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The Correction of the Vestibular System Inertial Biosensors

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Abstract: A mathematical model of the primary afferent neuron activity of the vestibular apparatus, which is the output signal of the vestibular inertial biosensor is presented. The model is based on experimental data from recordings in isolated vestibular neurons. Deterministic and stochastic analysis of our model has been done. Using this model, it might be possible, using galvanic stimulation of low amplitude applied to periauricular region, to correct the output from the vestibular apparatus. This galvanic stimulation should take place against a background of Gaussian white noise with optimal intensity. Computer analysis has shown that the formation of stochastic resonance makes galvanic stimulation more effective. Our model can process the corrective signal of the vestibular output in various conditions. An algorithm for the correction using galvanic stimulation is presented.

Keywords: Automatic correction, galvanic stimulation, primary neuron, vestibular apparatus.

1. Introduction

Vestibular apparatus and oculomotor system are essential for personal navigation. Sensors of the vestibular apparatus including the semicircular canals and otolith organs are inertial biosensors. Under extreme conditions of movement (microgravity, overload), when there are disorders of the vestibular apparatus, or due to aging, the functioning of these sensors is deficient. This raises the need for its correction. For this purpose various prototypes of vestibular prostheses have been proposed (DiGiovanna et al 2012; Shkel & Zeng 2006; Dai, Fridman & Della Santina 2011; Soto et al, 2014), but in the clinical practice they have not yet been implemented. One condition for the successful development of a vestibular function corrector is to design a software and device to detect and analyze human movement and generate the necessary corrective signals. In this work, the mathematical model of primary neuron activity, which is an output signal of vestibular inertial biosensors, is presented. A brief description of the model dynamics is presented in this work. The model can process corrective signals of the vestibular output in various conditions. It has been found that in microgravity there is a gaze stabilization lag, which can lead to disastrous results for manual control of a spacecraft, or for working in open space (Tomilovskaya et al 2011). In these circumstances the need for correction of vestibular function of vestibule-ocular reflex is needed. Improving the professionalism of the pilots can be achieved with the help of simulators. We also propose the use of an algorithm developed for flight simulation that can be used in training. For these purposes, the use of surface electrodes to apply vestibular galvanic stimulation is proposed (Fitzpatrick & Day 2004; Carrillo-Pliego A, 2013). This raises a question about the adequate parameters for the galvanic stimulation to be used to avoid unwanted side effects. We found that a weaker galvanic current can be applied using stochastic resonance. We propose the use of a MEMS-sensors-based corrector that consists of micro accelerometers, micro gyroscopes, and micro processor mounted in a helmet, whose output is processed using our embodiment of mathematical model. This system can be used as a prosthetic device for correction of vestibular biosensors.

2. Mathematical model of vestibular afferent neuron

We shall consider a description of action-potential-generation stochastic process, where the latter represents self-induced relaxation oscillations with constant amplitude and time variant frequency (propagation of these auto oscillations in the form of auto-waves is not being considered here).

The mathematical model is based on the Hodgkin-Huxley equations (Hodgkin & Huxley 1952), and was developed to simulate the action potential discharge dynamics of the vestibular afferent neurons of the rat (Limon et al 2005; Aleksandrov et al 2006). In contrast with other models (Goldwyn & Shea-Brown 2011; Ospeck 2012), our model is based in experimentally defined physiological parameters obtained from mammalian vestibule; and it includes a new coordinate related to the inactivation parameter of the potassium current, whose dynamics is described by the Kolmogorov equation for the Markov processes with a discrete number of states.

The novelties of the modified system that we are proposing are the following: in the description of the potassium current (I_K), we introduced an inactivation parameter h_K of the I_K and as a consequence we use one or more equations of Kolmogorov for the description on the average dynamics of this parameter (Aleksandrov 2006). The reduction of an order of the mathematical model in the presence of a small parameter τ_m at a derivative of the subsystem describing the average dynamics of the activation parameter m of I_{Na} has been justified (Moehlis 2006). The integral $n + h = c = constant$, where n is the activation parameter of the I_K and h is the inactivation parameter of the sodium current (I_{Na}), were used as a simplification of the Hodgkin-Huxley equations in various models. In our work it is modified according to experimental data as $n + h = C(V)$ where V is the membrane voltage. Thus, the modified Hodgkin-Huxley model is introduced in Couchy's third order form with small parameter on the right side of the equation, with the perturbation describing the probabilistic parameter dynamics h_K (Aleksandrov 2006). In this work we do not consider the time dependence of this parameter. Here the modified Hodgkin-Huxley model is introduced as a second order system:

$$C_m \frac{dV}{dt} = I_{com} - I_{Na} - I_K - I_L \tag{1}$$

$$\tau_n(V)\frac{dn}{dt} = \left(n_\infty(V) - n\right)\left(V - V_{Na}\right) \tag{2}$$

With

$$I_{Na} = g_{Na} m_\infty^3(V)\left(C(V) - n\right)\left(V - V_{Na}\right),$$

$$I_K = g_K n^4 h_{K\infty}\left(V - V_K\right), \qquad I_L = g_L\left(V - V_L\right),$$

$$C(V) = n_\infty(V) + h_{Na\infty}(V),$$

$$m_\infty = \frac{1}{1 + e^{-\frac{(V + 33.8)}{5.2}}}, \; h_{Na\infty} = \frac{1}{1 + e^{\frac{V + 60.5}{9.9}}},$$

$$n_\infty = \frac{1}{1 + e^{-\frac{(V + 35)}{5}}}, \; \tau_n = \frac{68}{e^{-\frac{(V + 25)}{15}} + e^{\frac{(V + 30)}{20}}}.$$

Where

- $I_{com} = I_{com}(I_{syn}, I_{cor})$ is the input current, I_{syn} - synaptic current, I_{cor} - output signal of corrector (galvanic current).
- V – variable "membrane potential" of afferent neuron.
- n – variable, which describes the process of potassium current activation. This parameter is a probability of the presence of potassium current activation particle in the potassium channels,
- h_k – a parameter, which describes the process of potassium current inactivation. This parameter represents the probability of absence of potassium current inactivation particles, here $h_k = h_{k\infty}$,
- h – a parameter, which describes the process of sodium current inactivation,
- τ_n – time constant of potassium current activation process,
- n_∞, m_∞ - stationary values of potassium and sodium current activation processes,
- $h_{Na\infty}$, $h_{K\infty}$ - stationary values of potassium an sodium current inactivation processe
- Q –parameter "temperature factor".

Numerical parameters are shown in table 1.

Table1. Model parameters

Numerical parameter	Value	Units	Numerical parameter	Value	Units
C_m	*1*	*pF/cm²*	Q	*6.47*	
V_{Na}	*52*	*mV*	I_{syn*}	*1.244*	*μA/cm²*
V_K	*-84*	*mV*	g_{Na}	*2.3*	*mS/cm²*
V_L	*-63*	*mV*	g_K	*2.4*	*mS/cm²*
h_K	*0.73*		g_L	*0.03*	*mS/cm²*

Computer analysis of average stochastic activity of primary afferent neuron (1-2), which form the output of the vestibular apparatus lead to the following results.

With the constant synaptic current $I_{com} = I_{syn}$, that has a value in the interval *[0.1, 70]* ($\mu A/cm^2$) there is only a point of Hopf bifurcation $I_{syn*} = 1024\,\mu A/cm^2$ which is the "center". To the left of this point there is a single critical point that is an asymptotically stable focus. To the right, there is a single critical point that is an unstable focus (Figure 1). The unstable focus is accompanied by the existence of an attractor that is an asymptotically orbital stable limit cycle. The frequency of action potential discharge, corresponding to the limit cycle is proportional to the value of the synaptic current; the amplitude of the action potentials is constant (Figure 2). Thus, the point of bifurcation is the threshold of sensitivity of inertial vestibular biosensors. If the synaptic current is more than I_{syn*}, a burst of action potentials is generated (Figure 2).

In the left neighbourhood of Hopf bifurcation point there are two attractors, a stable focus and a stable limit cycle

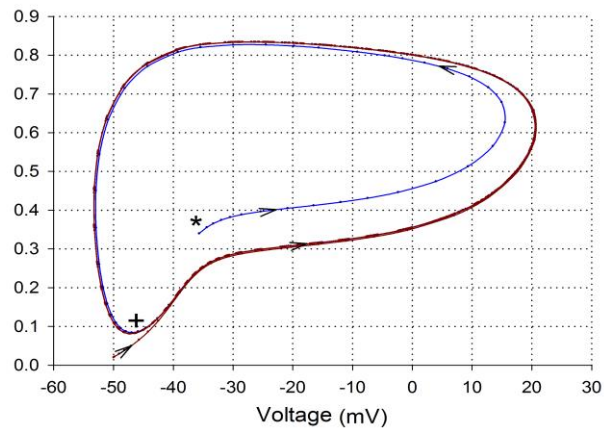

Figure 1. Limit cycle. Phase space diagram of the model (1-2) with a first bifurcation point $I_{syn*}=1.2444\ \mu A/cm^2$. Coordinates of two critical points, an unstable focus in *(-38.1098, 0.3493)* (star) for $I_{syn}=1.8\ \mu A/cm^2$, and a stable focus in *(-45.4804, 0.1095)* (plus sign) for $I_{syn}=0.5\ \mu A/cm^2$. Two paths are also shown, one with initial conditions *(-50, 0.02)* is outside of the limit cycle and, the other with initial conditions *(-35.68, 0.34)* is close to the unstable critical point. This two paths were obtained with $I_{syn}=1.8\ \mu A/cm^2$.

(Figure 1). When I_{syn} (constant) belongs to this neighbourhood, bursting can occur similarly as in the model snail neurons (Shilnikov 2005).

3. Galvanic stimulation and correction of the vestibular apparatus output signal.

Let us consider experiments in movement simulation (Moore, Dilda and MacDougall 2011; Maeda, Ando & Sugimoto 2005). Due to geometric constraints on the kinematics of the dynamic simulator platform, galvanic stimulation of the vestibular apparatus is used in order to simulate the effects of inertial forces encountered in flight and to act on the gravito-inertial mechanoreceptors and other inertial biosensors. Absence or presence of inertial forces can be described by the piecewise continuous function $\varepsilon P_j(t)$ that corresponds to the small galvanic current $I_{cor} = \varepsilon P_j(t)$. $P_0 \equiv 0$ on $[t_0, t_1]$ and $P_1 = constant$ is not zero on the $[t_1, t_2]$. Here $P_j(t)$ is the program signal generated in accordance with the dynamics of controlled flight. Let us suppose that the synaptic current I_{syn} is less than I_{syn*} because the simulator platform is motionless. Then the presence of $I_{com} = I_{syn}$ on the interval $[t_0, t_1]$, that corresponds to the absence of inertial forces, does not lead to the relaxation auto oscillations (Figure 2, $0 = t_0 \le t \le t_1 = 150$). If there is an inertial force presence, the program signal $P_j(t)$ is not zero on the interval $[t_1, t_2]$ and produce a burst of action potentials with high frequency (Figure 2, $150 = t_1 \le t \le t_2 = 300$).

Experiments have shown (Simiu 2002; Scinicariello et al 2001) that when white noise of a certain intensity was added to the program signal, $I_{com} = I_{syn} + I_{cor} = I_{syn} + \varepsilon(P_j(t) + rG(t))$ where $rG(t)$ is Gaussian white noise with intensity "r" it is possible to get stochastic resonance. This makes the galvanic stimulation more effective and allows the use of a weaker current. As a criterion, consider the finding of a maximum of the average number of action potentials ($\overline{NSP}$) on a given interval with variable intensity of Gaussian white noise "r". NSP - number of spikes (Figure 3).

For modeling let us assume $I_{cor} = \varepsilon(P_j(t) + rG(t))$. To model the stochastic component $rG(t)$, based on (Simiu 2002), we apply the Ornstein-Ulenbeck process $U(t)$ with the correlational function $R_u(s) = (1/(2c))Exp(-|s|/c)$, dispersion

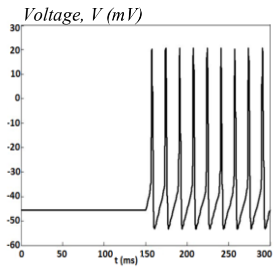

Figure 2. The model output $V(t)$ without noise.

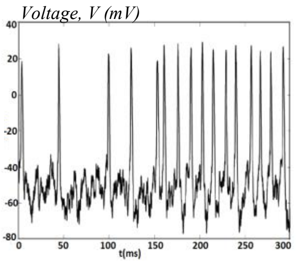

Figure 3. The model output $V(t)$ with noise.

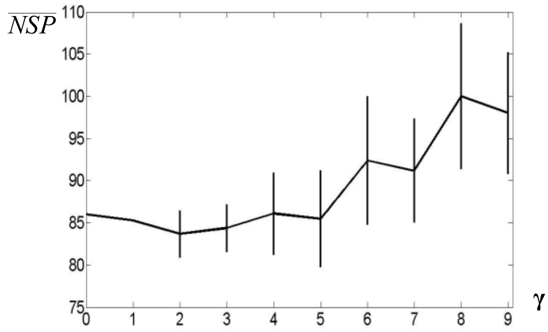

Figure 4. Stochastic resonance, $\gamma_{opt}=8$.

$1/(2c)$ and one sided spectral density $\psi_u^{o.s.}(\omega) = 2/(1 + c^2\omega^2)$ (which is connected with the spectral density as $\psi_u^{o.s.}(\omega) = \psi_u^-(\omega) + \psi_u^-(-\omega)$. Then the process $G(t) = (2c)^{1/2}U(t)$ is characterized by one side spectral density $\psi_G^{o.s.}(\omega) = 4c/(1 + c^2\omega^2)$.

Results correspond with the value $c=0.05$, at which we can examine $rG(t)$ as a process with spectral density close to constant value $\gamma^2=2cr^2$ (where γ is the intensity of the white noise $\gamma G0(t)$). We shall note that the dimension of coefficient r equals $\mu A/cm^2$, whereas that of $G(t)$ process is dimensionless.

For $G(t)$ we can apply an approximation with Katz-Shinozaki series $G_N(t)=(2/N)^{1/2}\Sigma^N_{i=1}Cos\ (\omega_i t+\varphi_{oi})$, where phases are uniformly distributed in the interval $[0,2\pi]$, and frequency distribution is characterized by the following density of probability $f_\omega(\omega)=(1/2\pi)\Psi_G^{o.s}(\omega)=(1/\pi)(2c/(1+c^2\omega^2))$ and the parameter N finite albeit large (Figures 3, 4 and 5 are realized with this conditions). Calculations were done under Matlab environment with $N=100$. The second order equation system was integrated applying Matlab function **ode23** at constant value $\varepsilon P_1(t)=1.8\ \mu A/cm^2\ t \in [t_1, t_2]=[1.5; 3]$ (seconds) and different realizations $rG(t)$, which correspond to different values r and at the same starting condition $(V, n)=(-45, 66\ (mV); 0,11)$.

Figure 4 shows the dependence of this statistical evaluation at different intensity values of "r". The presence of a maximum allows to ascertain that it is possible to select an optimal intensity of white noise in the second block of the corrector (Figure 6). In each of the five evaluations with length *1500 ms* for ten intensity values *r*, the number of action potentials has been calculated (thus, at every value *r* we have a selection with scope 10 for random variable *NSP*). In Figure 4 shows the dependence of mean $\overline{NSP}$ from intensity $\gamma^2=2cr^2$.

Thus, when $t \in [t_1; t_2]$, $\varepsilon P_1(t)$ are fixed we have a maximum of the average number $\overline{NSP}$. Applying Shapiro consent criterion, it can be shown that the necessary condition of the hypothesis of normality of the *NSP* probability distribution are fulfilled. Confidence intervals of statistical evaluation of $\overline{NSP}$, corresponding to the normal distribution are shown in Figure 4. The intensity of bursting strength depends on the amplitude of Gaussian white noise (Figure 5). Therefore, it

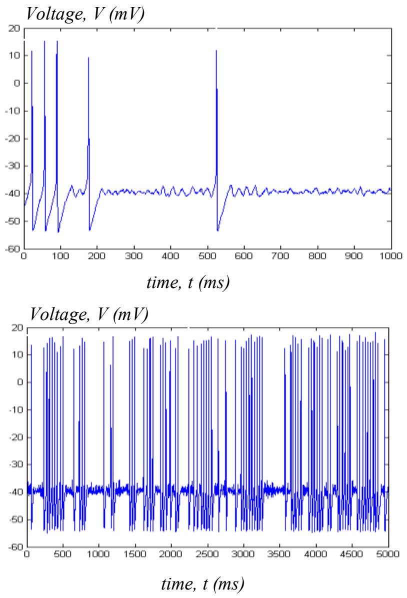

Figure 5. Model neuron action potential discharge. Both graphs, a) and b), were realized with $I_{syn}=0.99\ \mu A/cm^2$. In a) performance of white noise influence with intensity γ_1 , in b) with intensty γ_2 ,where $\gamma_1 < \gamma_2 < \gamma_{opt}$.

can be assumed that the algorithm of correction (Figure 6) by galvanic stimulation is as follows:

$$I_{com} = I_{syn} + I_{cor} = I_{syn} + \varepsilon\left(P_j(t) + r_j G(t)\right) \quad (3)$$

P_j - program signal of simulation algorithm
G -Gaussian white noise
r_j - optimal intensity of Gaussian white noise for stochastic resonance.
Optimal intensity r_j is constant at each time interval, it is selected like function of parameters Δt_j, P_j.

4. Aplication for automatic correction

Automatic correction scheme using galvanic stimulation is shown in Figure 7. Such scheme can be used to design a vestibular prosthesis for correction of posture (DiGiovanna et al 2012; Shkel & Zeng 2006; Dai, Fridman & Della Santina 2011)) and reduce gaze fixation time in extreme conditions in orbit (Sadovnichii 2013).

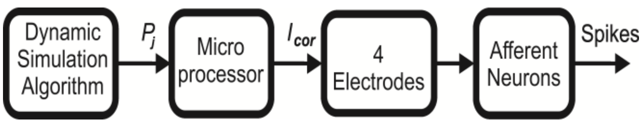

Figure 6. Corrector schematics.

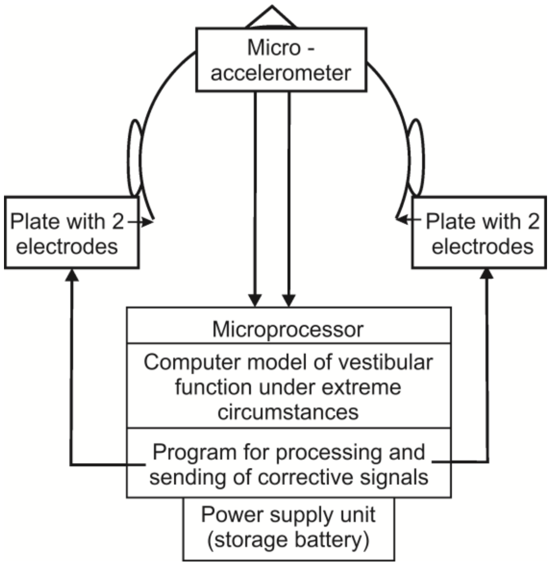

Figure 7. Scheme of MEMS corrector.

We used the above ideas to provide an alternative to improve gaze stabilization in orbital flight or to help stabilize the upright posture on Land obtained two patents related: 1. "Device for automatic correction of single sight alignment in visual motion control in microgravity environment" (MSU-BUAP, 2013 Russian Federation of Patent No. 2,500,375); 2. United States Patent " Vestibular Prosthesis" (BUAP-MSU Pub. No. US2014 / 0081346 A1, 2014). To analyze the possibility of correction of the vestibular output signal using MEMS sensors it has been developed a functional scheme and a helmet, whose output is used as an input to model system to generate the correction signals.

5. Conclusions

- A simplified mathematical model of the primary neuron activity of vestibular apparatus has been developed. The model describes in average the signal formation that is a stochastic Markov process. It gives the output information from gravitoinercial mechanoreceptors of the otolith and inertial biosensors of semicircular canals as a variable frequency of spikes. This model can be used to process correction signals of the vestibular apparatus output.
- The mathematical model and computer simulation show that applying Gaussian white noise of optimal intensity in addition to the program signal increases the number of action potentials at a fixed time interval due to the presence of stochastic resonance. Thus, a weaker galvanic stimulation can be used.
- Our results open the possibility of generating a pattern of the corrective output signal (I_{cor}) as in (3), and using it in the simulator to train pilots. The software component of a corrective signal is formed by an algorithm of the dynamic simulation of controlled flight in real time. It is accompanied by Gaussian white noise of optimal intensity, which is from a table determined by the function of two parameters (Δt_j and Pj). The table is created prior to training with the use of models (1), (2), (3).

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