The Extended Ear Type System and Possible Applications

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***Abstract*—A method for setting up an extended ear type system applicable for multiple inputs and/or outputs is presented. The extended system utilizing a nonlinear artificial neural network can be used to identify and model the human auditory system through the measured auditory evoked potential responses. An application includes the characterization of the auditory loss and disorder leading to a possible alternate noninvasive treatment. An example is given on the system of auditory brainstem responses with the two channel recordings.**

I. INTRODUCTION

The measurement of the auditory evoked potential responses inside the brain has been a valuable means to assess and make a clinical diagnosis of function of the human auditory system [1]-[2]. These electrophysiological signals reflect the mechanism and activities of auditory neurons within the central nervous system of the auditory pathway in the brain. The auditory brainstem response (ABR), the middle latency response (MLR), and the late latency response (LLR) also known as the auditory cortical response are examples of the commonly used signals. They are classified according to the time of the response occurrence after the evoked stimulus such as clicks or tone bursts. These temporal characteristics also represent the corresponding locations of which the responses are tentatively generated from. Therefore they are very useful tools for hearing function assessment and hearing loss and threshold evaluation especially in cases where the patient cannot give rational responsive indications, as in the case for young children and infants.

The measurement is conventionally performed in a far field differential recording manner in which signals between two points are measured by using electrodes placed on specific locations of the scalp. The placement is typically selected according to the established montages that generally yield the identifiable responses. The neural responses at the deep level of the auditory cortex such as those of the LLR are inevitably products of many underlying mechanisms from multiple brain regions [2]. The multiple-channel recordings are typically required using a number of electrodes with 16, 32, 64, or 128 channels to detect and reduce the artifacts. The electrode placements follow the standard or modified versions of the international 10 to 20 system [3] as shown in Fig. 1. Binaural stimuli can also be helpful in the evaluation of hearing function, cochlear implants [4], and auditory loss and disorder such as tinnitus [5]. We therefore investigate the ear type system extendable for applicability of these multiple inputs and outputs of auditory evoked potential responses and give an example using the auditory brainstem responses measured from a clinical hearing evaluation.

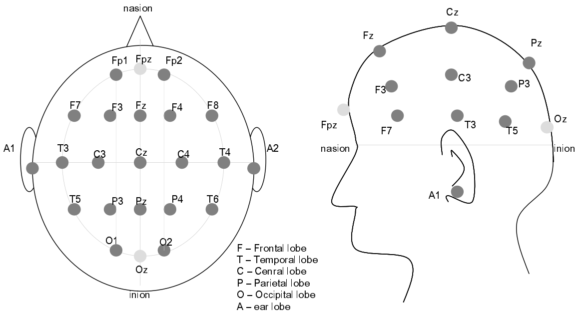

Figure 1. The electrode placements of the international 10-20 system

II. THE EXTENDED EAR TYPE SYSTEM

The ear type system is developed through the data from measurements. Identification of the human physiological systems using artificial neural network architecture is applied for deriving the mathematical representation of the ear type system. With its structure as a basis for other types of network architectures, we adapt and modify the recurrent nonlinear artificial neural network of the continuous time state space form to model the ear type system. The mathematically representative extended ear type system to multiple signals are expressed as

$$\mathbf{E}(d\mathbf{x}(t)/dt) = \mathbf{A}\mathbf{v}(t) + \mathbf{G} + \mathbf{B}\mathbf{u}(t) \tag{1}$$

$$\mathbf{v}(t) = \mathbf{f}(\mathbf{x}(t)) \tag{2}$$

$$\mathbf{y}(t) = [y_1(t)\ y_2(t)\ \ldots\ y_m(t)]^T = \mathbf{C}\mathbf{v}(t) + \mathbf{k} \tag{3}$$

where $\mathbf{u}(t)$ are the inputs and $\mathbf{y}(t)$ are the outputs of corresponding signals. For example, the input signals $\mathbf{u}(t)$ =

$[u_1(t)\ u_2(t)]^T$ where $u_1(t)$ is a 1-vector stimulus to a right ear, $u_2(t)$ is a 1-vector stimulus to a left ear, and $\mathbf{y}(t) = [y_1(t)\ y_2(t)\ \ldots\ y_m(t)]^T$ are the outputs from each of the m recording channels analyzed. The system variables and parameters are accordingly defined where $\mathbf{x}(t)$ is an internal state type n×1 column vector, $\mathbf{E}$ is a diagonal n×n matrix with diagonal entries equal to a constant e, $\mathbf{A}$ is a constant n×n weight matrix, $\mathbf{G}$ is a constant n×1 column bias vector, $\mathbf{B}$ is a constant n×2 matrix, $\mathbf{C}$ is a constant m×n matrix, and $\mathbf{k}$ are any output biases. All quantities are assumed real. The nonlinear activation function, $\mathbf{f}(.)$, is a hyperbolic tangent.

The estimation of system parameters becomes an optimization problem for which the numerical algorithms suitable for identification of a nonlinear system, such as the nonlinear least square algorithms [6], can be utilized. Basically the estimation begins with an initial choice of parameter values from which the iterative trainings are applied so as to minimize the error between signals from measurements and model simulations; error = $(1/N)\sum(y_{\mathrm{measured}}(t_i)-y_{\mathrm{modeled}}(t_i))^T(y_{\mathrm{measured}}(t_i)-y_{\mathrm{modeled}}(t_i))$ where N is the total number of signal points.

III. CLINICAL APPLICATION

The system can be used to characterize an individual with both normal and impaired hearing function. Deviation from normal activities and possible disorders of the auditory system can be identified and exhibited in the developed system. As such it can be found useful in alleviating and treating the effects from the auditory loss and other pertinent dysfunctions as well. For example, tinnitus which is the ringing of sound in the ear is believed to be likely generated from mechanisms of the auditory nervous system inside the brain rather than from those of the inner ear [7]. These signals measured from various points on the scalp can be utilized to determine the characteristics of abnormal behaviors resulting from the tinnitus for which the noninvasive device to control these unwanted effects can be set up and applied to cancel and correct them in a similar way to a current treatment utilizing the masking sound and/or the electrical and magnetic brain stimulation to reduce and suppress the tinnitus sound [8]-[10]. A development of a hearing aid type device where the inverse term used for cancellation of any detected responses with abnormal characteristics can also be implemented. Since the standard hearing test and the prescription of the conventional hearing aid with the standard pure tone audiogram require decision making and subjective responses back from the patients, it can be hard and even impossible in cases of children and infants. The increased uses of these auditory evoked potentials for evaluation of conventional hearing aids also show promising results [11]. These cortical responses can give a good assessment of underlying mechanism and function of the auditory nervous system deeper along the auditory pathway which is likely to be associated with speech perception of the brain from which the alternate improved assistive device can be developed.

Since the extended ear type system can be used to identify the differences of characteristics, a system that is inverse to the ear type system characterizing the abnormal hearing function and characteristics exhibited through the measured responses can be derived for which the control signal that makes these two system to cancel is obtained. As a result, the unwanted abnormal characteristics can be cancelled out. The way to apply these applications can be constructed using the derived inverse system following the sufficient conditions of the invertibility of the nonlinear system [12] of a general state space form with equal inputs and outputs which can accordingly be modified to be applicable for our extended ear type system. In order to obtain the inverse system whose outputs are equivalent to the inputs of the original system, the method makes use of the outputs from the original system and their derivatives. From the extended ear type system of (1)-(3), the differentiation of (3) gives

$$\begin{aligned}\mathbf{y}'(t) = [y_1'(t)\ldots y_m'(t)]^T &= \mathbf{C}\mathbf{v}'(t)\\ &= \mathbf{C}[d\mathbf{f}_{\mathbf{x}}\mathbf{I}](d\mathbf{x}(t)/dt) \qquad (4).\end{aligned}$$

Substituting (1) in (4) yields

$$\mathbf{y}'(t) = \mathbf{C}[d\mathbf{f}_{\mathbf{x}}\mathbf{I}]\mathbf{E}^{-1}\mathbf{A}\mathbf{f}(\mathbf{x}(t))+\mathbf{C}[d\mathbf{f}_{\mathbf{x}}\mathbf{I}]\mathbf{E}^{-1}\mathbf{G}+\mathbf{C}[d\mathbf{f}_{\mathbf{x}}\mathbf{I}]\mathbf{E}^{-1}\mathbf{B}[\mathbf{u}(t)]^T \quad (5)$$

where $\mathbf{E} = [e\times\mathbf{I}]$ so $\mathbf{E}^{-1} = [1/e\times\mathbf{I}]$ is a nonsingular matrix, $d\mathbf{f}_x$ is $d\mathbf{f}(x_i)/dx_i$, and all the coefficients are those of (1)-(3). Unlike the case of a single input single output ear type system for which a term $\mathbf{C}[d\mathbf{f}_{\mathbf{x}}\mathbf{I}]\mathbf{E}^{-1}\mathbf{B}$ is a nonsingular product such that its reciprocal product exists and for which the inverse system can be straightforwardly derived, the term $\mathbf{C}[d\mathbf{f}_{\mathbf{x}}\mathbf{I}]\mathbf{E}^{-1}\mathbf{B}$ in the case of multiple inputs and outputs is equal to a m×p matrix where m is the number of outputs, $m > 1$, and p is the numbers of inputs which is equal to 1 for monaural or 2 for binaural stimulations, such as those expressed in (1). The matrix $\mathbf{C}[d\mathbf{f}_{\mathbf{x}}\mathbf{I}]\mathbf{E}^{-1}\mathbf{B}$ of the extended ear type system has a full rank which is equal to the number of inputs in our case, so its inverse can be calculated for which it has the two-sided inverse when $m = p$ or the left inverse when $m > p$ [13]. The left inverse of $\mathbf{C}[d\mathbf{f}_{\mathbf{x}}\mathbf{I}]\mathbf{E}^{-1}\mathbf{B}$ is expressed as

$$\begin{aligned}\mathbf{H}(\mathbf{x}) &= (\mathbf{C}[d\mathbf{f}_{\mathbf{x}}\mathbf{I}]\mathbf{E}^{-1}\mathbf{B})^{\dagger}\\ &= ((\mathbf{C}[d\mathbf{f}_{\mathbf{x}}\mathbf{I}]\mathbf{E}^{-1}\mathbf{B})^T(\mathbf{C}[d\mathbf{f}_{\mathbf{x}}\mathbf{I}]\mathbf{E}^{-1}\mathbf{B}))^{-1}(\mathbf{C}[d\mathbf{f}_{\mathbf{x}}\mathbf{I}]\mathbf{E}^{-1}\mathbf{B})^T \quad (6)\end{aligned}$$

where $\mathbf{H}(\mathbf{x})$ results as a p×m matrix with $\mathbf{H}(\mathbf{x})\mathbf{C}[d\mathbf{f}_{\mathbf{x}}\mathbf{I}]\mathbf{E}^{-1}\mathbf{B} = \mathbf{I}_{p\times p}$. By substituting (6) in (5), it is therefore possible to obtain $\mathbf{u}(t)$ defined uniquely by the outputs, $\mathbf{y}(t)$, their derivatives, $\mathbf{y}'(t)$, and the internal state $\mathbf{x}(t)$. The system that is an inverse of the extended ear type system can then be represented as

$$\mathbf{E}_{\mathbf{inv}}(d\mathbf{x}_{\mathbf{inv}}(t)/dt) = \mathbf{A}_{\mathbf{inv}}\mathbf{v}_{\mathbf{inv}}(t) + \mathbf{G}_{\mathbf{inv}} + \mathbf{B}_{\mathbf{inv}}\mathbf{u}_{\mathbf{inv}}(t) \quad (7)$$

$$\mathbf{v}_{\mathbf{inv}}(t) = f(\mathbf{x}_{\mathbf{inv}}(t)) \quad (8)$$

$$\mathbf{y}_{\mathbf{inv}}(t) = \mathbf{C}_{\mathbf{inv}}\mathbf{v}_{\mathbf{inv}}(t) + \mathbf{G}_{\mathbf{inv}} + \mathbf{D}_{\mathbf{inv}}\mathbf{u}_{\mathbf{inv}}(t) \quad (9)$$

where $\mathbf{E}_{\mathbf{inv}} = \mathbf{E}$, $\mathbf{A}_{\mathbf{inv}} = \mathbf{A} - \mathbf{B}\mathbf{H}(\mathbf{x})\mathbf{C}[d\mathbf{f}_{\mathbf{x}}\mathbf{I}]\mathbf{E}^{-1}\mathbf{A}$, $\mathbf{G}_{\mathbf{inv}} = \mathbf{G} - \mathbf{B}\mathbf{H}(\mathbf{x})\mathbf{C}[d\mathbf{f}_{\mathbf{x}}\mathbf{I}]\mathbf{E}^{-1}\mathbf{G}$, $\mathbf{B}_{\mathbf{inv}} = \mathbf{B}\mathbf{H}(\mathbf{x})$, $\mathbf{C}_{\mathbf{inv}} = -\mathbf{H}(\mathbf{x})\mathbf{C}[d\mathbf{f}_{\mathbf{x}}\mathbf{I}]\mathbf{E}^{-1}\mathbf{A}$, $\mathbf{G}_{\mathbf{inv}} = -\mathbf{H}(\mathbf{x})\mathbf{C}[d\mathbf{f}_{\mathbf{x}}\mathbf{I}]\mathbf{E}^{-1}\mathbf{G}$, and $\mathbf{D}_{\mathbf{inv}} = \mathbf{H}(\mathbf{x})$. Given $\mathbf{u}_{\mathbf{inv}}(t) = \mathbf{y}'(t) = [y_1'(t)\ldots y_m'(t)]^T$ where $y(t)$ is the output to the extended ear type system of (1)-(3) from the input $\mathbf{u}(t)$ which can be equal to $[u_1(t)]$ or $[u_1(t)\ u_2(t)]^T$, the inverse system of (7)-(9) consequently yields its output $\mathbf{y}_{\mathbf{inv}}(t)$ equal to $\mathbf{u}(t)$, $\mathbf{y}_{\mathbf{inv}}(t) = \mathbf{u}(t)$. Since the dynamical nonlinear continuous time state space of the form utilized for the extended ear type system has a term $\mathbf{C}[d\mathbf{f}_{\mathbf{x}}\mathbf{I}]\mathbf{E}^{-1}\mathbf{B}$ whose rows are independent, the inverse system can generally be derived and defined only by the first derivatives of the outputs from the original system. The control signal for the invertibility of these two systems can conveniently be achieved from the available input-output signals from which the identity output is given in theoretic result and possibly with some delay in a practical hardware which will be further investigated.

IV. SYSTEM EXAMPLE

The example is given on the extended ear type system developed through the auditory brainstem responses (ABRs) measured in a two channel recording as shown in Fig. 2. The ipsilateral (same sided to the tested ear) and contralateral (opposite sided) ABRs are simultaneously measured with the click stimulus in one ear. The common noninverting electrodes are placed at Fz and the two inverting electrodes are placed at the ipsilateral and contralateral mastoids. The ABRs show normal characteristics and latencies of waves within normative limits of adults with normal hearing as shown in Fig. 3. The extended ear type system is set up through these signals using (1)-(3) in which the input $\mathbf{u}(t) = u(t)$ and the output $\mathbf{y}(t) = [y_1(t)\ y_2(t)]^T$ are applied in this case example. The system identification is carried out using the nonlinear least square methods in [6] to find the system orders and parameters. The algorithm is continued toward finding the optimum set of parameters until the criteria for stopping is met which can be that the mean square error is within a given limit or no further significant improvement is achieved. Here the final mean square error is equal to 2.5e-5. The number of signal points used is 2048. The model of the extended ear type system is given in Fig. 5. The developed extended ear type system is able to simulate the responses as presented in Fig. 4. which agree reasonably well with the referenced ABRs of Fig. 3. The system can capture the overall waveform and important waves which shows the possibility of the developed system for identification of neural activities inside the auditory system.

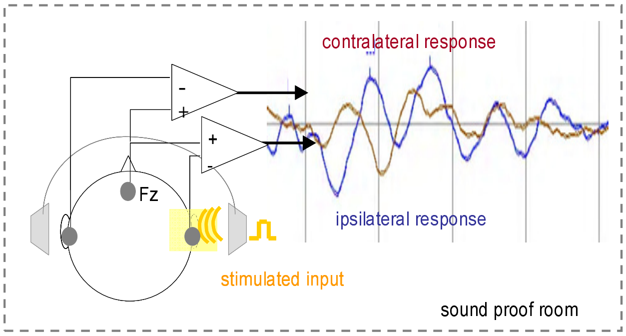

Figure 2. A two channel measurement of ABRs

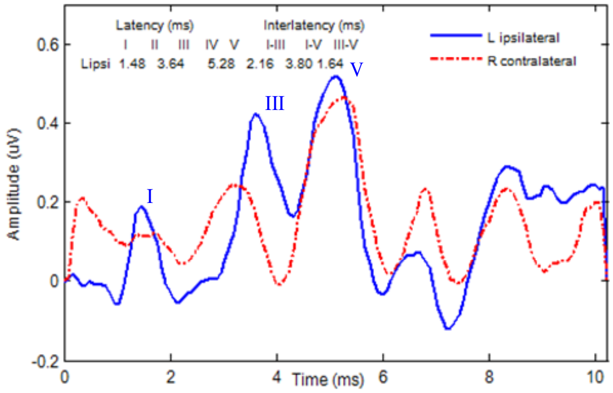

Figure 3. The ABRs from two channel measurement of Fig. 2

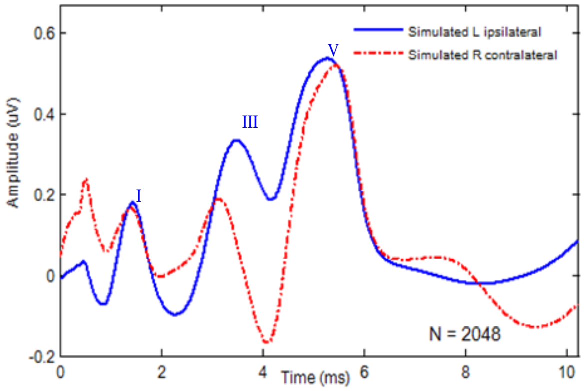

Figure 4. The two sided ABRs in the two channel recording with the stimulus in one ear simulated from the model of extended ear type system of Fig. 5.

V. CONCLUSIONS

The paper presents the ear type system extendable for multiple inputs and outputs for which the human auditory system can be characterized through the multichannel recordings of the auditory evoked potential responses. By using the multichannel recordings measured by multiple electrodes placed on the scalp, additional activities of neurons within the auditory pathway can be accounted for and mechanisms of the underlying areas of the brain giving rise to the detected responses can also be assessed which make these measured auditory evoked potential responses more useful in the diagnosis of auditory loss and disorder. The objective evaluation of the hearing function and sound perception is made possible. The extended ear type system developed and set up using the modified recurrent neural network can therefore be found useful assisting in noninvasive compensation and alleviation of some auditory loss and disorder.

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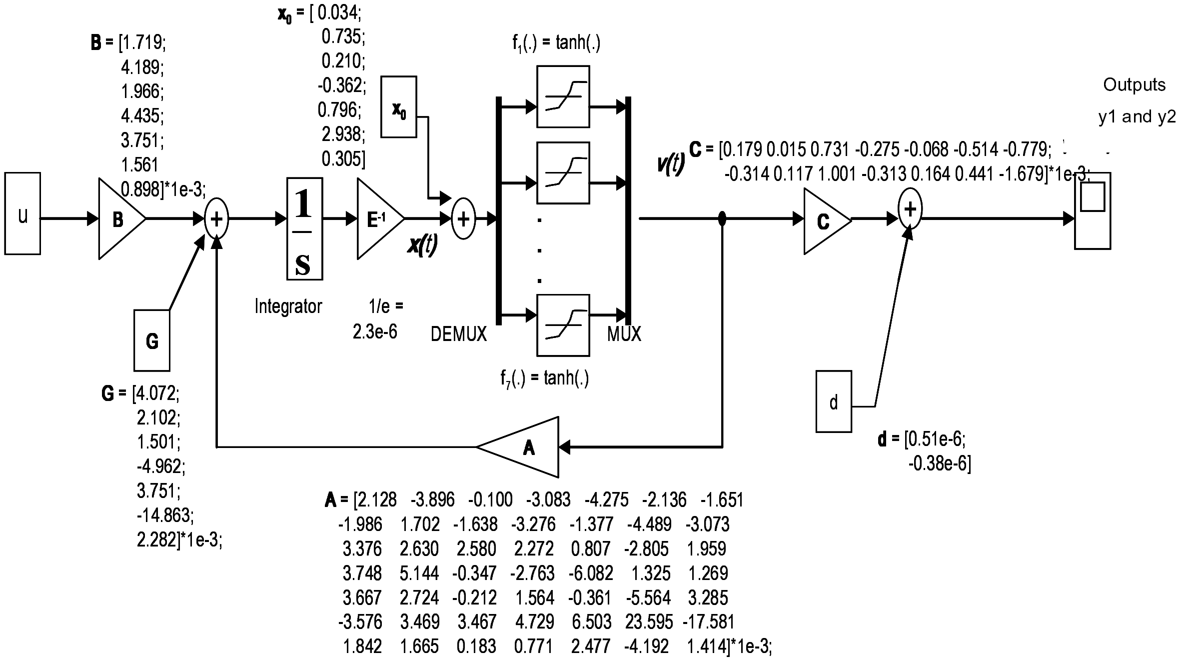

Figure 5. The Simulink model of the extended ear type system illustrative case of the two channel recording of ABRs