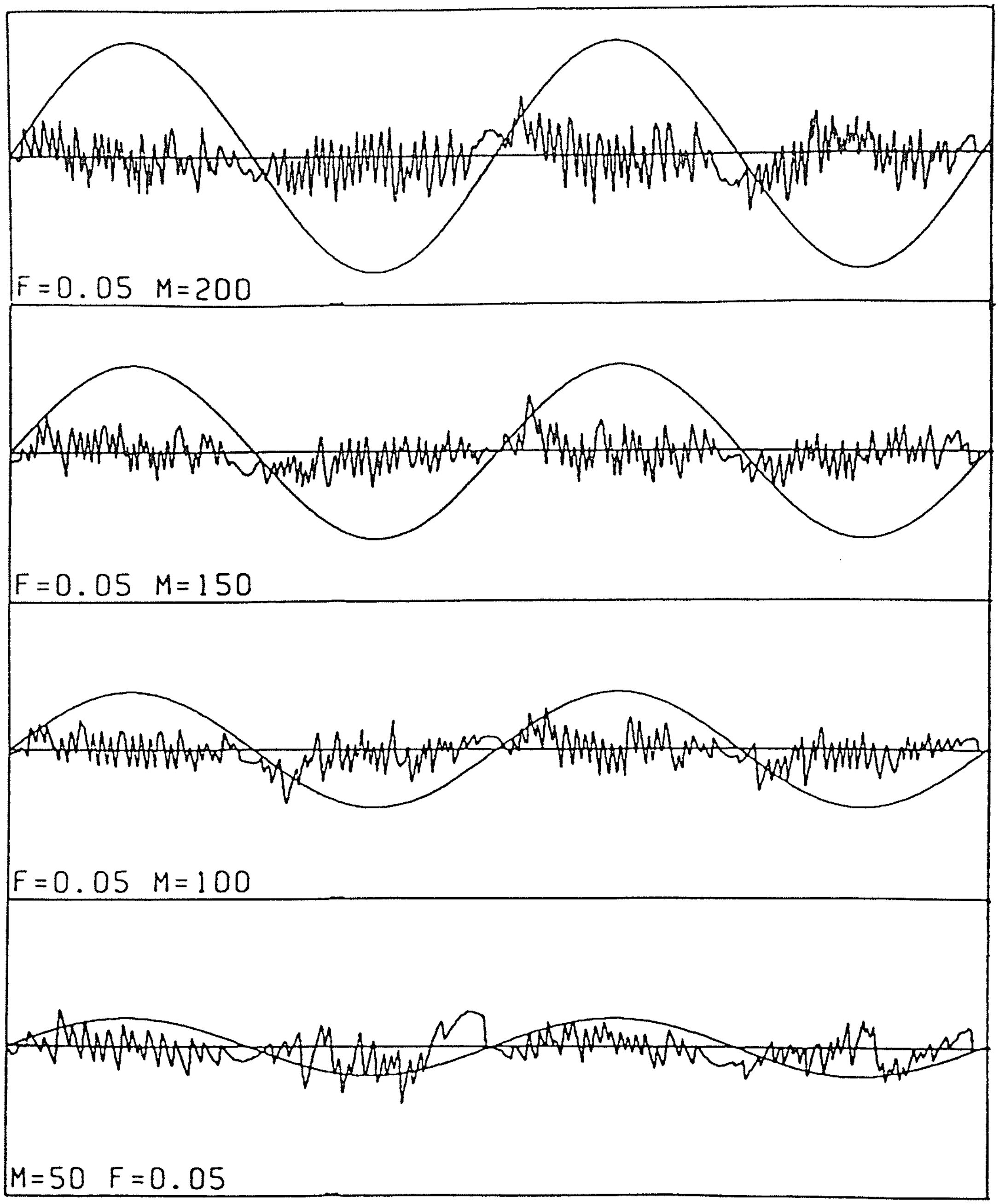


Fig.5-1 A set of recordings of a human subject's eye position in response to the sinusoidal head velocity $\dot{H}$ with different peak magnitudes. M:peak magnitude of sinusoidal head velocity; F:frequency of sinusoidal head velocity.

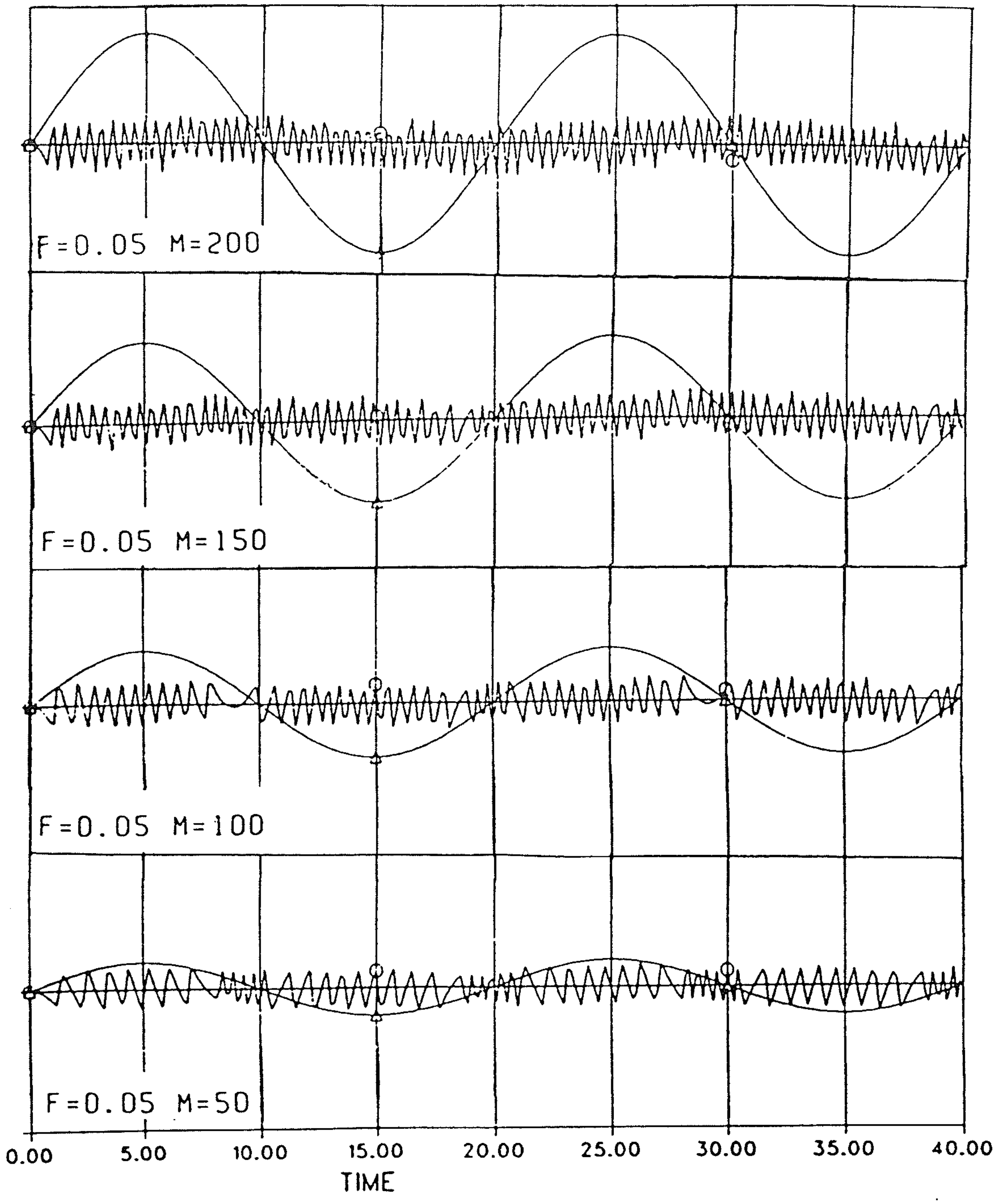


Fig.5-2 Responses of the model to sinusoidal velocity at 0.05Hz, with peak velocities of 200,150,100 and 50deg/sec.

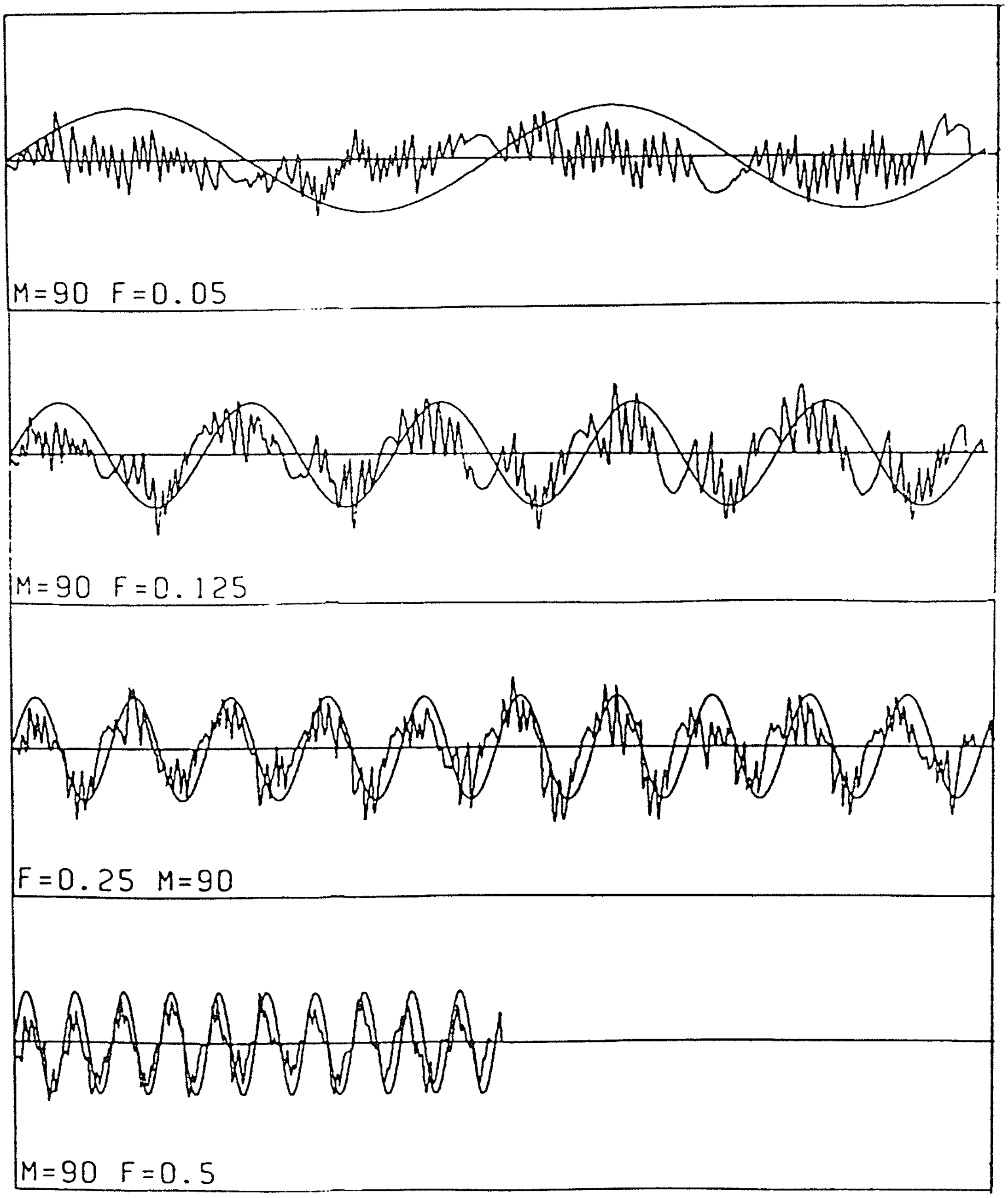


Fig.5-3 A set of recordings of subject's eye position in response to the sinusoidal head velocity $\dot{H}$ with different frequencies.

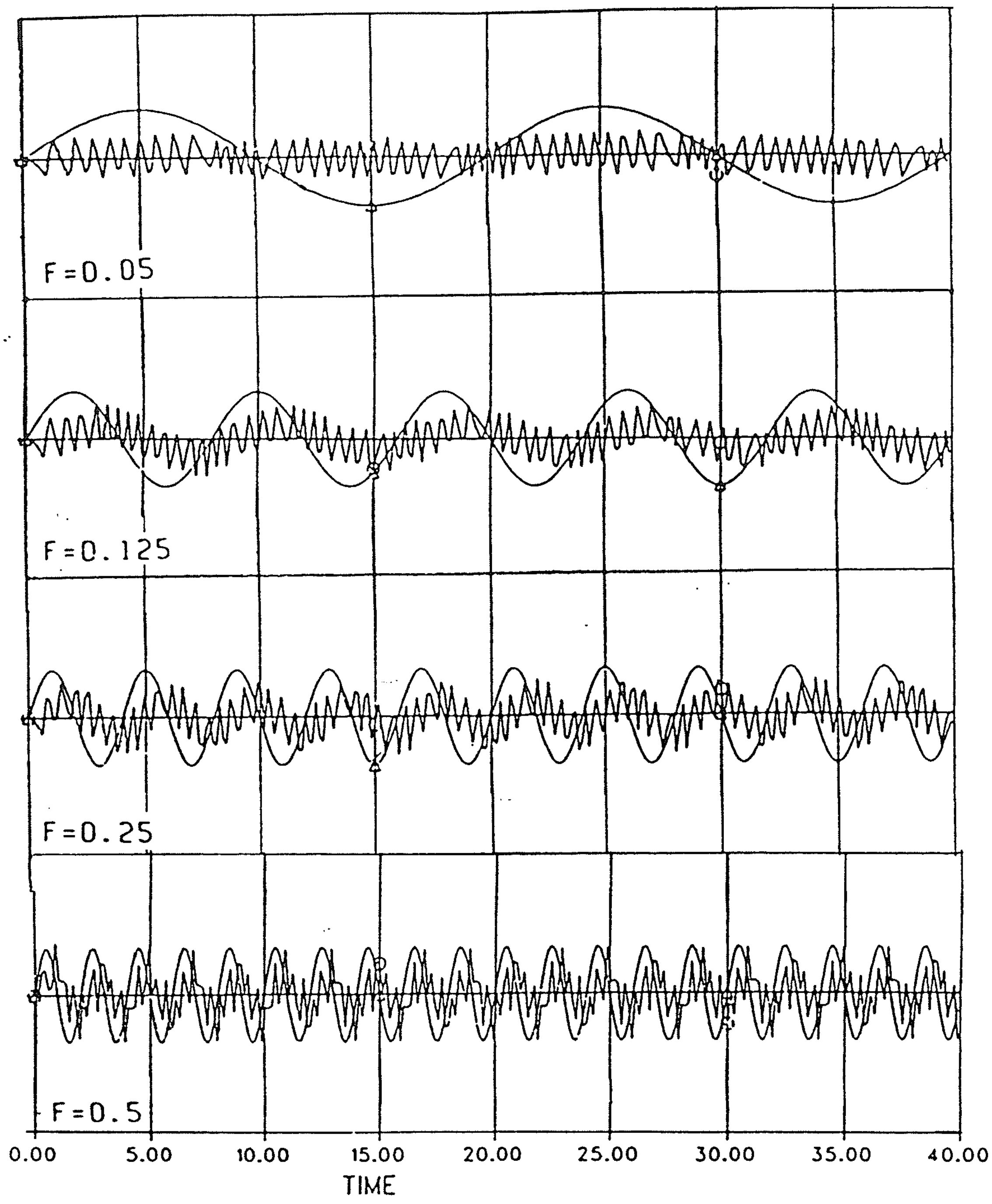
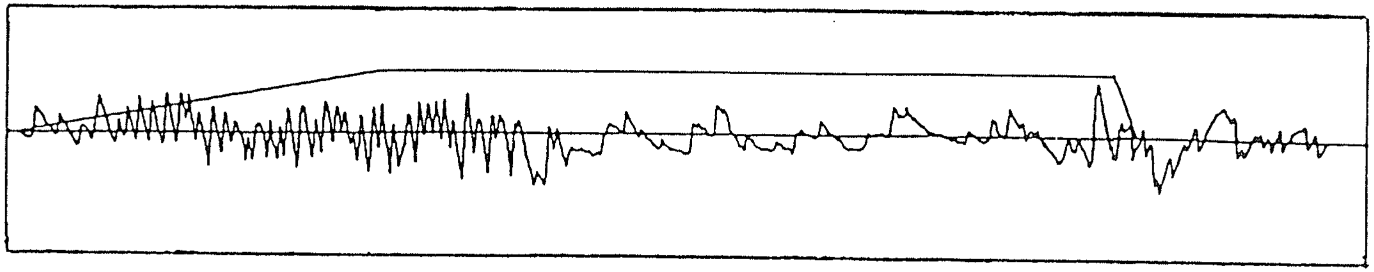
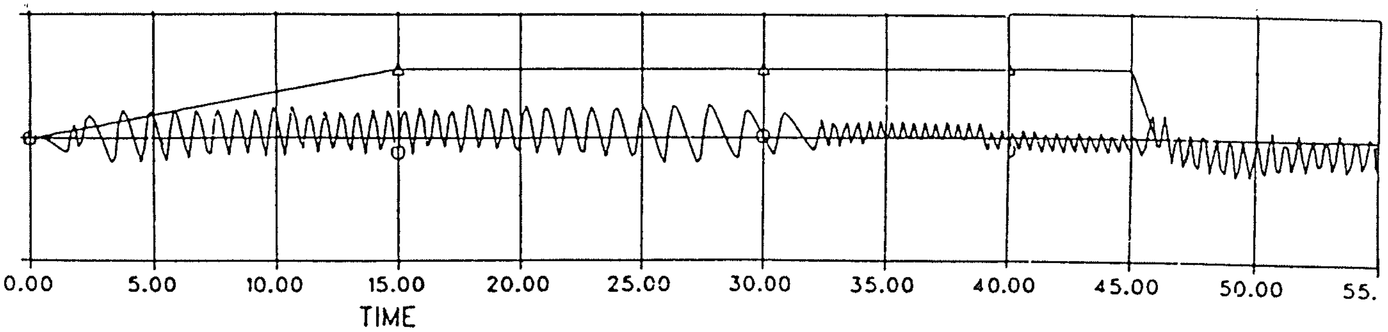


Fig.5-4 Responses of the model to sinusoidal velocities at 0.05Hz,0.125Hz,0.25Hz and 0.5 Hz with the peak velocity of 90deg/sec.



SUBJECT



MODEL

Fig.5-5 Responses of the subject and the model to trapezoidal head velocity.

Results from the theoretical model show a general agreement with experimental results for a wide range of head velocities. This means that the model can predict the following features of vestibular nystagmus.

1. The frequency of saccades increases with magnitude of the stimulus, since the threshold level Q is more often exceeded.

2. The slow phase eye velocity increases with magnitude of the head velocity, because the gain(slow phase eye velocity/head velocity) generally does not change with magnitude.

3. The saccadic velocity is a function of its magnitude and also changes with head velocity.

4. There is a null period when the head velocity passes through zero, since the threshold is increased for small head velocities.

5. Adjusting some parameters can account for the differences in saccadic patterns exhibited by different subjects. For example, decreasing the threshold level Q results in an increase in the frequency of saccadic beats.

6. When the input is a trapezoidal velocity, the nystagmus magnitude die out in the constant velocity section. However, the frequency is higher than expected. After this adaptation effects reverse the nystagmus.

5.2 THE QUANTITATIVE COMPARISONS

It is easier to fit the behavior qualitatively. To detect how well the model works, the quantitative comparisons are made here between the simulated results and the human VOR responses.

Table 5-1 and Table 5-2 show the characteristics of the subjects' and the model's sinusoidal responses with frequency 0.05Hz and magnitude from 200deg/sec to 50deg/sec.

The experimental data in Table 5-1 are the average EOG outcome of ten healthy subjects, 21-47 years of age and with normal vestibular function. The experiments are carried out in the dim room and subjects are instructed to perform mental arithmetic during the test run. Of these data the values of the slow phase eye movement are quite close to other researchers' experimental results[23,13]. The typical fast phase velocity of a cat, reported by Robinson, is 100 deg/sec, but results of quantitative analysis of human VOR fast phase have not been found, thus a comparison cannot be made.

In Table 5-2 the simulated data correspond to the output of computer simulation of the model shown in Fig.5-2. During the computer simulation all system parameter values are identical. It is noticed that the values of all entries in Table 5-1 are very close to those of the corresponding ones in Table 5-2.

Table 5-1: Responses of Human VOR

M	F	No	S.D.	G	S.D.	AG	S.D.
200	0.05	20	2.16	1.12	0.18	0.52	0.083
150	0.05	17	1.56	1.14	0.15	0.52	0.054
100	0.05	14	2.54	1.30	0.12	0.59	0.078
50	0.05	11	1.84	1.42	0.07	0.63	0.058

M	F	ASV	S.D.	AFV	S.D.
200	0.05	106.0	16.58	136.2	28.03
150	0.05	78.8	7.97	121.1	28.10
100	0.05	59.1	7.84	120.3	28.70
50	0.05	31.4	2.84	91.0	13.43

M: peak magnitude of head velocity,
F: frequency of head velocity,
S.D.: standard deviation,
No: the number of quick phase per half cycle,
G: gain(peak slow phase eye velocity/peak head velocity),
AG: mean gain(mean slow eye velocity/mean head velocity),
ASV: average slow phase velocity,
AFV: average fast phase velocity.

Table 5-2: Responses of VOR Model

M	F	No	G	AG	ASV	AFV
200	0.05	20	1.1	0.55	110	120
150	0.05	18	1.27	0.56	87	110
100	0.05	14	1.4	0.54	54	98
50	0.05	11	1.2	0.54	27	73

Next let us compare the characteristics of subjects' EOG data to that of the model at different frequencies with peak head velocity of 90deg/sec listed in Table 5-3 and Table 5-4. The meaning of parameters is the same as in Table 5-1.

The experimental conditions in Table 5-3 are the same as those in Table 5-1. Furthermore, during the computer simulation, the system parameter G is changed with head sinusoidal frequency and is listed in the Table 5-4 (G*). The data in Table 5-4 correspond to the output of the simulation shown in Fig.5-4.

5.3 SUMMARY

A dual pathway VOR model in the horizontal VOR has been investigated and refined. An attempt was made to provide a coherent explanation for the observed responses of eye movement during semicircular canal stimulation. The model can produce and exhibit the fundamental nystagmus patterns of human VOR responses to the head velocity for a wide range of frequencies and magnitudes. The more quantitative measures and comparisons indicate that the dual-pathway VOR model can predict quantitatively the features of human VOR responses.

Comparing Table 5-1 and Table 5-2, the saccadic frequencies increase with the peak magnitudes of the head velocity from 11 to 20Hz. The magnitude of the head velocity

Table 5-3: Responses of Human VOR

M	F	AG	S.D.	ASV	S.D.	AFV	S.D.
90	0.05	0.59	0.05	53.1	4.83	108.3	11.86
90	0.125	0.67	0.10	60.6	8.88	118.7	15.88
90	0.25	0.75	0.07	67.4	5.88	132.0	18.26
90	0.50	0.78	0.07	70.6	6.17	160.3	38.49

Table 5-4: Responses of VOR Model

M	F	AG	ASV	AFV	G*
90	0.05	0.60	54	91	0.05
90	0.125	0.62	56	95	0.15
90	0.25	0.68	61	110	0.25
90	0.50	0.77	69	130	0.35

does not affect the gain too much. However, an increase of the head sinusoidal frequency causes the gain to increase from 0.60 to 0.77 (see Table 5-3 and Table 5-4). The fast phase velocities increase with the increase of the magnitudes and frequencies of the head velocity. There is agreement about these fundamental features with previous reports about human VOR responses[19,23].

Inspecting the simulated results of the model (see Fig.5-2) in the case of the peak magnitude of 50 degrees, there is the unexpected increase of the saccades frequencies when the head velocity passes through zero. Decreasing the gain constant K will improve this problem, but the fast phase velocity will be altered from 73 to 57 deg/sec.

Chapter VI

COLLECTING EOG DATA

6.1 EXPERIMENTAL METHOD

6.1.1 Apparatus and Method

The computer-controlled vestibular research examination chair system is used to obtain human subject EOG data. The chair rotation is controlled by a 8088 microprocessor with maximum velocity 300 deg/sec and maximum acceleration 300 deg/sec/sec. The chair's angular velocity profile must be generated before experiments are performed using program 'NEWTRY1' or 'NEWTRY2'. Presently available velocity profiles for the chair are sinusoidal rotation 0.01Hz-0.5Hz, triangular waveform rotation at frequency 0.01Hz-0.5Hz and trapezoidal velocity profiles.

The program 'CONCATEN' can combine two or more velocity profiles with different rotation curves into one. The program 'INIFILE' is developed for initiating the velocity profile. The program 'SEEVEL' is used to check the velocity profile before running.

Subjects are seated on the examination chair with a head rest for stabilization. For calibrating the EOG data saccadic eye movements are elicited by fixation on sequential LED's placed in front of the subject at 10,20,and 30 degrees from the primary position in the horizontal plane. Spontaneous and gaze nystagmus are tested with eyes open and the subject performing mental arithmetic.

To minimize drift in the sensitivity of the EOG, experiments are carried out in a room illuminated with dim light. All subjects are adapted until successive recalibrations show that the corneoretical potential has stabilized (usually about 10 min). The calibration is performed before and after each series of tests.

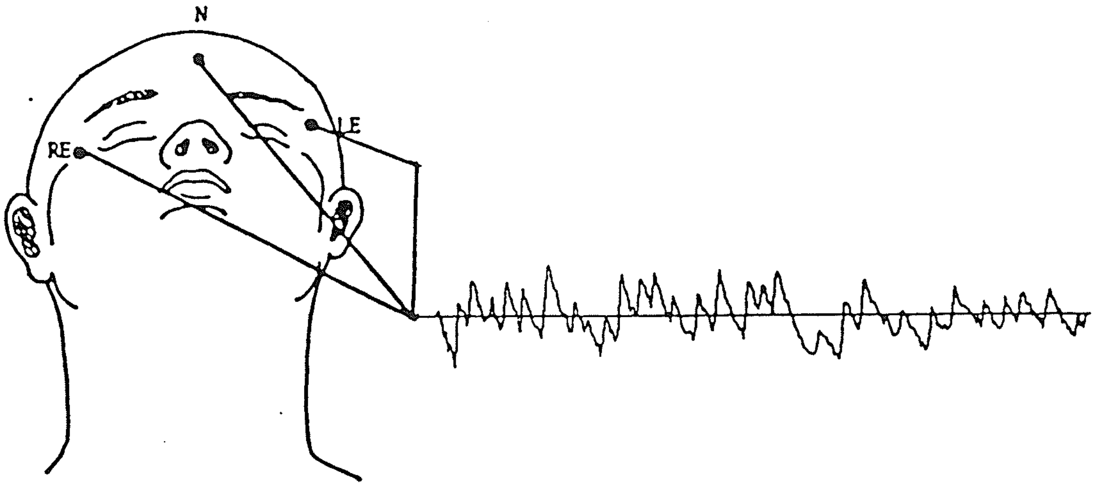


Fig.6-1 EOG electrode placement.

Horizontal eye position is recorded by dc Electro-Oculography(EOG). Electrodes are fixed to the lateral of both outer canthi and to the forehead for ground reference, to record bitemporal horizontal eye movements(see Fig.6-1).

The electrodes are small(7mm in diameter by 3mm thick) to allow for placement close to the eyes. The skin is cleansed thoroughly at the contact points before electrodes are applied.

6.1.2 Data Processing

The amplified EOG signal is digitized at a rate of 500 samples per second and recorded on a floppy disk in hexadecimal format as the chair rotates. This recording is synchronized with the velocity profile of the chair. Further data processing is done after the test runs. The first step is to convert the hexadecimal eye position data to ASC11 decimal data using the command 'EXTRACT' on a 'Visual 500' terminal connected to the Amdahl computer system. Then EOG data in ASC11 decimal are sent to the dataset on the Amdahl using command 'VTRAN'.

A computer program was written for the Amdahl computer to calculate the nystagmus beat frequency, the gain(slow phase peak eye velocity/peak head velocity), the mean gain(slow phase mean eye velocity/ mean head velocity), mean slow phase velocity and mean fast phase velocity. Before calculating these parameters, the data are calibrated and treated by a simple harmonic digital filter of the form:

$$Y_i = 0.25Y_{i-1}+0.5Y_i+0.25Y_{i+1}$$

The velocity is calculated for every interval between two smoothed samples. The criterion used to check whether the slow phase eye velocity is acceptable in order to eliminate the recording artifacts is as follows. The eye velocity is deemed valid if it is less than 1.5 times as large as it is supposed to be. Saccades are identified by setting a minimum duration. When the duration is longer than this minimum(usually 95 ms) a saccade is identified. Some artifacts such as eye blinks or electric interference are deleted by rejecting the cases which are less than the minimum duration. The program 'ANALY' is developed for this purpose. Finally, the EOG data can be plotted to intuitively analyze and to determine whether valid data were recorded. The programs 'VXER1' and 'HANDLE' produce output to the Xerox plotter.

6.2 ANALYSIS OF EOG DATA

Generally, there are some differences in the EOG data from day to day and subject to subject. Also, there are many factors which affect the quality of EOG data. Nevertheless, the critical effect on EOG data is the subject's mental state, such as voluntary visual and nonvisual fixation.

Thus, the instructions given to the subjects before the testing might affect the outcome. Furthermore, to analyze EOG data more correctly and efficiently, the different experimental conditions were studied.

Three experiments were made for this purpose and their results are shown below.

1) Nystagmus Suppression During Sinusoidal Head Oscillations

Here the subject is rotated sinusoidally at a frequency of 0.05Hz and a peak velocity of 100 deg/sec. Rotations are performed under the following six conditions, (1) with no instruction; (2) with the subject performing continuous mental arithmetic; (3) with blackened glasses; (4) with a small red light in front of subject and subject's eyes fixed on the light; (5) with a imaginary light directly in front of subject as in the prior test and keeping eyes fixed on this imaginary light. In above five conditions subjects are instructed to keep open their eyes. In the sixth condition, they are instructed to close their eyes in the first sinusoidal cycle and open them in the second cycle.

2) Fixation of Space-Stationary Visual and Nonvisual Targets During Sinusoidal Head Oscillation

The subject is accommodated in the chair. The chair is rotated sinusoidally at 0.5Hz and a peak amplitude of 90 degrees. Here the subject first fixates on the LED in front, then the LED is turned off and the subject fixates on an imaginary LED as in the previous test.

The calibration of eye movement is repeated at the end of the test.

3) Influence of Voluntary Ocular Deviation on Vestibular Nystagmus

The influence of voluntary gaze deviation on vestibular nystagmus is examined during a trapezoidal velocity profile with acceleration and decceleration rates of 15 deg/sec/sec and 90 deg/sec/sec, respectively, and separated by a 90 deg/sec constant velocity interval that is maintained for 29 seconds. Three conditions are tested, i.e.: (1) gazing deviation 21 degrees in the direction of the fast phase component of nystagmus(+21); (2) no deviation(0); (3) gazing deviation 21 degrees in the direction of the slow phase component of nystagmus(-21). Prior to the beginning of each condition, the target light(LED) is temporarily illuminated to permit calibration of eye position. This target light remained visible for approximately 15 seconds and extinguished. The subject's task is to continue fixating on the target light after it is extinguished throughout the velocity profile.

Results and Analysis

The typical nystagmus responses recorded while the subject was performing mental arithmetic(MA) in the dim room during sinusoidal head oscillation at 0.05Hz is shown in the first records of Fig.6-2 (the results of Experiment 1).

The reversal of nystagmus direction occurred almost in phase with the reversal of chair motion, and the compensatory slow-phase eye movement is phase opposite to head movement. The amplitude of nystagmus beats is modulated sinusoidally, with the largest beats occuring when chair velocity reaches its maximum values. The number of beats per half a period of chair oscillation is almost the same in the two directions of nystagmus.

When the subject is presented with a fixation target moving with him/her, the nystagmic response undergoes significant modifications. Both the slow and fast phases of nystagmus are suppressed and the eyes maintain the central position. A complete suppression of nystagmus is observed when a visual target is presented (Record VT in Fig. 6-2). When the subject is asked to maintain the fixation on an imaginary target rotating with him, there is a general reduction of nystagmus beat amplitude.

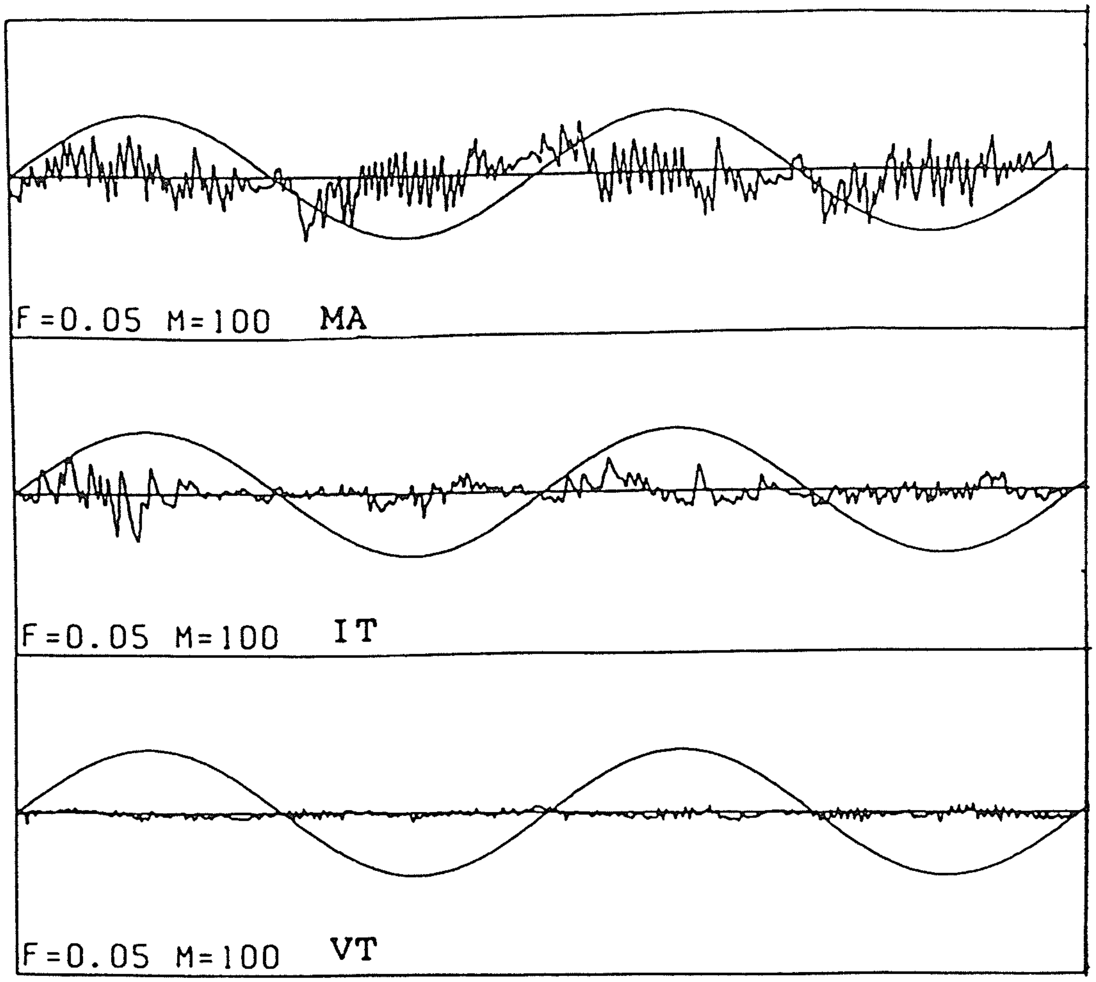


Fig.6-2 Nystagmus suppression during sinusoidal head velocity at 0.05Hz with a peak amplitude of 100 degrees. MA:mental arithmetic; IT:imaginary target; VT:visual target. Target were moving with the subject. Head velocity was given in each recording.

In contrast with this, observe the results of Experiment 2 shown in Fig.6-3. When the subject is oscillated at the frequency of 0.5Hz in front of a space stationary visual target, instead of a target moving with subject, the nystagmoid pattern of eye movement is different. A smooth eye movement fully compensates head rotation(Record SVT in Fig.6-3). The gain of the compensatory eye movement becomes close to unity with a visual target and little bit lower with an imaginary target.

What is the mechanism for these kinds of changes caused by visual fixation? Why do the two visual fixations(space stationary and chair stationary) cause completely different results? This still is controversial problem. It is not clear whether the nystagmus changes are mainly through the direct control of VOR gain, or through a contribution of smooth-pursuit system or through some other mechanism.

According to the smooth pursuit system control theory, when the subject rotates with a visual target moving with him, the eye deviation induced by the vestibular stimulation produces a retinal slip of target image, and the smooth pursuit system commands an eye movement that cancels the vestibular component. In contrast, when the subject is made to oscillate in front of a space-stationary visual target the retinal slip produced by incomplete VOR compensation forces the smooth pursuit system to cooperate up to a complete visual stabilization[23].

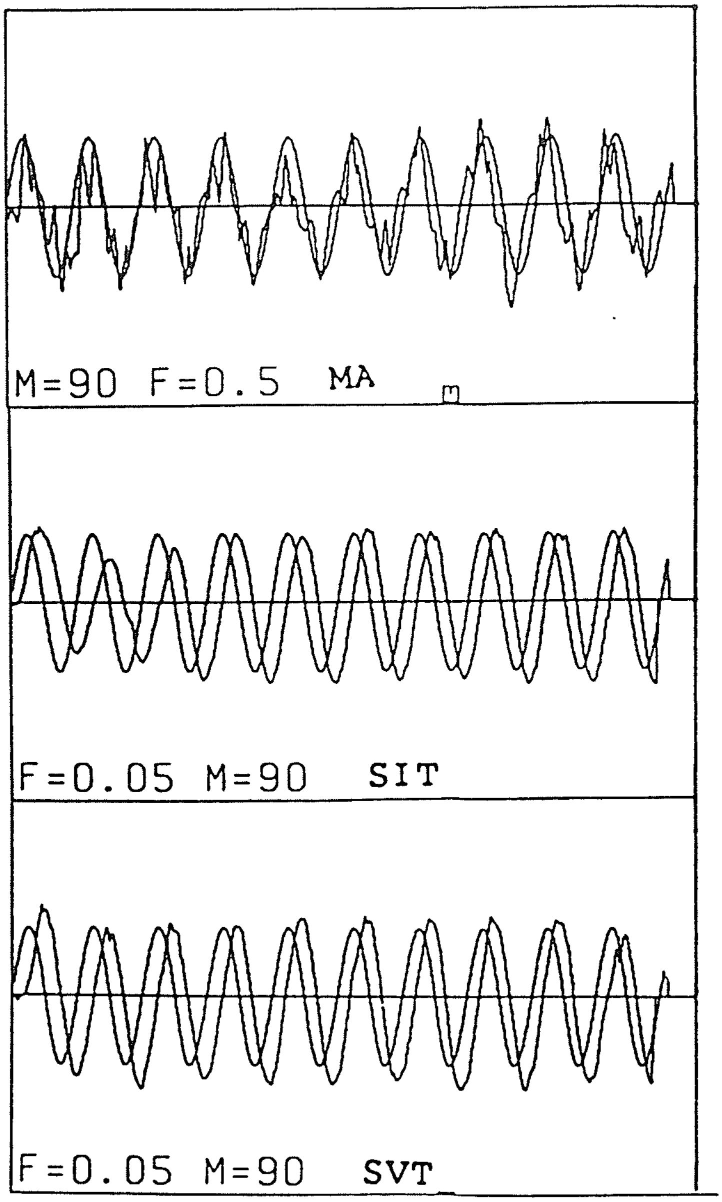


Fig.6-3 Eye movement recordings while a subject was rotated at sinusoidal frequency of 0.5Hz with a peak amplitude of 90 degrees. MA:no fixation target; SIT:imaginary LED on the wall; SVT:visual LED on the wall.

However, gain control theory[20] suggests that the gain of VOR is under the control of a central mechanism. That is, during nystagmus suppression by fixation of a visual target moving with the subject, the eye-velocity component of P-cells activity is zero and the head velocity component passes through the flocculus, reaches the brain-stem interneurons, and inhibits the VOR pathways, the gain of which is maintained equal to zero. During the fixation of a visual target stationary in space, the eye velocity component of P-cells activity is larger than the head-velocity component, and VOR gain is increased from 0.4-0.6 to unity. This mechanism does not require vision. One obvious argument against an exclusive role of smooth pursuit in fixation suppression is that nystagmus suppression can be produced during the first 100 milliseconds of transient responses, when the smooth pursuit has no time to intervene due to its latency of 130 milliseconds.

To prevent voluntary visual fixation in VOR tests it is suggested that the subject wear glasses or perform mental arithmetic during the test procedure. The latter also serves to keep the subject alert.

In clinics, Frezel's spectacles are used[29]. This is a set of glasses with very strong convex lenses and a built-in light source. These make the patient myopic and unable to fixate, while allowing the physician to observe easily the eye movement. Instead of the special spectacles, general blackened safety goggles are used in the laboratory to eliminate the possibility of visual fixation. Other patches to cover subject's eyes were tried. The resulting VOR is the same as that with wearing goggles.

Comparing graphical EOG data obtained when the subject's eyes are covered (Record WG in Fig.6-4) to that when mental arithmetic is performed, intuitively, it appears that the latter gives better results. There are not too many small saccades. Another notable point is that there is a decrease of the gain and velocities when a subject wears the blackened goggles. The quantitative comparison is made below.

Table 6-1 and Table 6-2 show the characteristics of the subjects' VOR responses in different experimental conditions. Actually, Table 6-1 is the same as Table 5-1. The test runs were carried out in dim light room with the subjects performing mental arithmetic. The entries in Table 6-2 are the average of four subjects' EOG data. During the test run subjects wear the blackened safety goggles. It is not quite clear whether the slight stress created by the lens and patch affects the EOG outcome. It is not very clear either whether the present measurement of the calibration is not suitable to the subject wearing glasses. This should be studied further.

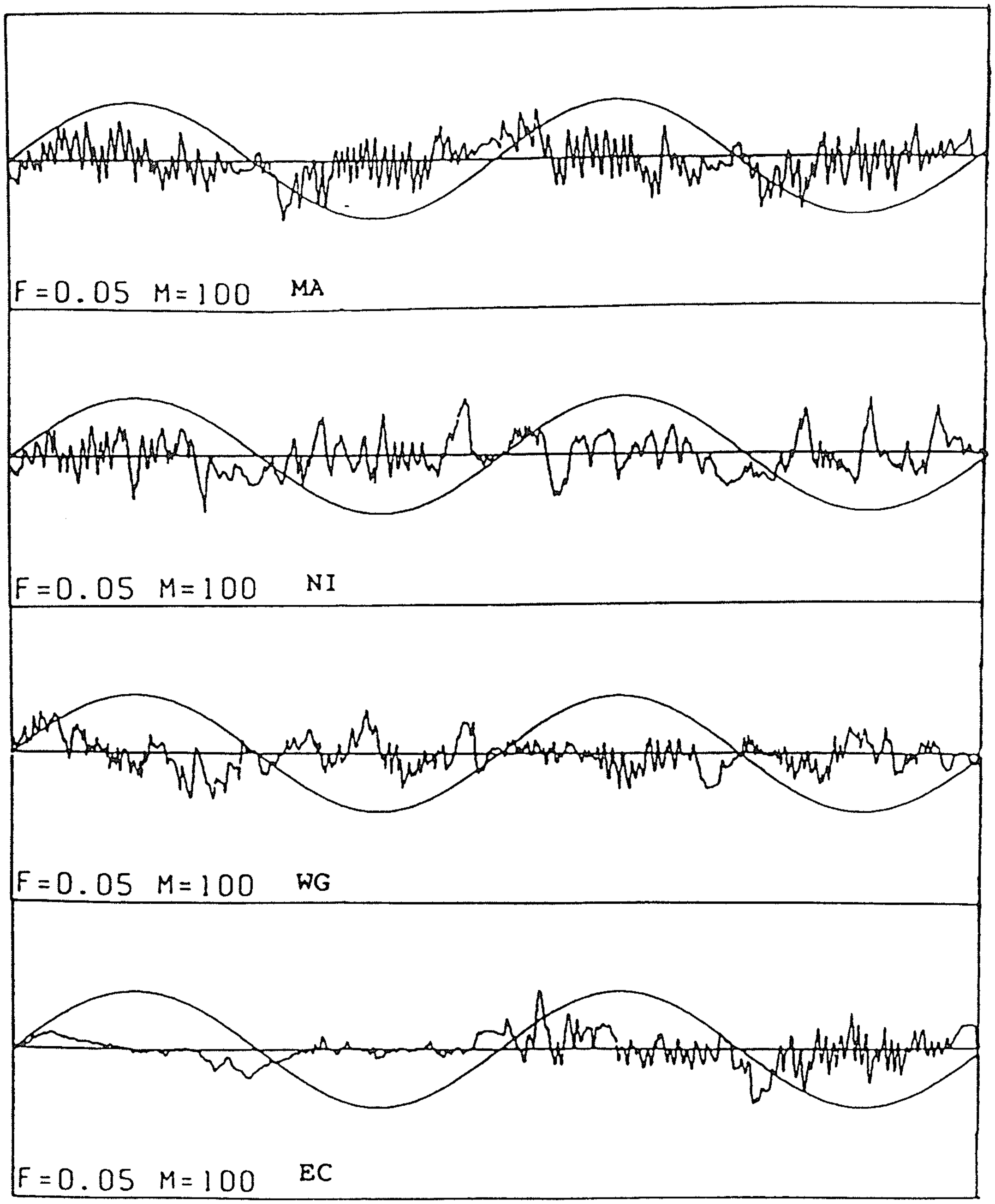


Fig.6-4 Eye movement recordings during sinusoidal head velocity at 0.05Hz with a peak amplitude of 100 degrees. NI:no instruction; WG:wearing blackened goggles; EC:eye closure in the first cycle.

Table 6-1: Responses of Human VOR

(in dim room, with subject performing mental arithmetic)

M	F	Beat No	G	AG	ASV	AFV
200	0.05	20	1.12	0.52	106.0	136.2
150	0.05	17	1.14	0.52	78.8	121.1
100	0.05	14	1.30	0.59	59.1	120.3
50	0.05	11	1.42	0.63	31.4	91.0

Table 6-2: Responses of VOR Model

(with subject wearing the blackened goggles)

M	F	Beat No	G	AG	ASV	AFV
200	0.05	20	1.1	0.39	77	113
150	0.05	18	1.17	0.42	64	79
100	0.05	15	1.37	0.50	50	62
50	0.05	11	1.4	0.54	27	58

The preceding Fig.6-4 NI(no instruction) shows the results with no instructions to subjects. Comparing NI to MA one thing is clear: any instruction to the subject is better than none at all. Without instruction a subject could unconsciously adopt a strategy that is confusing.

From Fig.6-4 EC(eye closure) the effect of eye closure on the vestibular spontaneous nystagmus can been seen. Generally the nystagmus are inhibited by voluntary lid closure.

It is considered that the eye is an electrical dipole, with the positive pole at the front and the negative pole at the back. As the eye rotates within the horizontal orbit each pole comes closer to one or the other of a pair of recording electrodes, causing the voltage difference between the two electrodes to change. If the eyeball moves up, the electrodes positioned at the nasal and temporal edges of the orbit(horizontal EOG) cannot record the VOR data correctly.

Finally, consider the influence of voluntary ocular deviation on vestibular nystagmus. Fig.6-5 shows the result of Experiment 3. It is obvious that gaze deviation in the direction of the fast phase component of nystagmus significantly increased slow phase amplitude and fast phase amplitude. Table 6-3 shows the increase of slow phase velocity. In contrast, gaze deviation in the direction of the slow phase marginally decreased these three properties. The voluntary positioning of the eyes systematically altered the nystagmus pattern. The systematic increase or decrease in nystagmus depending on gaze direction is known as 'Alexander's Law'. There have been suggestions that the effect of Alexander's Law demonstrated during vestibular nystagmus is accounted for entirely by the addition of the gaze nystagmus[26].

Table 6-3: Influence of Deviation

deviation angles	fast phase magnitude	mean slow phase velocity
21	17.1	57
0	14.8	46
-21	11.2	27

Robinson analyzed this behavior at motorneuron level[6]. The behavior of all ocular motoneurons can be described using the following equation:

$$R_m = R_0 + KE + r\frac{dE}{dt}$$

where: Rm: instantaneous discharge rate,

Ro: discharge at a constant rate measured in spike/sec,

E(t): instantaneous eye position.

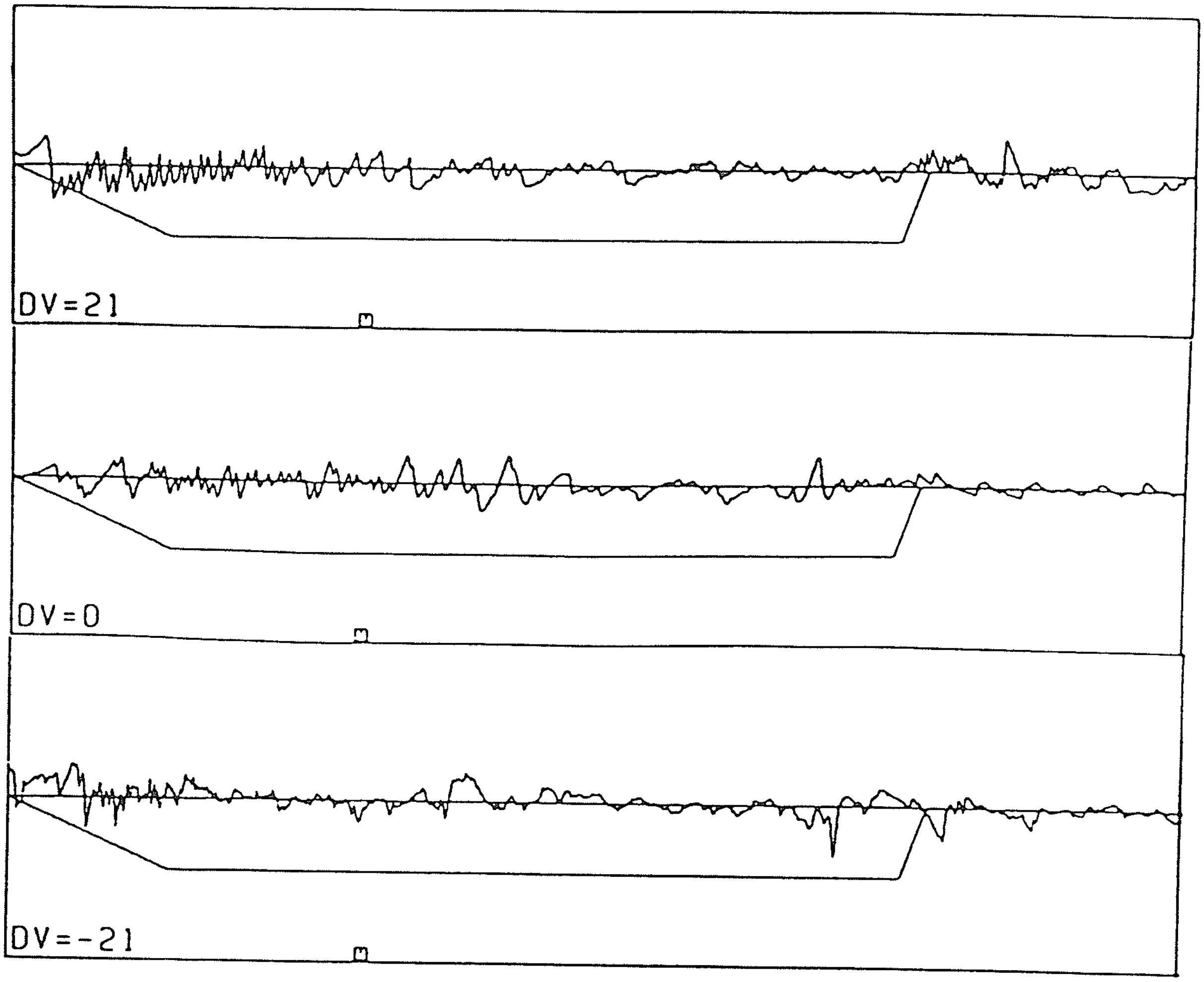


Fig.6-5 Influence of deviation on vestibular nystagmus. +21:gaze deviation in the direction of the nystagmus fast phase; 0:straight ahead; -21:gaze deviation in the direction of the nystagmus slow phase.

If the subject fixates at some angle E in the pulling direction of the muscle, the discharge rate is increased by the amount KE. In contrast, the rate decreases by KE. If the eye is also in motion, another force, proportional to velocity is represented by the term rdE/dt.

It is clear from the above discussion that the value of nystagmography can be greatly diminished if certain errors are not recognized and avoided. So the important thing is giving subjects clear instructions to let them know what is to be done and how to do it, especially, for the subject with no previous experience in this testing.

On the other hand, some errors are introduced by faulty recording techniques. The first is caused by faulty electrode application. High contact impedance at the electrode-skin junction will cause noise to be picked up more effectively and reduce the gain of the nystagmography, requiring an increase in amplification both of signal and noise. To minimize the noise by insuring that the electrode contact impedance is as low as possible, one should thoroughly clean the skin at the electrode sites before applying the electrodes. Previous studies[18] report that virtually noise-free recordings can be obtained by assiduously scrubbing the skin with an alcohol-soaked pad.

The second error source is from other biological potentials:

(1) In this case an EMG signal is one caused by contraction of the muscles of the face and neck. These changes appear as high frequency spikes shown in Fig.6-6A. They can usually be eliminated by asking the subject to relax.

(2) The potential change caused by eye blink looks like beats of nystagmus especially if one of the electrodes is placed slightly higher than the other(see in Fig.6-6B). The best way to detect these kinds of artifacts are by recording the vertical eye movements from a pair of electrodes, one placed above and the other below one of the eyes, and then eliminating the effect using data processing.

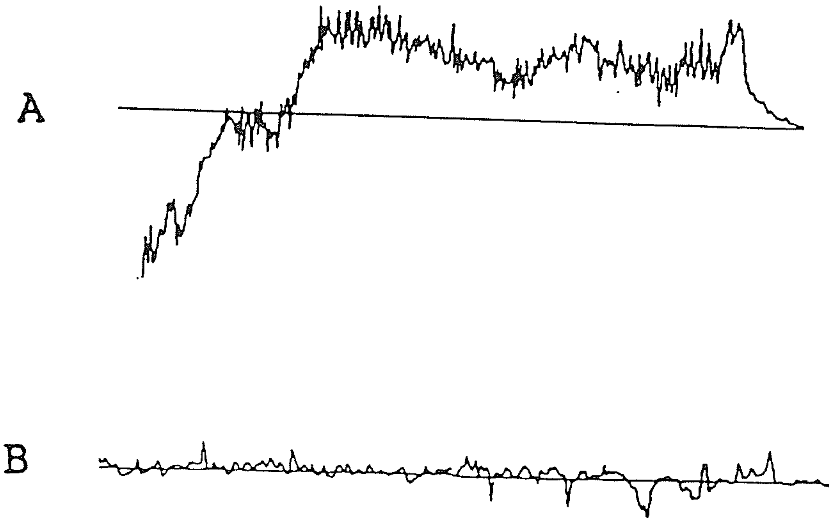


Fig.6-6A Muscle potential responses.
6-6B Eye blink potentials.

Chapter VII

CONCLUSIONS AND RECOMMENDATIONS

The overall goal of this thesis was to investigate, evaluate and refine the dual-pathway VOR model by comparing the model responses with the response of human subjects.

Based on the analyses of subjects' VOR responses, all of the system parameters of the dual-pathway VOR model were reconsidered and adjusted. Some physiological parameters, such as A,B,Q1,Q2, were reset to suit the human VOR system. Two non-linearity schemes, defining Q and SACP, were optimized. The gain constants were discussed in detail. Especially, by optimizing the schemes SACP and adjusting the gain constant K, the fast phase velocity from the model output can be matched to that of human VOR responses. Furthermore, a switch S3 was added to cause the fast phase velocity to increase with the head velocity.

As a result of these modifications the improved dual-pathway VOR model can produce and exhibit the fundamental nystagmus patterns of human VOR responses to the head velocity for a wide range of frequencies and magnitudes. It was found that there is a good agreement on quantitative analysis between the outcome of human VOR responses and the model output. Also, it was found that the quantitative analysis of slow phase eye movement data confirms the previously published results.

The study of EOG data indicated that the subjects' mental states mainly affect the quality of EOG data, in addition, faulty recording techniques may cause EOG data to be unexpected. To properly collect human VOR data, it is important to give subjects clear instructions concerning what is to be done and how to do it; also, it is useful to learn how to analyze the possible EOG data under different experimental conditions.

It has been shown that the behavior of the model output, in the case of peak magnitude of 50 degrees, was not good enough, when the head velocity passes through zero. It may be improved by further optimizing of the system parameters. Another feature that could use more attention too is the unexpected increase of saccadic frequency during the constant section of the trapezoidal head velocity. Further research is required to either improve the dual-pathway VOR model or extend the study on the modelling human VOR system. The topics for further research are:

(1) The study of the effect of a defective human physiological system in the dual-pathway VOR model. This could include investigating the VOR response of the patient with a defect in one side and adjusting system parameter values to produce an output that is similar to the patient's response.

(2) The study of the effect of the reciprocal commissaral loop in modelling VOR system.

From this study, it might be said that one would expect different human subjects to have different parameter values. Thus, one should not expect a single model to accurately describe all subjects. Also, one should not expect a single model to explain all phenomena of vestibular nystagmus. Otherwise, the model will be too complicated. The dual-pathway VOR model should have an advantage when studing the VOR response of the patient with one defective side.

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Appendix A

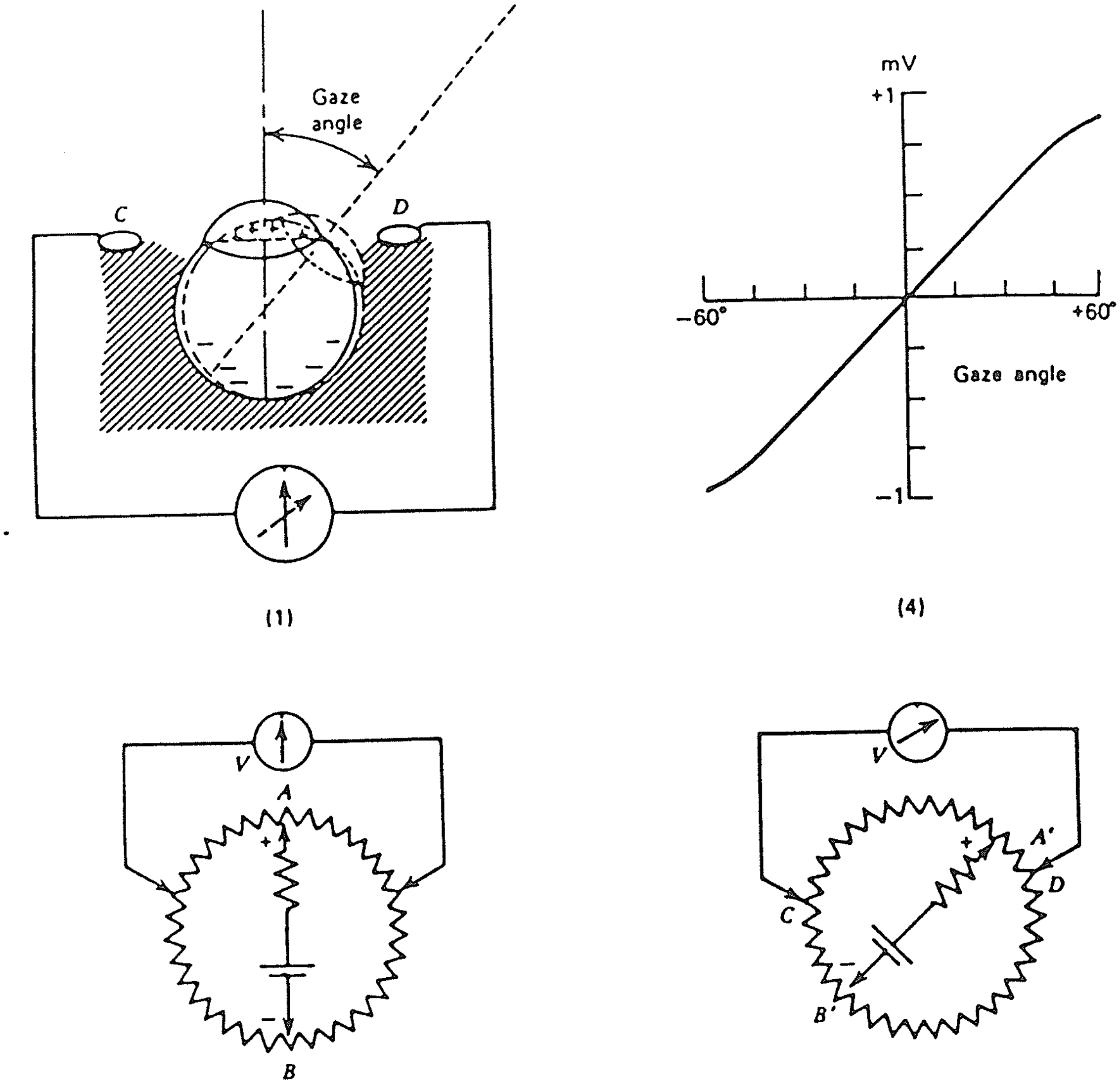
EOG AND DIPOLE THEORY

A.1 ELECTROOCULOGRAPHY

Placing one orthogonal pair of electrodes around an eye will permit measurement of potentials that can be used to identify the direction and the value of eye movement with respect to the head. The bioelectric event underlying these signals is a standing potential, measurable between the cornea and posterior pole of the eyeball. Thus the eyeball resembles a dipole that can move in a conductor(the head) as illustrated in Fig.A-1.

When the electrodes are fixed laterally to the eyes, the potential ought to be zero with eyeball directed forward. As the gazing angles of the eyes are from +30 to -30 degrees, the potentials are changed. It is found that a linear relationship exists between the gazing angles of eyes and change of potential value.

In the dark, a standing measurable potential exists across the various layers of the retina. When the retina is illuminated, cyclic changes occur in this potential, a recording of which constitutes the electroretinogram.



(1)

(4)

(2)

(3)

Fig.A-1 The corneoretinal potential (1) and its representation as an equivalent circuit(2,3) for forward and right gaze; (4) represents a typical voltage versus gaze angle relationship[28].

A.2 DIPOLE THEORY

(extracted from [28] 429-433)

Since active tissue is electronegative with respect to an inactive or recovered area, a boundary exists. The boundary between active and inactive tissue can be represented by a dipole, and because environmental tissues and fluids can conduct current, potential fields will be established, as in Fig.A-2.

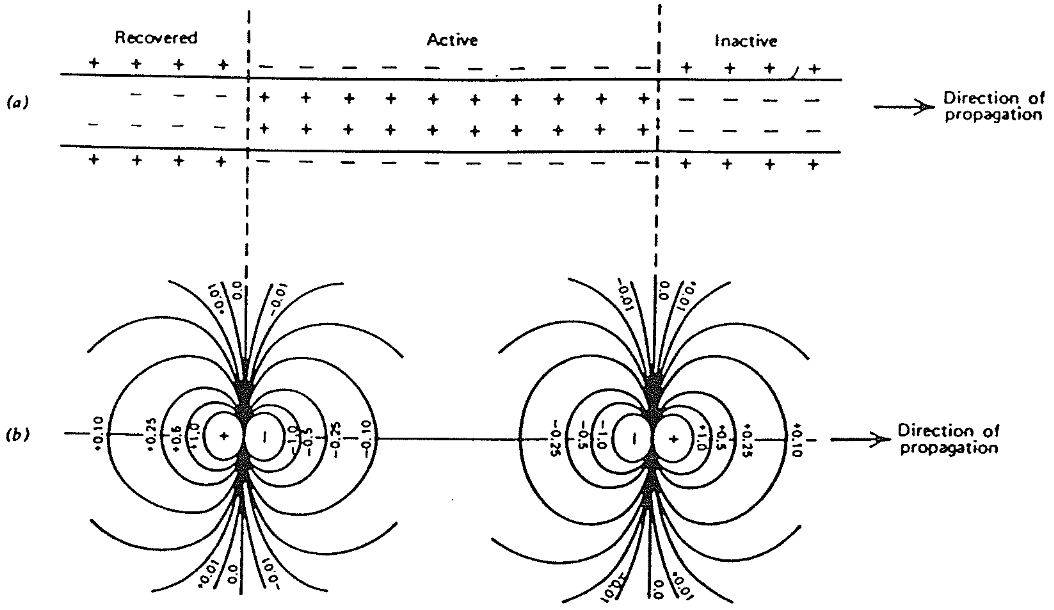
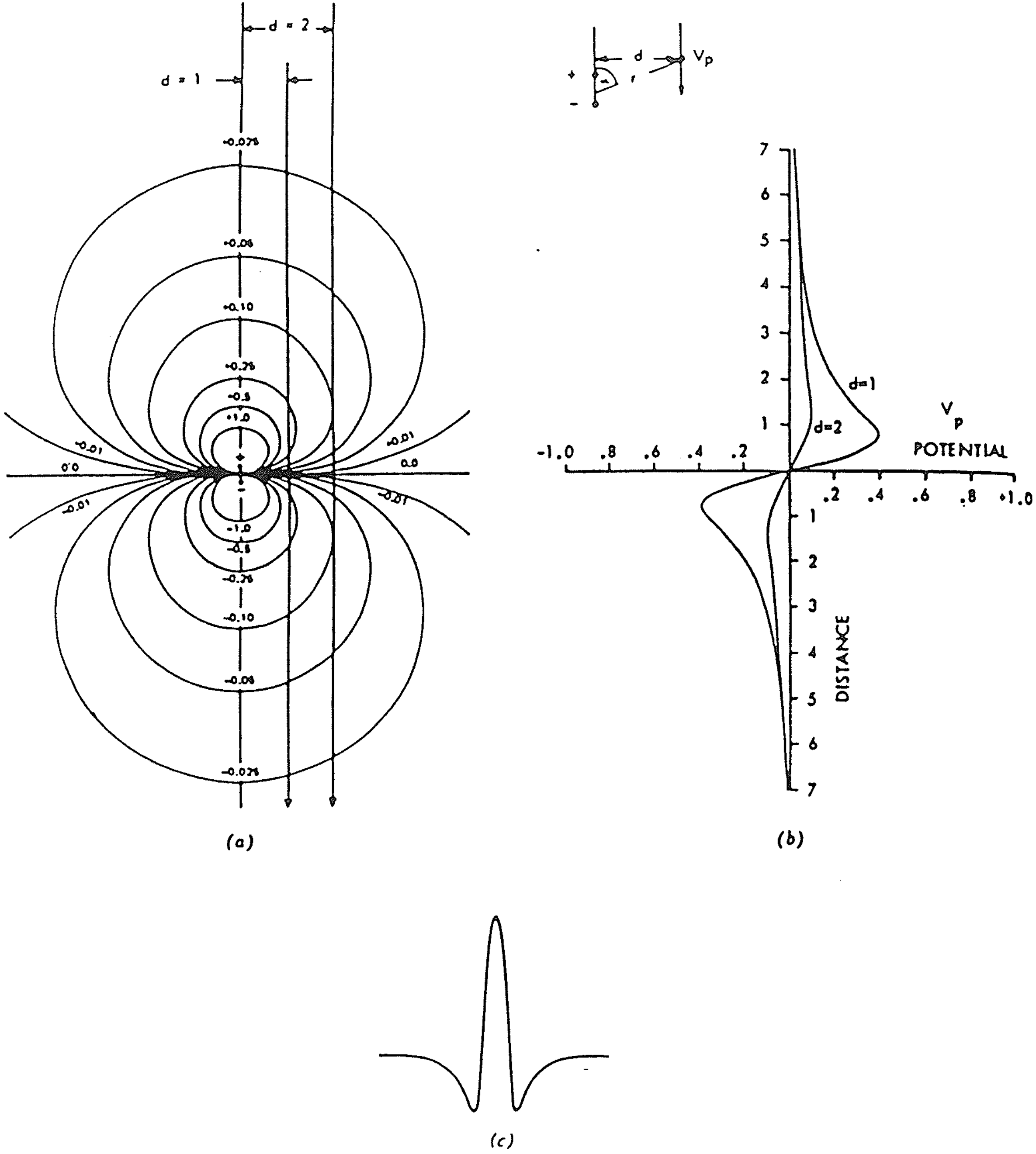


Fig.A-2 Application of the dipole concept to represent excitation and recovery[28].

The potential field surrounding a current dipole in an infinite volume conductor is represented in Fig.A-3. If the dipole moves along its axis, its field will accompany it, and the potential(Vp) at a nearby point will start to rise, then fall to zero, increase in the negative direction, then decrease as the dipole moves farther away. Thus a positive-negative diphasic wave will be described as in Fig.A-3 (d=1) as the dipole passes the measuring point. If the point is more distant, (d=2), the potential excursion will be in the same direction but decreased in amplitude. This sequence of events describes what is obtained with 'monopolar' recording; that is, one electrode is near active tissue, the other is at a distance in a region of no potential change.

According to the dipole concept, propagated excitation is equated to a dipole traveling with its positive pole facing the direction of propagation. Thus a nearby electrode will detect a positive-negative biphasic potential as excitation passes. Recovery (repolarization) is equated to a dipole with its negative pole facing the direction of propagation. Therefore, at a nearby point, the passage of recovery will be signaled by a negative-positive biphasic potential. If excitation occupied only a small amount of tissue, the potential waveform will be obtained in Fig.A-3C.



(a)

(b)

(c)

Fig.A-3 The dipole and its potential field.(a) potential distribution; (b) potential encountered by exploring electrode moving along lines(d=1,d=2) parallel to the dipole axis; (c) the waveform frequently encountered with monopolar recording[28].

Appendix B

COMPUTER PROGRAMS

B.1 SUBROUTINES FOR EMTDC

```
******************************************************
*  Main program of EMTDC call the seven subroutines. *
*  Of these subroutines  DSDYN and DSOUT  are ones   *
*  which are  completely the users  responsibility.  *
*  DSDYN is used to supplement dynamic modelling,    *
*  and DSOUT is used to process the output.          *
******************************************************
```

```
      SUBROUTINE DSDYN
      REAL LIMIT,INTGL3,LDLAG2,DIFPL2,REALP2
%INCLUDE 'EMTE'
      COMMON /S1/TIME,DELT,ICH
      COMMON /S2/STOR(5000),NEXC/S3/GVLV(4,4,24),NVLV
      COMMON /S4/VAR(100),CON(100),PGB(25)
      IO1=7
      OPEN(IO1,FILE='DAXIAO')
      REST=VAR(1)
      ACCO=VAR(2)
      TA=VAR(3)
      TE=VAR(4)
      EKE=VAR(5)
      T=VAR(6)
      G=VAR(7)
      A=VAR(18)
      B=14.00
      KC=VAR(22)
      TK=VAR(11)
      TM=VAR(12)
      TC=12.0
      L=130.0
      M1=20.0
      R=1.5
      L1=VAR(23)
      L2=VAR(24)
      Q1=VAR(8)
      Q2=VAR(9)
      STGTH=VAR(15)
      KL=85.0
      KM=1.0
```

```
C
       IF (TIME.EQ.0.0) VAR(66)=0.0
       IF (TIME.EQ.0.0) VAR(77)=0.0
C      IF (TIME.LT.15.00.AND.TIME.GE.0.00) DH=-6.0*TIME
C      IF (TIME.LT.45.0.AND.TIME.GE.15.00) DH=-90.0
C      IF (TIME.LT.46.00.AND.TIME.GE.45.00)
C           DH=-90.00+90.0*(TIME-45.0)
C      IF (TIME.GE.12.5) DH=0.0
C      IF (TIME.LT.0.01) DH=0.0
C      IF (TIME.GE.0.00.AND.TIME.LT.20.00)
C            DH=20.0*SIN(6.283*TIME*0.05)
C      IF (TIME.GE.20.00) DH=0.0
       DH=VAR(21)*SIN(6.283*TIME*VAR(16))
       VAR(50)=DH
C      CUP=REALP2(0.6,15.0,ACC)
C      CUP1=0.10*CUP
100    FORMAT(1X,2E10.4)
       CUP=DIFPL2(15.0,DH)
       CUP1=-VAR(22)*CUP/15
       THETA1=-REST/KL
       THETA2=VAR(17)/KL
       DUM2=LIMIT(THETA1,THETA2,CUP1)
       N1=REST+KL*DUM2
       X1=N1-REST
       Y1=REALP2(1.0,TA,X1)
       AD1=N1-Y1
C
       IF(VAR(77).NE.0) SACG1=VAR(77)
       IF(VAR(77).EQ.0) SACG1=AD1
       A1=SACG1-REST
       DUM3=REALP2(1.0,VAR(29),A1)
       B1=DUM3*VAR(29)
       P1=TK*SACG1+B1
       FMF1=REALP2(1.0,VAR(19),P1)
C
       CUP2=-CUP1
       DUMM2=LIMIT(THETA1,THETA2,CUP2)
       N2=REST+KL*DUMM2
       X2=N2-REST
       Y2=REALP2(1.0,TA,X2)
       AD2=N2-Y2
C
       IF(VAR(66).NE.0) SACG2=VAR(66)
       IF(VAR(66).EQ.0) SACG2=AD2
       A2=SACG2-REST
       DUMM3=REALP2(1.0,VAR(29),A2)
       B2=DUMM3*VAR(29)
       P2=TK*SACG2+B2
       FMF2=REALP2(1.0,VAR(19),P2)
C
       ENETFO=-(FMF2-FMF1)
       EYPOS=REALP2(EKE,TE,ENETFO)
       EYVEL=EKE/TE*DIFPL2(TE,ENETFO)
C
```

```
      ADN=-(AD1-AD2)
      XP1=REALP2(G,T,ADN)
      BB=-B
      X=LIMIT(BB,B,XP1)
      AA=-A
      Y=LIMIT(AA,A,ADN)
      C=X+Y
      VAR(35)=SACG1
      Q12=Q2-Q1
      DC=(Q2*L1-Q1*L2)/Q12
      EM=Q12/(L2-L1)
      ABSA=ABS(ADN)
      AABS=LIMIT(5.0,20.0,ABSA)
      Q=EM*(AABS-DC)
C
      E=-(B2-B1)*VAR(30)
      ERR=-(C-E)
      VAR(40)=E
C
      IF (ERR.LT.Q) TRIG1=0
      IF (ERR.GE.Q) TRIG1=1
      IF (VAR(66).GT.0.0.OR.TRIG1.GT.0.0) SS1=1.0
      IF (VAR(66).LE.0.0.AND.TRIG1.EQ.0.0) SS1=0.0
      ERRO1=SS1*ERR
      E0=VAR(26)
      E1=-(ERRO1+E0)/VAR(27)
      EE0=-E0
      IF (ERRO1.LE.EE0) SACP1=0.0
      IF (ERRO1.GT.EE0)
          SACP1=VAR(28)*(1-2.718**E1)+VAR(25)
      VAR(66)=SACP1
C
      ERR1=-ERR
      IF (ERR1.LT.Q) TRIG2=0
      IF (ERR1.GE.Q) TRIG2=1
      IF (VAR(77).GT.0.0.OR.TRIG2.GT.0.0) SS2=1.0
      IF (VAR(77).LE.0.0.AND.TRIG2.EQ.0.0) SS2=0.0
      ERRO2=SS2*ERR1
      E2=-(ERRO2+E0)/VAR(27)
      IF (ERRO2.LE.EE0) SACP2=0.0
      IF (ERRO2.GT.EEO)
          SACP2=VAR(28)*(1-2.718**E2)+VAR(25)
      VAR(77)=SACP2
C
      IPOS=INT(EYPOS*32)+2048
      WRITE(IO1,100) EYPOS,EYVEL
      ES(1,1)=EYPOS
C
      RETURN
      END
C
      SUBROUTINE DSOUT
      REAL LIMIT,INTGL3,LDLAG2,DIFPL2,REALP2
%INCLUDE 'EMTE'
```

```
      COMMON /S1/TIME,DELT,ICH
      COMMON /S2/STOR(5000),NEXC/S3/GVLV(4,4,24),NVLV
      COMMON /S4/VAR(100),CON(100),PGB(25)
      F1=VAR(14)
      PGB(1)=0.7*VDC(1,1)
      PGB(2)=0.7*VAR(50)/F1
      PGB(3)=VAR(35)/4
      PGB(4)=0
      PGB(5)=0
      RETURN
      END
C
C
      DATAMODEL10/TITLE
      0.050 40.0  0.15      /
      1 /NO OF SUBSYSTEMS
      2 /NO OF NODES IN SUBSYSTEM1
      0.0 /INITIAL NODE VOLTAGE
      1 2 1.0 0.0 0.0 /
        RESISTANCE OF 1.0 OHM BETWEEN NODE1 & 2
      -2 0 100 0.0 0.0 /
        RESISTANCE OF 100.0 OHMS BETWEEN NODE 2 & GND
      999 /END OF BRANCH DATA
      1 0.0001 /
      999 /END OF SOURCE DATA
      999 /END OF TRANSFORMER DATA
      999 /END OF TRANSMISSION LINE DATA
      -10.00 10.00/PRINTPLOT LIMITS(LEFT---RIGHT)
      10 /NO OF OUTPUT CHANNELS REQUIRED
      90.0 90.0 80.0 0.0604 1.0 1.0 0.050 6.0 17.0
      0.06 0.2 0.1 15.0 4.0 1.0 0.05 410.0 1.0 0.1
      6.00 100.0 0.06 0.00 20.0 090 0.0 11.0 250.0
      25.0  1.00/
      999 /
```

B.2 PROGRAM NEWTRY1

```
************************************************
*  Program for generating sinusoidal velocity  *
*  profiles at frequency 0.01Hz-1Hz.           *
************************************************


CONST
   QUIT   = 'Q';
   AMAX   = 300;
   VMAX   = 300;
   TINC   = 0.01;
   TLIMIT = 600.0;

TYPE
  IFILE  = FILE OF INTEGER;
  RFILE  = FILE OF REAL;
  ANSSET = SET OF CHAR;

VAR
  TMAX : REAL;
  ANS  : CHAR;
  X    : CHAR;
  XAFILE : RFILE;
  XVFILE : RFILE;
  INVALIDA : BOOLEAN;
  INVALIDV : BOOLEAN;
  CFILE : RFILE;

PROCEDURE READ_ANS(VAR ANS : CHAR);

CONST
  YES  = 'Y';       (* CHARACTER REPRESENTS `YES'.  *)
  NO   = 'N';       (* CHARACTER REPRESENTS `NO'.   *)
  QUIT = 'Q';       (* CHARACTER REPRESENTS `QUIT'. *)

VAR
  ANSWER : ANSSET; (* ANSWER SET (YES/NO/QUIT).    *)

BEGIN   (* PROCEDURE READ_ANS *)
  ANSWER := [YES,NO,QUIT];

  REPEAT
     WRITELN;
     WRITE(' ENTER (Y/N/Q) : ');
     READ(ANS);
     WRITELN;
     IF NOT(ANS IN ANSWER) THEN BEGIN
        (* AN INAVILD CHARACTER IS READ IN.  *)
        WRITELN;
        WRITELN(' => INVALID CHARACTER ');
     END;   (* IF *)
```

```
  UNTIL (ANS IN ANSWER);

  WRITELN;
END;   (* PROCEDURE READ_ANS *)

PROCEDURE READ_TIMEMAX(VAR TMAX   : REAL;
                           TLIMIT : REAL;
                       VAR ANS    : CHAR );

CONST
  YES  = 'Y';        (* CHARACTER REPRESENTS `YES'.   *)
  QUIT = 'Q';        (* CHARACTER REPRESENTS `NO'.    *)

VAR
  TFILE  : RFILE;         (* FILE STORES `TMAX'.  *)

BEGIN   (* PROCEDURE READ_TIMEMAX *)

  ASSIGN(TFILE,'TMAX.DAT');
  RESET(TFILE);

  READ(TFILE,TMAX);
  CLRSCR;
  WRITELN(' => TIME MAXIMUM IS ', TMAX:6:2, ' SECONDS');
  WRITELN;
  WRITELN(' => DO YOU WANT TO CHANGE THE MAXIMUM TIME ?');
  READ_ANS(ANS);

  IF ANS = QUIT THEN BEGIN
     (* USER WANTS TO QUIT. *)
     WRITELN(' => PROGRAM TERMINATED ');
  END   (* THEN *)
  ELSE BEGIN

     IF (ANS = YES) THEN BEGIN
        (* USER WANTS TO UPDATE THE TIME PERIOD. *)

        REPEAT
           WRITE(' => NEW MAXIMUM TIME ');
           WRITELN('(MINIMUM : 0.00 SECONDS, MAXIMUM : ',
                   ' TLIMIT:6:2, SECONDS)');
           WRITELN;
           WRITE(' ENTER : ');
           READ(TMAX);
           WRITELN;WRITELN;
           IF (TMAX < 0) OR (TMAX > TLIMIT) THEN BEGIN
          (* NEW TIME PERIOD EXCEEDS LIMIT (TOO SMALL OR
                                            TOO LARGE ).*)
              WRITELN(' => TIME EXCEEDS LIMIT');
              WRITELN;
           END;   (* IF *)
        UNTIL (TMAX >= 0) AND (TMAX <= TLIMIT);

        REWRITE(TFILE);
```

```
         WRITE(TFILE,TMAX);
         WRITELN(' => NEW MAXIMUM TIME ACCEPTED');
         WRITELN;
         WRITE(' => HIT RETURN TO CONTINUE : ');
         READ(X);
      END;   (* IF...ANS=YES *)

   END;   (* ELSE...ANS=QUIT *)
   CLOSE(TFILE);
END;   (* PROCEDURE READ_TIMEMAX *)

PROCEDURE SHOW_CONTROL(VAR CFILE : RFILE);

CONST
  NUM1 = 15;        (* NUMBER OF LINES.      *)

VAR
  TIME      : REAL;
  CONTROL   : REAL;
  NUM       : INTEGER;
  CONTROLI  : INTEGER;
  ANS       : CHAR;
  X         : CHAR;

BEGIN   (* PROCEDURE SHOW_CONTROL *)
  RESET(CFILE) ;
  CLRSCR;
  WRITELN(' => TIME(SEC)    COMMAND');
  WRITELN('    =========    =======');
  WRITELN;
  NUM := 0;

  WHILE NOT EOF(CFILE) DO BEGIN
     NUM := NUM + 1;
     READ(CFILE,TIME,CONTROL);
     WRITE(TIME:10:2, ' ':8);

     CONTROLI := ROUND(CONTROL);
     CASE CONTROLI OF
         0 : WRITELN('STOP ALL');
         1 : WRITELN('ROTATE W/ DATA AQU.');
         2 : WRITELN('TILT HEAD FORWARD');
         3 : WRITELN('TILT HEAD BACKWARD');
         4 : WRITELN('PITCH CHAIR  FORWARD');
         5 : WRITELN('PITCH CHAIR BACKWARD');
         6 : WRITELN('RAISE CHAIR');
         7 : WRITELN('LOWER CHAIR');
         8 : WRITELN('ROTATE W/O DATA AQU.');
         9 : WRITELN('STOP TILT');
        10 : WRITELN('STOP PITCH');
        11 : WRITELN('STOP ELEVATION');
        12 : WRITELN('RETURN HOME');
     END;   (* CASE...CONTROLI *)
```

```
        IF (NUM MOD NUM1 = 0) THEN BEGIN
        WRITELN;
        WRITE(' HIT RETURN TO CONTINUE : ');
        READ(X);
        CLRSCR;
        WRITELN(' => TIME(SEC)    CONTROL');
        WRITELN('    =========    =======');
        WRITELN;
     END;   (* IF...NUM MOD NUM1 = 0 *)
  END;   (* WHILE...NOT EOF(CFILE) *)

  WRITELN;
  WRITELN(' => CONTROL DATA SET COMPLETED');
  WRITELN;
  WRITE(' HIT RETURN TO CONTINUE : ');
  READ(X);
END;   (* PROCEDURE SHOW_CONTROL *)


PROCEDURE PRINT_INDEX(TMAX : REAL);

BEGIN   (* PROCEDURE PRINT_INDEX *)
  CLRSCR;
  WRITELN('==========================================');
  WRITELN(' | COMMAND            |  | COMMAND        ');
  WRITELN('------------------------------------------');
  WRITELN('0|STOP ALL            | 7|LOWER CHAIR     ');
  WRITELN('1|ROTATE W/ DATA AQU. | 8|ROTATA W/O DATA ');
  WRITELN('2|TILT HEAD FORWARD   | 9|STOP TILT       ');
  WRITELN('3|TILT HEAD BACKWARD  |10|STOP PITCH      ');
  WRITELN('4|PITCH CHAIR FORWARD |11|STOP ELEVATION  ');
  WRITELN('5|PITCH CHAIR BACKWARD|12|RETURN HOME     ');
  WRITELN('6|RAISE CHAIR         |  |                ');
  WRITELN('==========================================');
  WRITELN;
  WRITE(' => CONTINUE UNTIL TIME REACHES TIME LIMIT : ',
             TMAX:6:2);
  WRITELN(' SECONDS');
  WRITELN;
  WRITELN('         TIME(SEC)   INDEX');
  WRITELN('         =========   =====');
END;   (* PROCEDURE PRINT_INDEX *)


PROCEDURE READ_CONTROL(VAR CFILE  : RFILE;
                          TMAX   : REAL;
                          TINC   : REAL;
                      VAR ANS    : CHAR  );

CONST
  YES   = 'Y';      (* CHARACTER REPRESENTS `YES'. *)
  NO    = 'N';      (* CHARACTER REPRESENTS `NO'.  *)
  QUIT  = 'Q';      (* CHARACTER REPRESENTS `QUIT'.*)
  NUMR0 = 0.0;      (* FIRST INDEX FOR CONTROL DATA*)
```

```
  NUMR1 = 12.0;      (* LAST INDEX FOR CONTROL DATA.*)
  NUM1  = 7;         (* NUMBER OF LINES.            *)

VAR
  CONTROL : REAL;     (* CONTROL DATA.               *)
  TIME    : REAL;     (* TIME IN SECOND.             *)
  PRETIME : REAL;     (* PREVIOUS TIME IN SECOND.    *)
  NUM     : INTEGER;  (* COUNTER (NUMBER OF LINE).   *)
  X       : CHAR;     (* DUMMY CHARACTER.            *)

BEGIN   (* PROCEDURE READ_CONTROL *)

  REPEAT
     REWRITE(CFILE);
     CLRSCR;
     PRINT_INDEX(TMAX);
     NUM := 0;
     PRETIME := -0.01;

     REPEAT
        NUM := NUM + 1;
        WRITE(' ENTER : ');
        READ(TIME);

        IF (TIME < 0) OR (TIME > TMAX) OR ((TIME - PRETIME)
                                           <TINC)
           THEN BEGIN
           WRITELN;
           WRITELN(' => INVALID TIME ');
           NUM := NUM + 1;
           TIME := PRETIME;
        END   (* THEN *)
        ELSE BEGIN
           WRITE('           : ');
           READ(CONTROL);
           WRITELN;

           IF (CONTROL >= NUMR0) AND (CONTROL <= NUMR1)
              AND (ROUND(CONTROL*10) MOD 10=0) THEN BEGIN
              WRITE(CFILE,TIME,CONTROL);
           END   (* THEN *)
           ELSE BEGIN
              WRITELN(' => INVALID INDEX');
              TIME := PRETIME;
              NUM := NUM + 1;
           END;   (* ELSE...CONTROL >= NUMR0... *)

        END;   (* ELSE...TIME < 0... *)

        IF NUM >= NUM1 THEN BEGIN
           NUM := 0;
           PRINT_INDEX(TMAX);
        END;   (* IF...NUM >= NUM1 *)
```

```
            PRETIME := TIME;

         UNTIL TIME = TMAX;

         CLRSCR;
         WRITELN('=>DO YOU WANT TO CHANGE CURRENT CONTROL
                    DATA SET?');
         WRITELN;
         WRITE(' ENTER (Y/N) : ');
         READ(ANS);
      UNTIL ANS = NO;

      WRITELN;WRITELN;
      WRITELN(' => CURRENT CONTROL DATA SET ACCEPTED');
      WRITELN;
      WRITE(' => HIT RETURN TO CONTINUE : ');
      READ(X);

   END;    (* PROCEDURE WRITECONTROL *)


   PROCEDURE CONTROLDATA(VAR ANS    : CHAR;
                             TMAX   : REAL;
                             TINC   : REAL;
                             TLIMIT : REAL;
                         VAR CFILE :  RFILE);

   CONST
     YES  = 'Y';         (* CHARACTER REPRESENTS `YES'. *)
     QUIT = 'Q';         (* CHARACTER REPRESENTS `QUIT'.*)

   BEGIN   (* PROCEDURE CONTROLDATA *)
     ASSIGN(CFILE, 'CONTROL.TDAT');
     CLRSCR;
     WRITELN(' => DO YOU WANT TO SEE THE PREVIOUS CONTROL
                  DATA SET?');
     READ_ANS(ANS);

     IF ANS = 'Q' THEN BEGIN
        WRITELN(' => PROGRAM TERMINATED');
     END   (* THEN *)
     ELSE BEGIN

        IF ANS = YES THEN BEGIN
           SHOW_CONTROL(CFILE);
        END;   (* IF...ANS=YES *)

        CLRSCR;
        WRITELN(' => DO YOU WANT TO CHANGE THE CONTROL
                     DATA SET?');
        READ_ANS(ANS);

        IF ANS = QUIT THEN BEGIN
           WRITELN(' => PROGRAM TERMINATED');
```

```
      END   (* THEN *)
      ELSE BEGIN

         IF ANS = YES THEN BEGIN
            READ_CONTROL(CFILE,TMAX,TINC,ANS);
         END;   (* IF...ANS=YES *)

      END;   (* ELSE...ANS=QUIT *)

   END;   (* ELSE...ANS=QUIT *)
   CLOSE(CFILE);

END;   (* PROCEDURE CONTROLDATA *)


{$I COMPUT1.PAS }


BEGIN   (* MAINLINE *)
   READ_TIMEMAX(TMAX,TLIMIT,ANS);
   IF ANS <> QUIT THEN BEGIN
      CONTROLDATA(ANS,TMAX,TINC,TLIMIT,CFILE);
      IF ANS <> QUIT THEN BEGIN
         COMPUTE_THE_VELOCITY(XVFILE,INVALIDV,TMAX,
                                     VMAX,ANS,CFILE);
      END;   (* IF...2  *)
   END;   (* IF...1 *)
END. (* MAINLINE *)


PROCEDURE COMPUT1(VAR XVFILE: RFILE;
                      INVALIDV: BOOLEAN;
                      TMAX    : REAL;
                      VMAX    : INTEGER;
                  VAR ANS     : CHAR;
                  VAR CFILE   : RFILE);
CONST
   TINC  = 0.01;
   QUIT  = 'Q';
   YES   = 'Y';
   NUMR  = 0.0;
   LIMIT = 300.00;
   ZERO  = 0;
   HUND  = 100;
   NEG   = 512;
   NUM0  = 16384;
   NUM1  = 17408;
   NUM2  = 18432;
   NUM3  = 19456;
   NUM4  = 20480;
   NUM5  = 21504;
   NUM6  = 22528;
   NUM7  = 23552;
   NUM8  = 24576;
```

```
   NUM9  = 25600;
   NUM10 = 26624;
   NUM11 = 27648;
   NUM12 = 28672;
   NUM13 = 31744;

VAR
   TIME        : REAL;
   CONTROL     : REAL;
   PRETIME     : REAL;
   ACCEL1      : REAL;
   ACCEL2      : REAL;
   VELOCITYR   : REAL;
   XVEL        : REAL;
   I           : INTEGER;
   VELOCITY    : INTEGER;
   DATA        : INTEGER;
   PRETIMEI    : INTEGER;
   TIMEI       : INTEGER;
   CONTROLI    : INTEGER;
   VFILE       : IFILE;
   DFILE       : IFILE;
   VFILENAME   : STRING[10];
   M           : REAL;
   F           : REAL;


FUNCTION VEL(M:REAL;
             F: REAL;
            TIME : REAL )


BEGIN   (* FUNCTION VEL *)
   VEL := M*SIN(6.2831*F*TIME);
END;   (* FUNCTION VEL *)


BEGIN   (* PROCEDURE COMPUT1 *)
   CLRSCR;
   WRITELN(' => DID YOU CHANGE THE MAXIMUM TIME OR
                          THE CONTROL DATA SET?');
   READ_ANS(ANS);

   IF ANS = 'Q' THEN BEGIN
      WRITELN(' => PROGRAM TERMINATED');
   END   (* THEN *)
   ELSE BEGIN

      IF ANS = YES THEN BEGIN
         WRITE('Enter name of file to store
                             velocity data in : ');
         READ(VFILENAME);
         WRITELN;
         WRITE('Enter maximum magnitude M of velocity:');
```

```
READ(M);
WRITELN;
WRITE('Enter frequency F of velocity :   ');
READ(F);
WRITELN;
WRITELN(' => PLEASE WAIT...');

ASSIGN(VFILE, 'VELOCITY.DAT');
REWRITE(VFILE);
ASSIGN(CFILE, 'CONTROL.TDAT');
RESET(CFILE);
ASSIGN(DFILE, VFILENAME+'.DAT');
REWRITE(DFILE);
ASSIGN(XVFILE, 'XVEL.DAT');
REWRITE(XVFILE);

TIME := 0.0;

VELOCITYR := 0.0;
VELOCITY := ROUND(VELOCITYR);
WRITE(VFILE,VELOCITY);

WHILE TIME < TMAX DO BEGIN
   TIME := TIME + TINC;

   VELOCITYR := VEL(M,F,TIME);
   VELOCITY := ROUND(VELOCITYR);

   IF ABS(VELOCITY) > VMAX THEN BEGIN
      WRITE(XVFILE,TIME,VELOCITYR);
      INVALIDV := FALSE;
   END;   (* IF *)

   WRITE(VFILE,VELOCITY);

END;   (* WHILE *)

CLOSE(VFILE);
CLOSE(XVFILE);
RESET(VFILE);

VELOCITY := NUM13;
WRITE(DFILE,VELOCITY);
PRETIME := NUMR;
 WHILE NOT EOF(CFILE) DO BEGIN
   READ(CFILE,TIME,CONTROL);

   PRETIMEI:=ROUND((PRETIME+0.01) * HUND);
   TIMEI := ROUND(TIME * HUND);

   FOR  I:=PRETIMEI TO (TIMEI - 1) DO BEGIN
      READ(VFILE,VELOCITY);

      IF VELOCITY < ZERO THEN BEGIN
```

```
                VELOCITY := -VELOCITY + NEG;
             END;   (* IF *)

             VELOCITY:= VELOCITY+NUM13;
             WRITE(DFILE,VELOCITY);
          END;   (* FOR *)

          READ(VFILE,VELOCITY);

          IF VELOCITY <ZERO THEN BEGIN
             VELOCITY :=-VELOCITY+ NEG;
          END;  (* IF *)

          CONTROLI := ROUND(CONTROL);

          CASE CONTROLI OF
             0 : VELOCITY := VELOCITY + NUM0;
             1 : VELOCITY := VELOCITY + NUM1;
             2 : VELOCITY := VELOCITY + NUM2;
             3 : VELOCITY := VELOCITY + NUM3;
             4 : VELOCITY := VELOCITY + NUM4;
             5 : VELOCITY := VELOCITY + NUM5;
             6 : VELOCITY := VELOCITY + NUM6;
             7 : VELOCITY := VELOCITY + NUM7;
             8 : VELOCITY := VELOCITY + NUM8;
             9 : VELOCITY := VELOCITY + NUM9;
            10 : VELOCITY := VELOCITY + NUM10;
            11 : VELOCITY := VELOCITY + NUM11;
            12 : VELOCITY := VELOCITY + NUM12;
          END;   (* CASE *)

          WRITE(DFILE,VELOCITY);
          PRETIME :=TIME;

       END;   (* WHILE *)

       VELOCITY := ZERO;
       WRITE(DFILE,VELOCITY);

       CLOSE(CFILE);
       CLOSE(VFILE);
       CLOSE(DFILE);

    END;   (* IF *)

    WRITELN;
    WRITELN(' => PROGRAM COMPLETED');
    WRITELN;

 END;   (* ELSE *)

END;   (* PROCEDURE COMPUTE1 *)
```

B.3 PROGRAM NEWTRY2

```
****************************************************
* Program for generating trianglar and trapezoidal *
* velocity profiles.                               *
****************************************************


CONST
  QUIT   = 'Q';
  AMAX   = 300;
  VMAX   = 300;
  TINC   = 0.01;
  TLIMIT = 600.0;
  T      = 4.0;
  K1     = 125.0;
  K2     = 200.0;
  S1     = 0.2;
  S2     = 0.4;

TYPE
  IFILE  = FILE OF INTEGER;
  RFILE  = FILE OF REAL;
  ANSSET = SET OF CHAR;

VAR
  TMAX : REAL;
  ANS  : CHAR;
  X    : CHAR;
  XAFILE : RFILE;
  XVFILE : RFILE;
  INVALIDA : BOOLEAN;
  INVALIDV : BOOLEAN;
  CFILE : RFILE;


PROCEDURE  ACCELTRI ( T:REAL;
                        K1:REAL;
                        K2:REAL;
                    VAR ACCEL2:REAL;
                    VAR TIME:REAL);
VAR TIME2:REAL;

BEGIN (* PROCEDURE ACCELTRI *)
     TIME2:=TIME;
     WHILE TIME>T DO
       TIME:=TIME-T;

    IF (TIME<=0.5*T)  THEN
      ACCEL2:=K1
    ELSE
      ACCEL2:=-K1;
    TIME:=TIME2;
```

```
END; (* PROCEDURE *)


PROCEDURE ACCELTRAP (VAR ACCEL2:REAL;
                     VAR TIME:REAL;
                         T:REAL;
                         S1:REAL;
                         S2:REAL;
                         K1:REAL;
                         K2:REAL);

VAR T1:REAL;
   T2:REAL;
   TIME2:REAL;

BEGIN  (* PROCEDURE ACCELTRAP *)
     T1:=S1*T;
     T2:=S2*T;
     TIME2:=TIME;
     WHILE TIME>T DO
     TIME:=TIME-T;
     IF  (TIME<=T1) THEN
        ACCEL2:=K1
     ELSE BEGIN
        IF (TIME<T)  AND (TIME>=T2) THEN
        ACCEL2:=-K2
              ELSE
                ACCEL2:=0.0;
     END;
     TIME:=TIME2;
END;  (* PROCEDURE ACCELTRAP *)


PROCEDURE READ_ANS(VAR ANS : CHAR);

CONST
  YES   = 'Y';
  NO    = 'N';
  QUIT = 'Q';

VAR
  ANSWER : ANSSET; (* ANSWER SET (YES/NO/QUIT).    *)

BEGIN   (* PROCEDURE READ_ANS *)
  ANSWER := [YES,NO,QUIT];

  REPEAT
     WRITELN;
     WRITE(' ENTER (Y/N/Q) : ');
     READ(ANS);
     WRITELN;
     IF NOT(ANS IN ANSWER) THEN BEGIN
        (* AN INAVILD CHARACTER IS READ IN.  *)
        WRITELN;
```

```
        WRITELN(' => INVALID CHARACTER ');
     END;   (* IF *)
  UNTIL (ANS IN ANSWER);

  WRITELN;
END;   (* PROCEDURE READ_ANS *)


PROCEDURE READ_TIMEMAX(VAR TMAX   : REAL;
                           TLIMIT : REAL;
                       VAR ANS    : CHAR );

CONST
  YES  = 'Y';
  QUIT = 'Q';

VAR
  TFILE  : RFILE;

BEGIN   (* PROCEDURE READ_TIMEMAX *)

  ASSIGN(TFILE,'TMAX.DAT');
  RESET(TFILE);

  READ(TFILE,TMAX);
  CLRSCR;
  WRITELN('=>TIME MAXIMUM IS',TMAX:6:2,'SECONDS');
  WRITELN;
  WRITELN('=>DO YOU WANT TO CHANGE THE MAXIMUM TIME?');
  READ_ANS(ANS);

  IF ANS = QUIT THEN BEGIN
     (* USER WANTS TO QUIT. *)
     WRITELN(' => PROGRAM TERMINATED ');
  END   (* THEN *)
  ELSE BEGIN

     IF (ANS = YES) THEN BEGIN
        (* USER WANTS TO UPDATE THE TIME PERIOD. *)

        REPEAT
           WRITE(' => NEW MAXIMUM TIME ');
           WRITELN('(MINIMUM : 0.00 SECONDS, MAXIMUM :',
                                  TLIMIT:6:2,'SECONDS)');
           WRITELN;
           WRITE(' ENTER : ');
           READ(TMAX);
           WRITELN;WRITELN;
           IF (TMAX < 0) OR (TMAX > TLIMIT) THEN BEGIN
              WRITELN(' => TIME EXCEEDS LIMIT');
              WRITELN;
           END;   (* IF *)
        UNTIL (TMAX >= 0) AND (TMAX <= TLIMIT);
```

```
         REWRITE(TFILE);
         WRITE(TFILE,TMAX);
         WRITELN(' => NEW MAXIMUM TIME ACCEPTED');
         WRITELN;
         WRITE(' => HIT RETURN TO CONTINUE : ');
         READ(X);
      END;   (* IF...ANS=YES *)

   END;   (* ELSE...ANS=QUIT *)
   CLOSE(TFILE);
END;   (* PROCEDURE READ_TIMEMAX *)


PROCEDURE SHOW_CONTROL(VAR CFILE : RFILE);

CONST
  NUM1 = 15;        (* NUMBER OF LINES.      *)

VAR
  TIME      : REAL;
  CONTROL   : REAL;
  NUM       : INTEGER;
  CONTROLI  : INTEGER;
  ANS       : CHAR;
  X         : CHAR;

BEGIN   (* PROCEDURE SHOW_CONTROL *)
  RESET(CFILE) ;
  CLRSCR;
  WRITELN(' => TIME(SEC)    COMMAND');
  WRITELN('    =========    =======');
  WRITELN;
  NUM := 0;

  WHILE NOT EOF(CFILE) DO BEGIN
     NUM := NUM + 1;
     READ(CFILE,TIME,CONTROL);
     WRITE(TIME:10:2, ' ':8);

     CONTROLI := ROUND(CONTROL);
     CASE CONTROLI OF
         0 : WRITELN('STOP ALL');
         1 : WRITELN('ROTATE W/ DATA AQU.');
         2 : WRITELN('TILT HEAD FORWARD');
         3 : WRITELN('TILT HEAD BACKWARD');
         4 : WRITELN('PITCH CHAIR  FORWARD');
         5 : WRITELN('PITCH CHAIR BACKWARD');
         6 : WRITELN('RAISE CHAIR');
         7 : WRITELN('LOWER CHAIR');
         8 : WRITELN('ROTATE W/O DATA AQU.');
         9 : WRITELN('STOP TILT');
        10 : WRITELN('STOP PITCH');
        11 : WRITELN('STOP ELEVATION');
        12 : WRITELN('RETURN HOME');
```

```
     END;    (* CASE...CONTROLI *)

        IF (NUM MOD NUM1 = 0) THEN BEGIN
        WRITELN;
        WRITE(' HIT RETURN TO CONTINUE : ');
        READ(X);
        CLRSCR;
        WRITELN(' => TIME(SEC)    CONTROL');
        WRITELN('    =========    =======');
        WRITELN;
     END;    (* IF...NUM MOD NUM1 = 0 *)
  END;    (* WHILE...NOT EOF(CFILE) *)

  WRITELN;
  WRITELN(' => CONTROL DATA SET COMPLETED');
  WRITELN;
  WRITE(' HIT RETURN TO CONTINUE : ');
  READ(X);
END;    (* PROCEDURE SHOW_CONTROL *)


PROCEDURE READ_CONTROL(VAR CFILE   : RFILE;
                           TMAX    : REAL;
                           TINC    : REAL;
                       VAR ANS     : CHAR  );

CONST
  YES    = 'Y';
  NO     = 'N';
  QUIT   = 'Q';
  NUMR0  = 0.0;
  NUMR1  = 12.0;
  NUM1   = 7;

VAR
  CONTROL : REAL;
  TIME    : REAL;
  PRETIME : REAL;
  NUM     : INTEGER;
  X       : CHAR;

BEGIN   (* PROCEDURE READ_CONTROL *)

  REPEAT

     REWRITE(CFILE);
     CLRSCR;
     PRINT_INDEX(TMAX);
     NUM := 0;
     PRETIME := -0.01;

     REPEAT
        NUM := NUM + 1;
        WRITE(' ENTER : ');
```

```
        READ(TIME);

        IF(TIME < 0) OR (TIME > TMAX) OR ((TIME-PRETIME)
                                          < TINC)
           THEN BEGIN
           WRITELN;
           WRITELN(' => INVALID TIME ');
           NUM := NUM + 1;
           TIME := PRETIME;
        END   (* THEN *)
        ELSE BEGIN
           WRITE('          : ');
           READ(CONTROL);
           WRITELN;

           IF (CONTROL >= NUMR0) AND (CONTROL <= NUMR1)
              AND (ROUND(CONTROL * 10) MOD 10 = 0)
                                        THEN BEGIN
              WRITE(CFILE,TIME,CONTROL);
           END   (* THEN *)
           ELSE BEGIN
              WRITELN(' => INVALID INDEX');
              TIME := PRETIME;
              NUM := NUM + 1;
           END;   (* ELSE...CONTROL >= NUMR0... *)

        END;   (* ELSE...TIME < 0... *)

        IF NUM >= NUM1 THEN BEGIN
           NUM := 0;
           PRINT_INDEX(TMAX);
        END;   (* IF...NUM >= NUM1 *)

        PRETIME := TIME;

     UNTIL TIME = TMAX;

     CLRSCR;
     WRITELN(' => DO YOU WANT TO CHANGE THE CURRENT
                                    CONTRAL DATA SET?');
     WRITELN;
     WRITE(' ENTER (Y/N) : ');
     READ(ANS);
  UNTIL ANS = NO;

  WRITELN;WRITELN;
  WRITELN(' => CURRENT CONTROL DATA SET ACCEPTED');
  WRITELN;
  WRITE(' => HIT RETURN TO CONTINUE : ');
  READ(X);

END;   (* PROCEDURE WRITECONTROL *)
```

```
PROCEDURE CONTROLDATA(VAR ANS    : CHAR;
                          TMAX   : REAL;
                          TINC   : REAL;
                          TLIMIT : REAL;
                      VAR CFILE :  RFILE);
CONST
  YES  = 'Y';
  QUIT = 'Q';


BEGIN   (* PROCEDURE CONTROLDATA *)
  ASSIGN(CFILE, 'CONTROL.TDAT');
  CLRSCR;
  WRITELN(' => DO YOU WANT TO SEE THE PREVIOUS
                               CONTROL DATA SET?');
  READ_ANS(ANS);

  IF ANS = 'Q' THEN BEGIN
     WRITELN(' => PROGRAM TERMINATED');
  END   (* THEN *)
  ELSE BEGIN

     IF ANS = YES THEN BEGIN
        SHOW_CONTROL(CFILE);
     END;   (* IF...ANS=YES *)

     CLRSCR;
     WRITELN(' => DO YOU WANT TO CHANGE THE
                    CONTROL DATA SET?');
     READ_ANS(ANS);

     IF ANS=QUIT  THEN BEGIN
        WRITELN(' => PROGRAM TERMINATED');
     END   (* THEN *)
     ELSE BEGIN

        IF ANS = YES THEN BEGIN
           READ_CONTROL(CFILE,TMAX,TINC,ANS);
        END;   (* IF...ANS=YES *)

     END;   (* ELSE...ANS=QUIT *)

  END;   (* ELSE...ANS=QUIT *)
  CLOSE(CFILE);

END;   (* PROCEDURE CONTROLDATA *)


{$I COMPUT2.PAS }


BEGIN   (* MAINLINE *)
  READ_TIMEMAX(TMAX,TLIMIT,ANS);
  IF ANS <> QUIT THEN BEGIN
```

```
  CONTROLDATA(ANS,TMAX,TINC,TLIMIT,CFILE);
     IF ANS <> QUIT THEN BEGIN
        COMPUTE2(XAFILE,XVFILE,INVALIDA,INVALIDV,
                          X,VMAX,AMAX,ANS,CFILE);
     END;   (* IF...2  *)
  END;   (* IF...1 *)
END. (* MAINLINE *)


PROCEDURE COMPUT2(VAR XAFILE : RFILE;
                 VAR    XVFILE : RFILE;
                       INVALIDA: BOOLEAN;
                       INVALIDV: BOOLEAN;
                       TMAX    : REAL;
                       VMAX    : INTEGER;
                       AMAX    : INTEGER;
                   VAR ANS     : CHAR;
                   VAR CFILE   : RFILE);
CONST
  TINC  = 0.01;
  QUIT  = 'Q';
  YES   = 'Y';
  NUMR  = 0.0;
  LIMIT = 300.00;
  ZERO  = 0;
  HUND  = 100;
  NEG   = 512;
  NUM0  = 16384;
  NUM1  = 17408;
  NUM2  = 18432;
  NUM3  = 19456;
  NUM4  = 20480;
  NUM5  = 21504;
  NUM6  = 22528;
  NUM7  = 23552;
  NUM8  = 24576;
  NUM9  = 25600;
  NUM10 = 26624;
  NUM11 = 27648;
  NUM12 = 28672;
  NUM13 = 31744;

VAR
   TIME       : REAL;
   CONTROL    : REAL;
   PRETIME    : REAL;
   ACCEL1     : REAL;
   ACCEL2     : REAL;
   VELOCITYR  : REAL;
   XACCEL     : REAL;
   XVEL       : REAL;
   I          : INTEGER;
   AINTEGER   : INTEGER;
   VELOCITY   : INTEGER;
```

```
  DATA       : INTEGER;
  PRETIMEI   : INTEGER;
  TIMEI      : INTEGER;
  CONTROLI   : INTEGER;
  AFILE      : IFILE;
  VFILE      : IFILE;
  DFILE      : IFILE;
  VFILENAME  : STRING[10];


FUNCTION ACCEL(TIME : REAL) : REAL;

BEGIN   (* FUNCTION ACCEL *)
  ACCEL := 185*COS(6.2831*TIME);
END;   (* FUNCTION ACCEL *)



FUNCTION VEL(ACCEL1 : REAL;
            ACCEL2 : REAL;
            TINC   : REAL ) : REAL;

CONST
  HALF = 0.5;

BEGIN   (* FUNCTION VEL *)
  VEL := ((ACCEL1 - ACCEL2) * HALF + ACCEL1) * TINC;
END;   (* FUNCTION VEL *)



BEGIN   (* PROCEDURE COMPUTE2 *)
  CLRSCR;
  WRITELN('=>DID YOU CHANGE THE MAXIMUM TIME OR THE
                              CONTROL DATA SET?');
 READ_ANS(ANS);

  IF ANS = 'Q' THEN BEGIN
     WRITELN(' => PROGRAM TERMINATED');
  END   (* THEN *)
  ELSE BEGIN

     IF ANS = YES THEN BEGIN
        WRITE('Enter name of file to store velocity data
                                             data in:');
        READ(VFILENAME);
        WRITELN;
        WRITELN(' => PLEASE WAIT...');

        ASSIGN(AFILE, 'AINTEGER.DAT');
        REWRITE(AFILE);
        ASSIGN(VFILE, 'VELOCITY.DAT');
        REWRITE(VFILE);
        ASSIGN(CFILE, 'CONTROL.TDAT');
```

```
RESET(CFILE);
ASSIGN(DFILE, VFILENAME+'.DAT');
REWRITE(DFILE);
ASSIGN(XAFILE, 'XACCEL.DAT');
REWRITE(XAFILE);
ASSIGN(XVFILE, 'XVEL.DAT');
REWRITE(XVFILE);

TIME := 0.0;
INVALIDA := FALSE;
INVALIDV := FALSE;

ACCEL1 := K1;
AINTEGER := ROUND(ACCEL1);

IF ABS(AINTEGER) > AMAX THEN BEGIN
   WRITE(XAFILE,TIME,ACCEL1);
   INVALIDA := TRUE;
END;   (* IF *)

WRITE(AFILE,AINTEGER);
VELOCITYR := 0.0;
VELOCITY := ROUND(VELOCITYR);
WRITE(VFILE,VELOCITY);

WHILE TIME < TMAX DO BEGIN
   TIME := TIME + TINC;
   ACCELTRI(T,K1,K2,ACCEL2,TIME);
   AINTEGER := ROUND(ACCEL2);

   IF ABS(AINTEGER) > AMAX THEN BEGIN
      WRITE(XAFILE,TIME,ACCEL2);
      INVALIDA := TRUE;
   END;   (* IF *)

   WRITE(AFILE,AINTEGER);

   VELOCITYR := VELOCITYR+VEL(ACCEL1,ACCEL2,TINC);
   VELOCITY := ROUND(VELOCITYR);

   IF ABS(VELOCITY) > VMAX THEN BEGIN
      WRITE(XVFILE,TIME,VELOCITYR);
      INVALIDV := TRUE;
   END;   (* IF *)

   WRITE(VFILE,VELOCITY);

   ACCEL1 := ACCEL2;
END;   (* WHILE *)

CLOSE(AFILE);
CLOSE(VFILE);
CLOSE(XAFILE);
CLOSE(XVFILE);
```

```
RESET(VFILE);


VELOCITY := NUM13;
WRITE(DFILE,VELOCITY);
PRETIME := NUMR;
WHILE NOT EOF(CFILE) DO BEGIN
   READ(CFILE,TIME,CONTROL);

   PRETIMEI:=ROUND((PRETIME+ 0.01) * HUND);
   TIMEI := ROUND(TIME * HUND);

   FOR I := PRETIMEI  TO (TIMEI-1)  DO BEGIN
      READ(VFILE,VELOCITY);

      IF VELOCITY < ZERO THEN BEGIN
         VELOCITY := -VELOCITY + NEG;
      END;   (* IF *)

      VELOCITY:=VELOCITY+NUM13;
      WRITE(DFILE,VELOCITY);
   END;   (*  FOR  *)

   READ(VFILE,VELOCITY);

   IF VELOCITY<ZERO THEN BEGIN
      VELOCITY:=-VELOCITY+ NEG;
   END;  (* IF *)

   CONTROLI := ROUND(CONTROL);

   CASE CONTROLI OF
       0 : VELOCITY := VELOCITY + NUM0;
       1 : VELOCITY := VELOCITY + NUM1;
       2 : VELOCITY := VELOCITY + NUM2;
       3 : VELOCITY := VELOCITY + NUM3;
       4 : VELOCITY := VELOCITY + NUM4;
       5 : VELOCITY := VELOCITY + NUM5;
       6 : VELOCITY := VELOCITY + NUM6;
       7 : VELOCITY := VELOCITY + NUM7;
       8 : VELOCITY := VELOCITY + NUM8;
       9 : VELOCITY := VELOCITY + NUM9;
      10 : VELOCITY := VELOCITY + NUM10;
      11 : VELOCITY := VELOCITY + NUM11;
      12 : VELOCITY := VELOCITY + NUM12;
   END;   (* CASE *)

   WRITE(DFILE,VELOCITY);
   PRETIME :=TIME;
END;   (* WHILE *)

VELOCITY := ZERO;
WRITE(DFILE,VELOCITY);
```

```
            CLOSE(CFILE);
            CLOSE(VFILE);
            CLOSE(DFILE);

         END;   (* IF *)

         WRITELN;
         WRITELN(' => PROGRAM COMPLETED');
         WRITELN;

      END;   (* ELSE *)

    END;   (* PROCEDURE COMPUTE2 *)
```

B.4 PROGRAM CONCATEN

```
VAR
  VELOCITY:  INTEGER;
  DFILE   :  FILE OF INTEGER;
  EFILE   :  FILE OF INTEGER;
  FFILE   :  FILE OF INTEGER;

BEGIN
   ASSIGN (DFILE,'VEL.DAT');
   ASSIGN (EFILE,'NEWVEL.DAT');
   ASSIGN (FFILE,'VEL16.DAT');

   RESET (DFILE);
   RESET (EFILE);
   REWRITE (FFILE);
   CLRSCR;

   WHILE NOT EOF(DFILE) DO BEGIN
    READ (DFILE,VELOCITY);
    WRITE (FFILE,VELOCITY);
   END;

   WHILE NOT EOF(EFILE) DO BEGIN
    READ (EFILE,VELOCITY);
    WRITE (FFILE,VELOCITY);
   END;

   CLOSE (DFILE);
   CLOSE (EFILE);
   CLOSE (FFILE);

END.
```

B.5 PROGRAM INIFILE

```
CONST
   TMAX=001.00;
VAR
   CONTROL:REAL;
   TIME:   REAL;
   CFILE:  FILE OF REAL;
BEGIN
   ASSIGN(CFILE,'CONTROL.TDAT');
   REWRITE(CFILE);

   CLRSCR;
   WRITELN('       TIME(SEC)     INDEX');
   WRITELN('       =========     =====');
   REPEAT
     WRITE('ENTER');
     READ(TIME);
     WRITE('            :        ');
     READ(CONTROL);
     WRITELN;
     WRITE(CFILE,TIME,CONTROL);
   UNTIL TIME=TMAX;

   CLOSE(CFILE);
   RESET(CFILE);
   CLRSCR;
   WRITELN('        TIME           CONTROL');
   WRITELN('        ====           =======');
   WRITELN;

   WHILE NOT EOF(CFILE) DO BEGIN
     READ(CFILE,TIME,CONTROL);
     WRITELN('TIME=',TIME:6:2,'CONTROL=',CONTROL:6);
   END;

   CLOSE(CFILE);
END.
```

B.6 PROGRAM SEEVEL

```
CONST
   NUM1 = 150;

VAR
  NUM: INTEGER;
  VELOCITY : INTEGER;
  I        : INTEGER;
  DFILE    : FILE OF INTEGER;
  X        : CHAR;

BEGIN
  NUM:=0;
  ASSIGN(DFILE,'NEWVEL.DAT');
  RESET(DFILE);
  CLRSCR;

  WHILE NOT EOF(DFILE) DO BEGIN
    NUM:=NUM+1;
    READ(DFILE,VELOCITY);
    WRITE('    ',VELOCITY:6);
    IF (NUM MOD NUM1=0) THEN BEGIN
    WRITELN;
    WRITE(' HIT RETURN TO CONTINUE:');
    READ(X);
    CLRSCR;
    END;(* IF...NUM MOD NUM1=0 *)
  END; (* WHILE *)

  CLOSE(DFILE);

END. (* seevel *)
```

B.7 PROGRAM HANDLE

```
//XIAO JOB ',,T=10,I=40,L=10','XIAO'
// EXEC FORTXCLG,USERLIB='SYS4.DRIVER.DYLOAD'
//FORT.SYSIN DD *
        INTEGER DATA(40,768),A,B,I,J,K
        INTEGER SAMPLE(2000),OS(2000)
        REAL    T1,T,F,M
        DO 1 I=1,27
        READ(11,100) (DATA(I,J),J=1,768)
100     FORMAT(16I4)
1       CONTINUE
C
        K=0
        K1=768
        DO 2 I=1,27
        DO 3 J=1,768
        JJ=J-1
        A=JJ/30
        B=30*A
        IF (B.NE.JJ) GO TO 3
        K=K+1
        SAMPLE(K)=DATA(I,J)
        SAMPLE(K)=+(SAMPLE(K)-2030)*2+2048
3       CONTINUE
2       CONTINUE
        KK=K+1
        IF (K.GT.768.AND.K.LT.1536) K1=1536
        IF (K.GT.1536) K1=2304
        IF (K.EQ.768) GO TO 5
        DO 4 I=KK,K1
4       SAMPLE(I)=2048
5       WRITE(20,100) (SAMPLE(K),K=1,K1)
        WRITE(6,100) (SAMPLE(K),K=1,K1)
        M=100.000
        F=0.05
        T1=0.0585938
        DO 6 I=1,689
        T=I*T1
6       OS(I)=INT(8*M*SIN(6.28*T*F))+2048
        II=I+1
        DO 7 I=I,K1
7       OS(I)=2048
        WRITE(20,100) (OS(K),K=1,K1)
        WRITE(6,100) (OS(K),K=1,K1)
        STOP
        END
/*
//GO.FT20F001 DD DSN=XIAO.DATA10,DISP=OLD
//GO.FT11F001 DD DSN=XIAO.DAT2,DISP=SHR
/*
```

B.8 PROGRAM VXER1

```
//XIAO JOB ',,,T=10,I=40,L=10',XIAO
// EXEC FORTXCLG,USERLIB='SYS4.DRIVER.DYLOAD'
//FORT.SYSIN DD *
C
      INTEGER DATA(40,770),DD(40,770)
      INTEGER NUMSEG,REM,NUNIT,DUNIT,FUNIT,ROW,COL
      INTEGER I,J,K
C
      REAL XL,XR,YB,YT,YA
      REAL SF,XINC,YINC,XCELL,YCELL,GROUP
      DIMENSION IBUF(6000),SAMPLE(770),TIME(770),OS(770)
C
      SF=2.54
      F=0.05
      M=200
C
      XINC=1.5
      YINC=2.048
C
      XL=0.0
      XR=7.68
      YB=0.0
      YT=4096.0/2000.0
      YA=2048.0/2000.0
C
      FUNIT=9
      NUNIT=10
C
      READ(FUNIT,101) K
C
      DUNIT=K+10
      GROUP=K
C
      DO 8 I=1,K
      READ(NUNIT,101) REM
101   FORMAT(I3)
      WRITE(6,101) REM
8     CONTINUE
C
301   NUMSEG=REM
      REM=0
      IF(NUMSEG.LE.40)GOTO 300
      REM=NUMSEG-40
      NUMSEG=40
C
300   DO 1 I=1,NUMSEG
      READ(DUNIT,102) (DATA(I,J),J=1,768)
      WRITE(6,101) NUMSEG
102   FORMAT(16I4)
1     CONTINUE
```

```
C
      DO 11 I=1,NUMSEG
      READ(DUNIT,102) (DD(I,J),J=1,768)
11    CONTINUE
C
      DO 2 I=1,768
      TIME(I)=I
2     CONTINUE
C
      CALL PINIT(IBUF,TIME,GROUP,ROW,COL,XCELL,YCELL,F,M)
C
C
      DO 3 I=1,NUMSEG
C
      DO 4 J=1,768
      SAMPLE(J)=DATA(I,J)
4     CONTINUE
C
      DO 44 J=1,768
      OS(J)=DD(I,J)
44    CONTINUE
C
      CALL PLOT(XCELL,YCELL,-3)
C
      CALL PLOT(XL,YT,2)
      CALL PLOT(XR,YT,2)
      CALL PLOT(XR,YB,2)
      CALL PLOT(XL,YB,2)
C
      CALL PLOT(XL,YA,3)
      CALL PLOT(XR,YA,2)
      CALL PLOT(XL,YB,3)
C
      SAMPLE(769)=0.0
      SAMPLE(770)=2000.0
C
      OS(769)=0.0
      OS(770)=2000
C
      CALL LINE(TIME,SAMPLE,768,1,0,0)
      CALL LINE(TIME,OS,768,1,0,0)
C
      CALL PLOT(0.0,0.0,3)
      CALL PLOT(-XCELL,-YCELL,-3)
C
      ROW=ROW+1
      YCELL=YCELL+YINC
C
201   IF(ROW.GT.5)GOTO 202
5     CONTINUE
3     CONTINUE
      IF(REM.NE.0)GOTO 301
C
      CALL PLOT(0.0,0.0,9999)
```

```
      STOP
C
202   CALL PLOT(0.0,0.0,999)
      CALL PINIT(IBUF,TIME,GROUP,ROW,COL,XCELL,YCELL)
      GOTO 5
C
      END
C
      SUBROUTINE PINIT(IBUF,TIME,GROUP,ROW,COL,XCELL,
                                          YCELL,F,M)
C
      DIMENSION IBUF(6000),TIME(770)
      INTEGER ROW,COL
      REAL XCELL,YCELL,SF,GROUP
C
      CALL AREA(8.25,10.75)
      CALL PLOTS(IBUF,6000)
      CALL PLOT(0.0,0.0,-3)
      CALL SYMBOL(0.45,0.45,0.14,'F=0.05 M=100 HR4',0,17)
      CALL PLOT(0.0,0.0,3)
      TIME(769)=0.0
      TIME(770)=100.0
C
      SF=2.54
      ROW=1
      COL=1
      XCELL=1/SF
      YCELL=1/SF
C
      RETURN
      END
/*
//GO.FT09F001 DD DSN=XIAO.SPEC.DATA,DISP=SHR
//GO.FT10F001 DD DSN=XIAO.PAGES,DISP=SHR
//GO.FT11F001 DD DSN=XIAO.N1,DISP=SHR
//GO.FT12F001 DD DSN=XIAO.N2,DISP=SHR
//GO.FT13F001 DD DSN=XIAO.N3,DISP=SHR
//GO.FT14F001 DD DSN=XIAO.N4,DISP=SHR
//GO.FT15F001 DD DSN=XIAO.N5,DISP=SHR
//GO.FT16F001 DD DSN=XIAO.N6,DISP=SHR
//GO.FT17F001 DD DSN=XIAO.N7,DISP=SHR
//GO.FT18F001 DD DSN=XIAO.N8,DISP=SHR
//GO.FT19F001 DD DSN=XIAO.N9,DISP=SHR
//GO.FT20F001 DD DSN=XIAO.DATA10,DISP=SHR
//GO.FT22F001 DD SYSOUT=A
//GO.FT23F001 DD DSN=SYS4.EPIC.PARMS,DISP=SHR
//GO.FT24F001 DD DSN=&&FT01F001,SPACE=(6144,300),
// DCB=(BLKSIZE=6144,DSORG=DA,OPTCD=C,RECFM=F),
// DISP=(,PASS),UNIT=SYSDA
//GO.PLOTLIB  DD DSN=SYS4.DRIVER.XEROX,DISP=SHR
// EXEC XPLOT
/*
```

B.9 PROGRAM ANALY

```
//XIAO JOB ',,T=10,I=20,L=10','XIAO'
// EXEC WATFIV,SIZE=1024K
//SYSIN DD *
$JOB WATFIV,TIME=1,NOEXT
C     TEMPERATURE CONVERSION PROGRAM
        INTEGER DATA(40,768),A,B,I,J,K,CAL,TT,
               SC1,N2,MM,SAMPL(2000)
        REAL SAMPLE(2000),DD(418)
        DIMENSION  SAMP(2000)
        REAL    G,AG,APSV,APFV,SC2,SC3,SC4,SC5
        DO 1 I=1,27
        READ(11,100) (DATA(I,J),J=1,768)
100     FORMAT(16I4)
1       CONTINUE
C
        CAL=500
        K=0
        DO 2 I=1,27
        DO 3 J=1,768
        JJ=J-1
        A=JJ/12
        B=12*A
        IF(B.NE.JJ) GO TO 3
        K=K+1
        SAMPL(K)=DATA(I,J)
        SAMPLE(K)=(SAMPL(K)-2032)*60/CAL*0.9
3       CONTINUE
2       CONTINUE
        SC2=0.0
        SC3=0.0
        SC4=0.0
        SC5=0.0
        SC1=0
        KK=K-1
        SAMP(1)=SAMPLE(1)
        DO 4 I=2,KK
4       SAMP(I)=0.25*SAMPLE(I-1)+0.5*SAMPLE(I)
                         +0.25*SAMPLE(I+1)
        SAMP(K)=0.5*SAMPLE(K-1)+0.5*SAMPLE(K)
C
        DO 11 I=1,417
        II=I+1
11      DD(II)=SAMP(I)
        DD(1)=0.0
        CALL XYZ(DD,SC1,SC2,SC3,SC4,SC5)
        DO 12 I=417,834
        II=I-416
12      DD(II)=-SAMP(I)
        CALL XYZ(DD,SC1,SC2,SC3,SC4,SC5)
        DO 13 I=834,1251
```

```
        II=I-833
13      DD(II)=SAMP(I)
        CALL XYZ(DD,SC1,SC2,SC3,SC4,SC5)
        DO 14 I=1251,1668
        II=I-1250
14      DD(II)=-SAMP(I)
        CALL XYZ(DD,SC1,SC2,SC3,SC4,SC5)
        MM=4
        SC1=SC1/MM
        SC2=SC2/MM
        SC3=SC3/MM
        SC4=SC4/MM
        SC5=SC5/MM
        WRITE(6,24) SC1
24      FORMAT(I4)
        WRITE(6,99) SC2,SC3,SC4,SC5
99      FORMAT(4E14.4)
        STOP
        END
C
C
        SUBROUTINE XYZ(DD,SC1,SC2,SC3,SC4,SC5)
        INTEGER TT,N1,N2,SC1,N11,N22
        REAL  DD(418),EYVEL(418),VELSUM
        REAL  TEMP(100),MAVS,PP,APSVSU
        REAL  SAVEL(400),FAVEL(400),APFVSU,APSV,APFV,AG,G
        REAL  SC2,SC3,SC4,SC5,T1,F,COM
        N1=1
        N2=1
        NN=4
        MAVS=0.0
        TT=8
        PP=50.000
        F=0.05
        NUM=0
        DO 5  I=2,418
5       EYVEL(I)=(DD(I)-DD(I-1))*41.6
C33      FORMAT(1X,3E10.4)
C        DO 70 I=2,418
C70      WRITE(6,33) DD(I),EYVEL(I)
        DO 70 I=2,418
        T1=(I-1)*0.024
        COM=-1.5*PP*SIN(2*3.141592*T1*F)
        IF(EYVEL(I).LE.COM) EYVEL(I)=COM
70      CONTINUE
        DO 6 I=2,418
        IF(DD(I)-DD(I-1)) 20,30,10
10      IF(I.GE.TT) GO TO 11
        FLAG=1
        GO TO 30
11      IF(FLAG.EQ.1.OR.DD(I).LT.DD(I-1)) GO TO 30
        FLAG=1
        VELSUM=0
        IF(NUM.LE.NN) GO TO 41
```

```
        DO 40 J=1,NUM
        TEMP(J)=-TEMP(J)
        VELSUM=VELSUM+TEMP(J)
        IF(MAVS.LT.TEMP(J)) MAVS=TEMP(J)
40      CONTINUE
        SAVEL(N1)=VELSUM/NUM
        N1=N1+1
41      NUM=0
        GO TO 30
20      IF(I.GE.TT) GO TO 21
        FLAG=0
        GO TO 30
21      IF(FLAG.EQ.0.OR.DD(I).GT.DD(I-1)) GO TO 30
        FLAG=0
        VELSUM=0
        IF(NUM.LE.NN) GO TO 51
        DO 50 J=1,NUM
50      VELSUM=VELSUM+TEMP(J)
        FAVEL(N2)=VELSUM/NUM
        N2=N2+1
51      NUM=0
30      NUM=NUM+1
        TEMP(NUM)=EYVEL(I)
6       CONTINUE
        APSVSU=0.0
        N11=N1-1
        DO 7 I=1,N11
        APSVSU=APSVSU+SAVEL(I)
7       CONTINUE
        APSV=APSVSU/N11
        APFVSU=0.0
        N22=N2-1
        DO 8 I=1,N22
8       APFVSU=APFVSU+FAVEL(I)
        APFV=APFVSU/N22
        G=MAVS/PP
        AG=APSV/PP
        WRITE(6,22) N22
22      FORMAT(I4)
        WRITE(6,9) G,AG,APSV,APFV
9       FORMAT(4E14.4)
        SC1=SC1+N22
        SC2=SC2+G
        SC3=SC3+AG
        SC4=SC4+APSV
        SC5=SC5+APFV
        RETURN
        END
$ENTRY
//FT06F001 DD SYSOUT=A
//FT20F001 DD DSN=XIAO.DATA10,DISP=OLD
//FT11F001 DD DSN=XIAO.B4,DISP=SHR
//
/*
```

Appendix C

CIRCUIT DIAGRAM

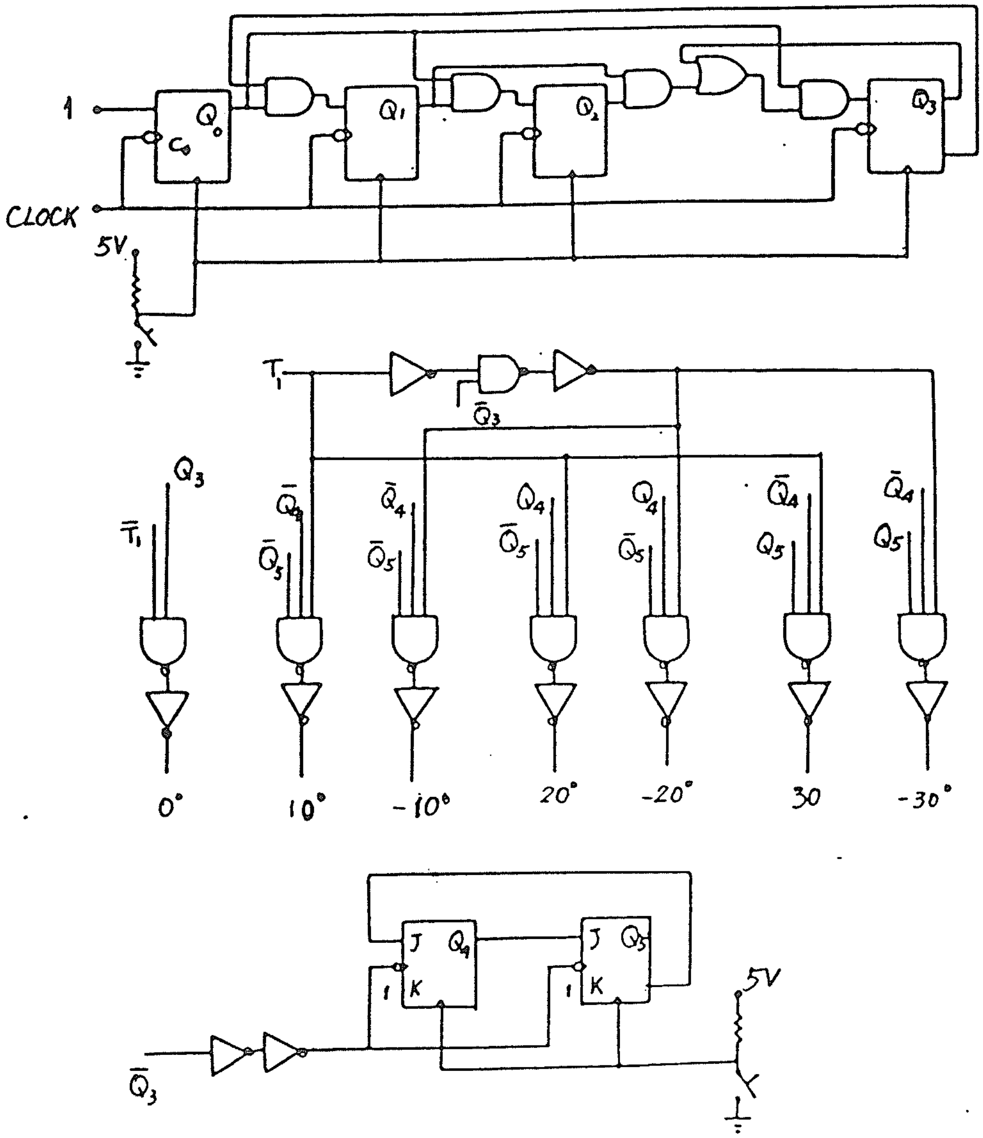


Fig.C Circuit diagram of the calibration LED.

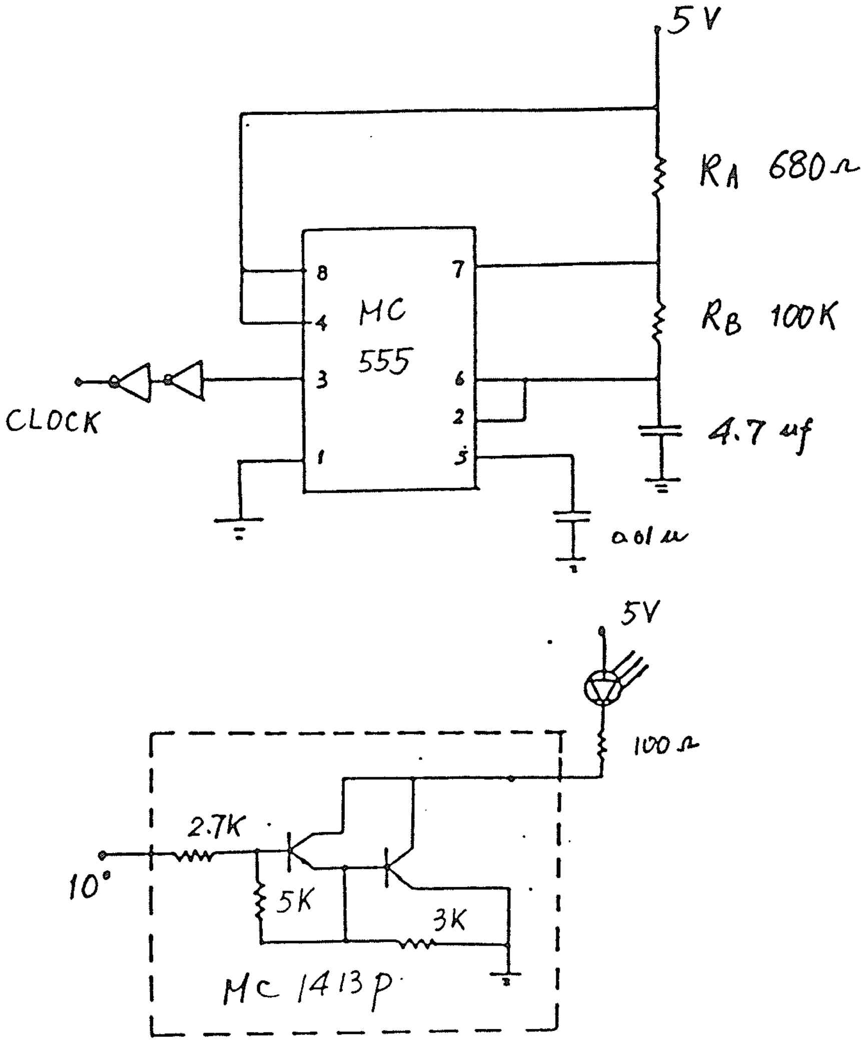


Fig.C(cont'd) Circuit diagram of the calibration LED.