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Modeling of the EEG signal

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Abstract *– This article describes important and wide academic field, EEG signals modeling. A major division of this field into two branches, EEG-like signals modeling and seizure-like signals modeling, is introduced and analyzed. Three models to generate EEG activity are represented including their structure, analytic description and parameters' setting. Finally results of implemented models are introduced, discussed and mutually compared with regard to expected EEG activity.*

1 Introduction

Electroencephalographic recording system serves to the examination of a brain activity. Depending on a human brain activity, several types of electroencephalographic (EEG) waves can be distinguished [1]. Deviations of the normal EEG waves corresponding to alpha or beta activity, i.e. sharp spikes, can refer to pathologic patterns accompanying neurogical illnesses. Based on a detection of pathologic patterns recurring with period of one or a few seconds in EEG signal, electroencephalographic recording system has been used to diagnose diseases such as epilepsy or polio [1], [2]. Because of the important role of the EEG examination in neurological diseases diagnostics, there have been several attempts to simulate a real EEG signal by artificial models.

Modeling of the EEG signals is a very wide academic area divided in several branches. A brief overview of possible branches of EEG modeling is introduced in [3]. This article is focused on two branches of EEG modeling concerning alpha and beta activity simulation.

The first branch of modeling EEG signals includes simulation of EEG-like waves corresponding to the psychological EEG record without any pathologic pattern. Although, simulation of alpha and beta activity were performed by several different mathematical models (Freeman's model, Lopez da Silva's model, Jansen's model, etc. [3]), all mathematical models had been developed as macroscopic models. The structure of macroscopic models describes an interaction of excitatory and inhibitory neurons populations. The neuronal networks of the cortex are considered as a spatially continuous network and properties of neurons at a local region are summarized into state variables as the mean firing rates or the mean values of the cell membrane potential. Values of state variables are functions of time and space. Macroscopic models approach has been developed to better comprehension of the functional meaning of the arising cortex dynamics [3].

The second branch of EEG modeling is partially connected with the first one. The structure of macroscopic models, namely Lopez da Silva's model, is extended to the structure of models that can simulate EEG seizure-like signals representing neurological pathologies that could be markers for the neurological diseases [3].

Models of EEG-like and EEG seizure-like signals were implemented. Obtained EEG-like and EEG sizure-like signals had been involved in experiments where the brain environment was replaced by a phantom and EEG signal transmission was analyzed. The aim of this paper is to introduce obtained EEG signals of own implementation and to compare characteristic features (i.e. the shape, the magnitude and the frequency range) of obtained EEG signals of both above-mentioned branches of EEG modeling with respective characteristic features of real EEG signals.

2 Jansen's single-column model

Generally, Jansen's models are inspired by the mathematical model designed by Lopes da Silva and Van Rotterdam in 1982 [4]. Jansen's single-column model is based on the idea of cortical columns representing the excitatory or the inhibitory neuronal populations, detailed description in [5], [6]. This mathematical model has been designed to simulate the spontaneous electrical activity of neurons recorded using the EEG device focusing on a simulation of the alpha waves. The neuronal populations interact through the excitation and the inhibition which produces the alpha waves. Additionally Jansen's single-column model is able to simulate the EEG activity where spikes associated with epilepsy can be observed [7].

Jansen's single-column model represents the population of the pyramidal neurons which receives the feedback from the local inter-neurons located in the same column and the excitatory input from the other columns or the subcortical structures (e.g. the thalamus). The excitatory input can be represented by an average firing rate that can correspond to a noise. The external input corresponds to the excitatory input and this input is marked as variable $p(t)$ [8]. The structure of Jansen's single-column model is introduced in Figure 1.

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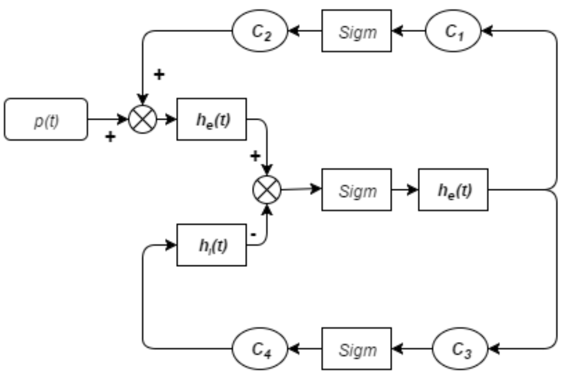

Figure 1: Structure of Jansen's single-column model

2.1 Post-synaptic box

Jansen's model can be divided into the several parts, *boxes*. The first of them is *post-synaptic box* described by variables $h_e(t)$ and $h_i(t)$ depending on the neuronal population that should be represent by this box.

These boxes simulate synapses between the neuronal populations. The input of the box is represented as the average value of the action potentials (the average firing rate of the pre-synaptic population) and converted into the average value of the post-synaptic potential through a second order differential linear transformation [5], [6].

2.2 Sigmoid box

These boxes represent the cell bodies of the neurons. Integration of *Sigmoid boxes* into the macroscopic model implies a nonlinear transformation of the average membrane potential of a neural population into the average firing rate. The function of the *Sigmoid* is introduced in the equation below, 1:

$$Sigm(v) = \frac{2e_0}{1 + e^{r(v_0 - v)}}. \tag{1}$$

Acording to the previous works [5] and [6], the variable e_0 represents a half of the maximum firing rate of the neural populations, the variable v_0 represents the value of the potential for which a 50% firing rate is achieved and this variable can be understood as a firing threshold or as the excitability of the neuronal populations. The variable r represents the slope of the sigmoid at v_0. The curve of the sigmoid is symmetric around the point, v_0, e_0.

The shape of the sigmoid simulates characteristics of neurons. As long as the potential is under the excitable threshold neurons produce APs. The firing rate grows almost linear close the excitable threshold until saturation which is caused by the refractory period of neuron.

2.3 Constants

Jansen's model includes also constants C_i. These constants represent the power of the synaptic connection between neuronal populations therefore, indicating the number of synapses. The setting of the number of synapses is experimental and empirical according to [6], but the strongest constant is the first one, C_1, that sets the maximum number of synapses between neuronal populations. For example, the value of C_1 for the simulation of alpha activity is 135. Based on the strongest constant C_1 the other constants are proportionaly set, the constant C_2 equals 80% of C_1 and constants C_3 and C_4 equal 25% of C_1.

2.4 Analytic description and parameters setting

Mentioned above, each post-synaptic block performs a conversion of the action potencials into the average value of the post-synaptic potential through a second order differential linear transformation [6]. The result of such a linear transformation corresponds with a solution of the differential equation mentioned below:

$$\ddot{y} = Aax(t) - 2a\dot{y}(t) + a^2y(t), \tag{2}$$

where the variable A determines the maximal amplitude of the post-synaptic potential in the case of the excitatory population, in the case of the inhibitory population the parameter B is used instead of the parameter A. The variable a is a constant representing a delay of the synaptic transmission in the case of the excitatory population, in the case of the inhibitory population the parameter b is used. The whole Jansen's model can be described via three second order differential equations introduced below. Set of these equations can be extended into a set of six first order differential equations stated in [6].

$$\ddot{y_0}(t) = AaSigm\left[y_1(t) - y_2(t)\right] - 2a\dot{y_0}(t) - a^2y_0(t) \tag{3}$$

$$\ddot{y_1}(t) = Aa\left\{p(t) + C_2Sigm\left[C_1y_0(t)\right]\right\} \tag{4}$$

$$-2a\dot{y_1}(t) - a^2y_1(t)$$

$$\ddot{y_2}(t) = Bb\left\{C_4Sigm\left[C_3y_0(t)\right]\right\} - 2b\dot{y_2}(t) - b^2y_2(t) \tag{5}$$

The importance of parameters' setting is emphasized due to the fact that Jansen's single-column model has been designed to simulate alpha activity. Parameters A, B, a, b have been set by Jansen and Rit [5]. The overview of parameters' setting is presented in Table 1.

Table 1: Parameters' setting of Jansen's single-column model

Parameter	Value	Parameter	Value
A	3.25 mV	C_1	135
B	22 mV	C_2	108
a	$100\,\mathrm{s}^{-1}$	C_3	33.75
b	$50\,\mathrm{s}^{-1}$	C_4	33.75

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Reagarding the remaining parameters, the variable v_0 can take different values because the excitability of cortical neurons can vary under the action of several substances. Due to the alpha activity simulation parameter v_0 equals 6 mV, it has been suggested by Jansen and Rit [5]. Furthermore, other variables have been suggested by Jansen and Rit, r equals $0.56\,\mathrm{mV}^{-1}$, e_0 equals $2.5\,\mathrm{s}^{-1}$.

As for the parameter $p(t)$, a white noise ranging from 120 to 320 pulses per second is used. 120 Hz is the lower limit and 320 Hz is the upper limit of the range of a white noise.

3 Jansen's double-column model

Jansen's double-column model is an extension of previous model. Jansen et al. merged two single-column models to examine the hypothesis that certain visual evoked potential (VEP) components are caused by the interaction of two or more cortical areas [7]. Each column is proposed according to the same set of equations as the single-column model but the system of parameters is different for each column.

Two columns are connected into a loop. Each column is fed by two uncorrelated random inputs and also fed by output of the other column.

The double-column model extension includes two connectivity constants, K_1 and K_2, to determine the strenght of the connection between columns. These constants are added into the loop prior to columns to attenuate the output of the column [7]. The whole structure of Jansen's double-column model is shown in the picture below Figure 2.

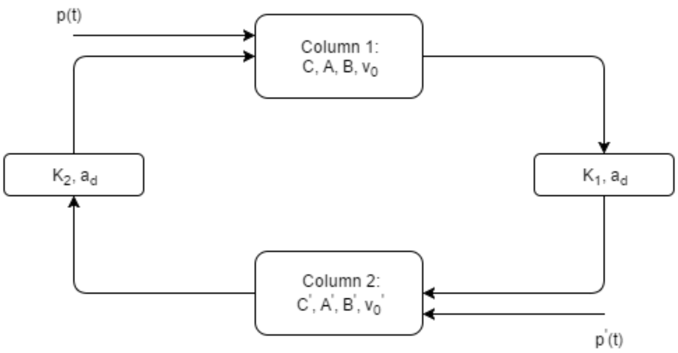

Figure 2: Structure of Jansen's double-column model

The examinations of VEP components caused by the interaction between the visual cortex and prefrontal cortex have been explored by Jansen and Rit [5]. In case of their experiments the column representing the visual cortex was made to produce alpha activity. The prefrontal cortex was designed to generate beta activity.

For each cortical column same cortical column model can be assumed, while the situation with parameters' system is different. In these cortical parts the structure of cells differs from one cortical area to the next. Therefore, each column has the own parameters' setting representing the differences in cell structure [5].

Other important parameter can be included in the coupled model, intercolumn delay a_d (Figure 2). This parameter is related to delays occuring during processing of a visual stimulus by the prefrontal cortex and with the feedback to the occipital visual cortex. These delays are represented by linear transformation similar to the transformation used in the single-column model, $h_e(t)$ but with latency three times longer, $a_d \approx a/3$, detailed description of an interncolumn delay is introduced in [5] and [6].

3.1 Analytic dscription

The analytic description of this model uses twice as many variables as for a single-column model. In addition there are variables describing the connection between column 1 and column 2. The set of a second order linear equations is represented below. In previous works [5] and [6] the set of a first order linear equations is proposed.

The first three variables, y_0, y_1, y_2, describe column 1, the next three variables, y_3, y_4, y_5, describe column 2.

$$\ddot{y_0}(t) = AaSigm\left[y_1(t) - y_2(t)\right] - 2a\dot{y_0}(t) - a^2 y_0(t) \quad (6)$$

$$\ddot{y_1}(t) = Aa\left\{p(t) + C_2 Sigm\left[C_1 y_0(t) + K_2 y21\right]\right\} \quad (7)$$

$$-2a\dot{y_1}(t) - a^2 y_1(t)$$

$$\ddot{y_2}(t) = Bb\left\{C_4 Sigm\left[C_3 y_0(t)\right]\right\} - 2b\dot{y_2}(t) - b^2 y_2(t) \quad (8)$$

$$\ddot{y_3}(t) = A' aSigm\left[y_4(t) - y_5(t)\right] - 2a\dot{y_3}(t) - a^2 y_3(t) \quad (9)$$

$$\ddot{y_4}(t) = A' a\left\{p'(t) + C_2' Sigm\left[C_1' y_3(t) + K_1 y12\right]\right. \quad (10)$$

$$\left.-2a\dot{y_4}(t) - a^2 y_4(t)\right.$$

$$\ddot{y_5}(t) = B' b\left\{C_4' Sigm\left[C_3' y_3(t)\right]\right\} - 2b\dot{y_5}(t) - b^2 y_5(t) \quad (11)$$

The two variables, y_{12}, y_{21}, describe the connection between column 1 and column 2.

$$\ddot{y_{12}}(t) = A' a_d Sigm\left[y_1(t) - y_2(t)\right] - 2a_d \dot{y_{12}}(t) \quad (12)$$

$$-a^2 y_{12}(t)$$

$$\ddot{y_{21}}(t) = A' a_d Sigm\left[y_4(t) - y_5(t)\right] - 2a_d \dot{y_{21}}(t) \quad (13)$$

$$-a^2 y_{21}(t)$$

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3.2 Parameters' setting

Simulation of the interaction between column 1 located in the visual cortex and column 2 located in the prefrontal cortex has been proposed. Column 1 simulates the visual cortex alpha activity. Therefore, the parameters' setting stayes the same as in the single-column model case, while column 2 is supposed to represent the prefrontal cortex beta activity with different parameters' system. The parameters' setting is selected according to Jansen and Rit study [5], variables that are different from the single-column model setting are introduced in Table 2.

Table 2: Different parameters' setting from Jansen's single-column model

Parameter	Value	Parameter	Value
$A^{'}$	3.25 mV	$C_2^{'}$	86.4
$B^{'}$	17.6 mV	$C_3^{'}$	27
$C_1^{'}$	108	$C_4^{'}$	27

According to Jansen and Rit study [5], the connectivity constants, K_1 and K_2, are varied in the different ranges. The variation of the first one, K_1, is performed between 0 and 8000 in steps increasing from 50 to 4000 units. The variation of the second one, K_2, is performed between 0 and 1500 in steps increasing from 100 to 500 units [5]. The relations between these two connectivity constants are shown in Figure 3.

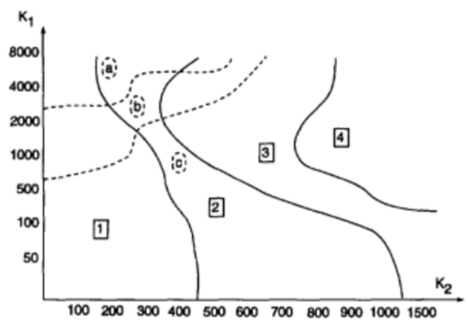

Figure 3: Relationship between the connectivity constants (edited from [5])

The relations between the connectivity constants and their impact on the signals from both columns are shown in Figure 4 (i.e. if the value of K_1 is between 0 and 500 units which represents area c and value of K_2 is between 0 and 400 which represents area 1 the output signal of column 1 should be alpha activity and the output of column 2 should be beta activity, the detailed description of relation bewteen conncetivity constants is described in Jansen and Rit study [5]).

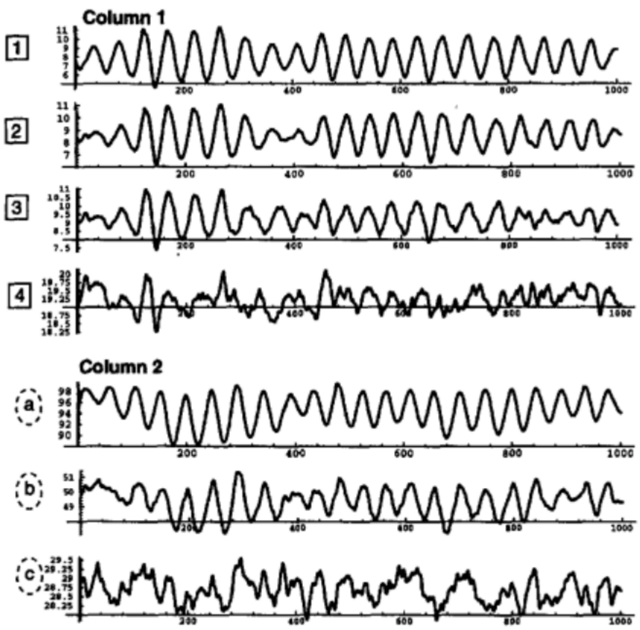

Figure 4: Outputs from the both columns depending on the connectity constants (edited from [5])

4 Wendling's model

Wendling's model is based on the work of Jansen and Rit [5], [6]. A new inhibitory feedback loop is added in order to represent a subset of interneurons providing somatic inhibiton to pyramidal cells. The structure of Wendling's model is suggested in Figure 5.

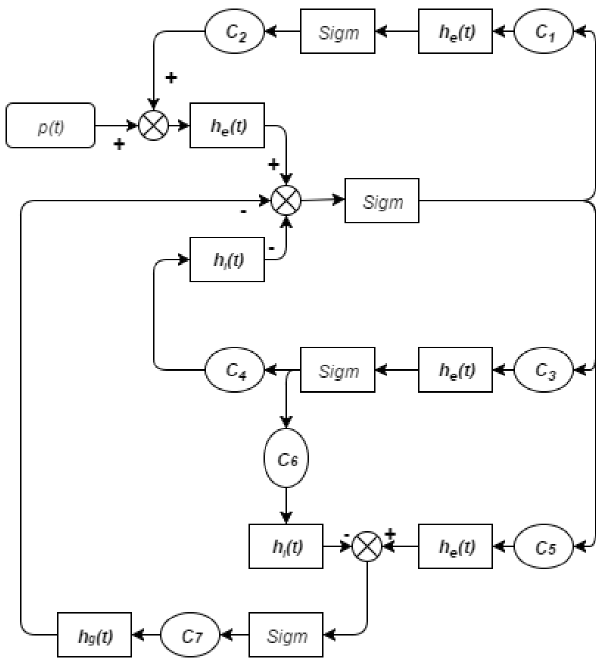

Figure 5: Structure of Wendling's model

The output of Wendling's model is a set of six different types of EEG activity including seizure activity refering to

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epileptic attack [8], [9]. One of the biggest strengths of Wendling's model is to simulate the realistic epileptiform activity that should be caused by an imbalance between excitatory and inhibitory synaptic gains [9].

As mentioned above, the inhibitory feedback loop is added into Jansen's model therefore Wendling's model consists of four subsections corresponding to pyramidal cells, excitatory cells, slow inhibitory cells and the last subsection represents fast inhibitory cells.

4.1 Analytic description

The analytic description of added block representing fast inhibitory cells, $h_g(t)$, is analogous to post-synaptic blocks of Jansen's model, $h_e(t)$ and $h_i(t)$ (the full definition is introduced in [8]). Therefore the analytic description of Wendling's model includes two variables more, $y_3(t)$ and $y_4(t)$, and is performed by the set of a second order differential equations as Jansen's model [8], [9].

$$\ddot{y_0}(t) = AaSigm\left[y_1(t) - y_2(t) - y_3(t)\right] \qquad (14)$$

$$-2a\dot{y_0}(t) - a^2 y_0(t)$$

$$\ddot{y_1}(t) = Aa\left\{p(t) + C_2 Sigm\left[C_1 y_0(t)\right]\right\} \qquad (15)$$

$$-2a\dot{y_1}(t) - a^2 y_1(t)$$

$$\ddot{y_2}(t) = Bb\left\{C_4 Sigm\left[C_3 y_0(t)\right]\right\} - 2b\dot{y_2}(t) - b^2 y_2(t) \qquad (16)$$

$$\ddot{y_3}(t) = Gg\left\{C_7 Sigm\left[C_5 y_0(t) - C_6 y_4(t)\right]\right\} \qquad (17)$$

$$-2g\dot{y_3}(t) - g^2 y_3(t)$$

$$\ddot{y_4}(t) = Bb\left\{C_4 Sigm\left[C_3 y_0(t)\right]\right\} - 2b\dot{y_4}(t) - b^2 y_4(t) \qquad (18)$$

4.2 Parameters' setting

According to the research of Wendling et al.[9], Wendling's model is able to generate six types of EEG activity according to the parameters' setting. Parameters' system of A, B and G parameters is changed in the certain ranges to generate these types of EEG activity, the rest of paramteres remains the same as in Jansen's model case. The range of parameter A is varied from 3.25 to 7 mV, the range of parameter B is changed from 22 to 47 mV and the range of parameter G is varied from 3 to 25 mV. As the input of Wendling's model a Gaussian noise with mean and variance adjusted to receive a rate ranging from 30 to 150 pulses per second is used [8].

Type 1 and type 2 of EEG activity obtained from Wendling's model refer to normal background and sporadic spikes. Type 3 and type 4 should correspond to sustaining spikes activity and slow rhytmic activity. Type 5 represents a low-amplitude rapid discharges appearing at the beginning of ictal periods. The last one, type 6, refers to slow quasi-sinusoidal activity, [8].

5 Results

The mathematical models presented above are based on the idea of macroscopic model and their structures differ according to the type of EEG activity that should be obtained from these models. All these models were implemented and results were compared to expected results. The differential equations were solved using Matlab R2012b, Simulink with solver 'ode45'. Results of Jansen's single-column and double-column models generating EEG-like signals and results of models of seizure are introduced respectively.

5.1 EEG-like signals

The first set of results was acquired from Jansen's single-column model. By varying constant C_1, six results ongoing for two seconds were obtained (in Figure 6).

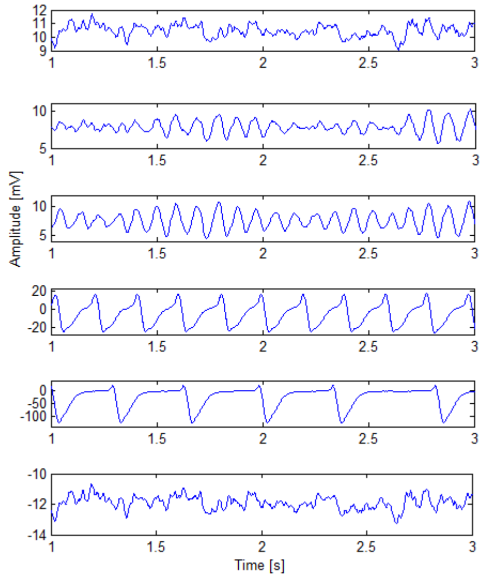

Figure 6: Results of Jansen's single-column model acquired by varying constant C_1

Obtained EEG activity from Jansen's single column model apparently changed from beta activity to alpha activity according to a value of the constant $C1$ (from the top to the bottom C_1 equals 68, 128, 135, 270, 675 and 1350 respectively). Alpha activity was acquired for the constant C_1 equal to 135 with signal amplitude in the range from 6 to 11 mV, beta activity was received for the low values of the constant C_1 equal to 68 (signal amplitude from 9 to 12 mV) and 128 (signal amplitude from 5 to 10 mV). Beta activity as the result of Jansen's single-column model was obtained even for the highest value of the constant C_1 equal to 1350 but the range of signal amplitude is negative from -14 to -11 mV.

The second set of results was obtained from Jansen's double-column model. Practically, Jansen's double-column model included three more varibles compared to

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the previous model due to the principle of the connection of two cortical columns. Connectivity constants K_1 and K_2 and delay a_d featured the connection of two cortical columns.

First result of Jansen's double-column model represented two different types of EEG activity. The connectivity constants were chosen in the range according to relation of the connectivity constants shown above to obtain alpha activity as an output of column 1 and beta activity as an output of column 2. The values of K_1 and K_2 were adjusted to 50 and 500 respectively due to the penetration of these two values corresponded to the area 2 (alpha activity) of column 1 and the area c of column 2 (beta activity) shown in Figure 7.

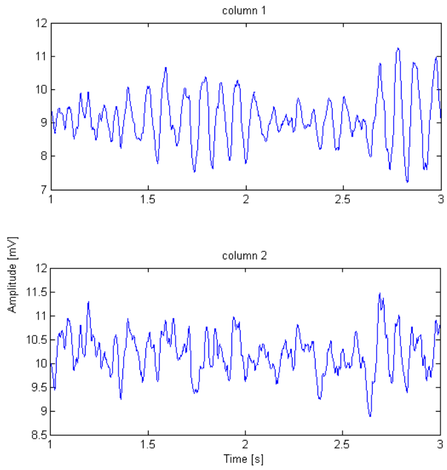

Figure 7: Results of Jansen's double-column model, alpha and beta activity

Second result of Jansen's double-column model corresponded only to one type of EEG activity. The values of K_1 and K_2 were adjusted to 7000 and 10 respectively due to the penetration of these two values of connectivity constants corresponding to area 1 (alpha activity) of column 1 and the area a (alpha activity) of column 2. Outputs of both columns were signals representing alpha activity shown in Figure 8.

Obtained types of EEG activity were consistent with expectations. Artificially created types of EEG activities, alpha and beta activity, were comparable to real acquired types of EEG activity. Signal amplitudes and spectral properties of obtained results were the identical to real EEG signals representing alpha and beta activity.

5.2 EEG seizure-like signals

The basic Jansen's single-column model could be set to generate seizure-like signals of EEG activity. Gaussian noise corresponding to a firing rate between 30 and 150 Hz could be used as the input. To generating seizure-like signals, the excitation/inhibition ratio A/B was increased. Results represented in Figure 9

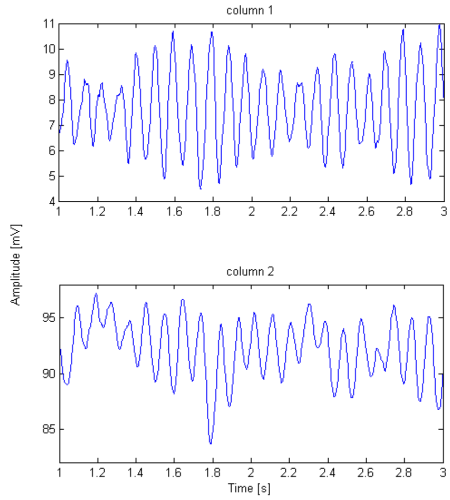

Figure 8: Results of Jansen's double-column model, alpha activity

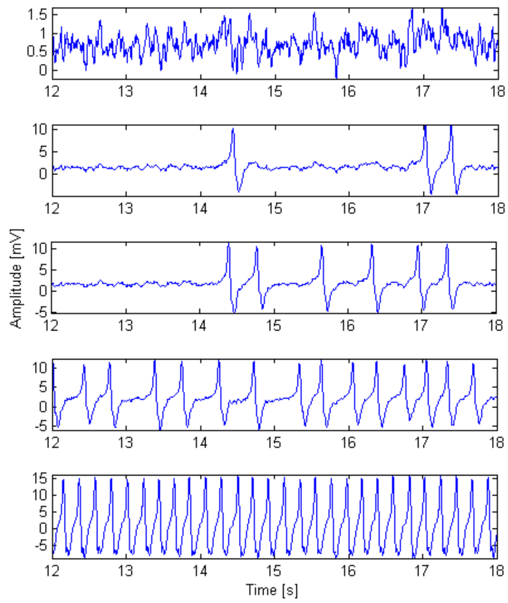

Figure 9: Seizure-like signals generated from Jansen's single-column model

From the top to the bottom signals were acquired with increasing parameter A, A was varied from 3.25 to 5 mV, parameter B remained the same equal to 22 mV. As the excitation/inhibition ratio was increased we observed sporadic spikes followed by increasingly periodic activities.

Wendling's model was the extension of basic Jansen's single-column model. This model included the addition of the block representing the fast inhibitory cells and better described the essence of the emergence and spread of signals in the brain. As results from Wendling's model, six signals are represented below in Figure 10.

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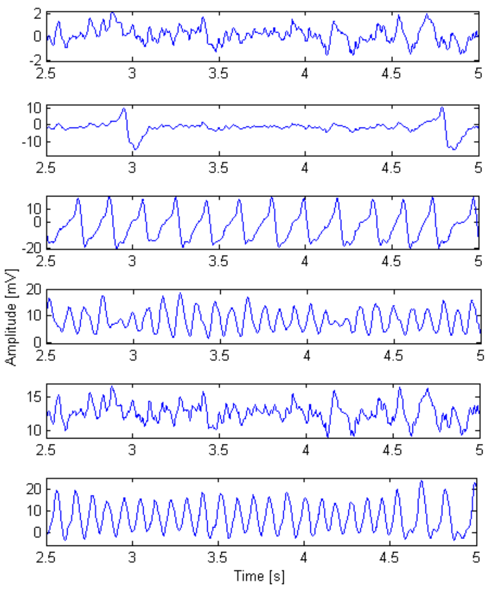

Figure 10: Seizure-like signals generated from Wendling's model, Signal 1-Signal 6 respectively from the top to the bottom

Six different types of EEG seizure activity were generated by varying parameters A (average excitatory synaptic gain), B (average slow inhibitory synaptic gain) and G (average fast inhibitory synaptic gain). For clarity, values of these parameters are introduced in Table 3. Altogether, six combination of these parameters describing six types of the seizure-like signals were obtained.

Table 3: Parameters' setting of Wendling's model, all values are in mV

Signal	1	2	3	4	5	6
A	3.25	5.6	7	7	7	7
B	22	47	35	15	10	19
G	10	25	10	10	25	3

The parameters' setting was chosen based on recommendations from the literature to obtain signals including the seizure-like activity. Results from Wendling's model were similar as results obtained from Jansen's single-column model but as it was mentioned above, Wendlin's model was more accurate model respecting the anatomy of neurons and their networks.

The spectral properties of obtained EEG seizure-like signals were compared to real EEG seizure-like signals and theoretical expectations were fulfilled.

6 Conclusion

In this article two main parts of EEG modeling were described. Firstly, the modeling of EEG-like signals was represented by Jansen's single-column and double-column model, the second part was the modeling of seizure-like EEG activity represented by Jansen's single-column model and Wendling's model. The spectral analysis was applied to the results of each model introduced in that article. It was found that the spectral properties of the the simulated signals correspond to the properties of the real signals. In both cases, structures of models, analytic descriptions, the important parameters and their settings were discussed to better understanding and imagination how these models worked. This article can serves as a brief overview of EEG modeling and it could serve as a basis for modeling of complex situations.

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