Inhibition of Oscillation in a Plastic Neural Network Model of Tinnitus Therapy Using Noise Stimulus

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ABSTRACT

Tinnitus is the perception of phantom sounds in the ears or in the head. Accordingly sound therapy for tinnitus has been used. To account for mechanisms of tinnitus generation and the clinical effects of sound therapies from the viewpoint of neural engineering, we have proposed a plastic neural network model for the human auditory system. We found that this model has a bistable state, i.e., a stable oscillatory state and a stable equilibrium (non-oscillatory) state coexist at a certain parameter region. This paper describes inhibition of the oscillation for various kinds of noise stimuli, because noise stimuli are presented to tinnitus sufferers for therapeutic purposes. Through several numerical simulations it was shown that noise stimulus can inhibit the oscillation (similar to residual inhibition as seen in clinical studies), however, the oscillation is not inhibited in all cases, i.e., the effect of inhibition is not pervasive as in the case of inhibition in clinical cases.

Keywords: Plastic neural model, inhibition, oscillation, tinnitus therapy, noise stimuli

I. Introduction

Tinnitus is the perception of phantom sounds in the ears or in the head. A mechanism of tinnitus generation has been hypothesized from the viewpoint of general neurophysiology[1]. Accordingly, there are two typical sound therapy techniques where those who suffer from tinnitus listen to these therapeutic sounds for several hours a day[2]: TM (Tinnitus Masking) technique and TRT (Tinnitus Retraining Therapy). White noise or spectrum modified white noise are introduced to tinnitus sufferers as therapeutic sound. These sounds are usually presented via a custom-made noise generator or a tinnitus masker. The sound therapies have the clinical effect that the sufferers temporarily stop perceiving tinnitus after the treatment. This cessation of tinnitus following the presentation of a masking stimulus is referred to as residual inhibition.

The purpose of our study is to explain mechanisms of tinnitus generation and the clinical effect of the sound therapies from the viewpoint of neural engineering. Accrodingly we have proposed a plastic neural network model for the human auditory system[3]. Our team previously reported that an oscillatory state and an equilibrium (non-oscillatory) state coexist at a certain parameter region. It was shown that the oscillatory state is inhibited into the equilibrium by supplying sinusoidal stimulus[4], [5]. By hypothesizing that the oscillation and the equilibrium correspond to generation and inhibition of tinnitus, respectively, we reported that these phenomena could explain the fact that the habituated human auditory system temporarily halts perception of tinnitus following sound therapy.

The current paper describe inhibition of the oscillation in the proposed model using a variety of noise stimuli as therapeutic sound. In the tinnitus clinics across the globe, similar noise stimuli have been employed for treatment of tinnitus.

II. Model description

The human auditory system has a peripheral nervous system and a central nervous system. Hair cells at the cochlea are in the peripheral nervous system and transform acoustic vibrations received by the ear into neural signals. The cerebral limbic system receives the auditory signals that have travelled via the hearing nerve to the cochlear nucleus, the superior olivary complex, the inferior colliculus, the medical geniculate body, and the auditory cortex; and subsequently the brain perceives the neural signals as sound. When cochlear dysfunction occurs, abnormal neural signals from the cochlea causes abnormality in the central nervous system. Consequently, tinnitus can be triggered. In addition to ascending pathway, the cochlear nucleus complex receives descending efferent fiber bundles to control[6].

We have proposed a conceptual neural network model to account for tinnitus generation and its inhibition from the viewpoint of neural engineering[3]. Figure 1 shows the proposed neural network model of the human auditory system. The hair cells are represented by an aggregate of excitatory neurons "E_1". This has an incoming signal, S, which is associated with a sound signal. The central auditory pathway is simply represented as a neural oscillator which consists of an aggregate of excitatory neurons and an aggregate of inhibitory neurons: "E_2" and "I". The neural coupling from the j-th aggregate to the i-th aggregate is expressed by the positive constant C_{ij}, $(i, j \in \{1, 2, I\})$. However, from the fact the efferent auditory pathway controls the sensitivity of outer hair cells[6], we assume that the coupling from E_2 to E_1 is plastic, i.e., C_{12} is one of variables. Then the dynamics of the model is described by

$$\frac{dx_1}{dt} = \left(-x_1 + C_{12}Z_2 + S\right)/\tau_1 \qquad (1)$$

$$\frac{dx_2}{dt} = \left(-x_2 + C_{21}Z_1 - C_{2I}Z_i\right)/\tau_2 \qquad (2)$$

$$\frac{dx_I}{dt} = \left(-x_I + C_{I2}Z_2\right)/\tau_I \qquad (3)$$

$$\frac{dC_{12}}{dt} = \left(-C_{12} + bZ_1Z_2 + C_0\right)/\tau_c \qquad (4)$$

where z_j is the output of the j-th aggregate, which is given by

$$z_j = (2/\pi)\tan^{-1}(x_j). \qquad (5)$$

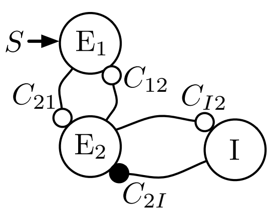


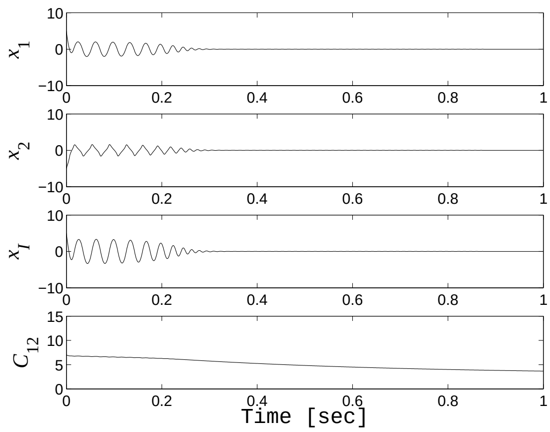
Fig. 1. A neural network model on the human auditory system

The x_j and τ_j are the membrane potential and the time constant of the j-th aggregate, respectively. The C_0, b, and τ_c are also positive constants which denote the equilibrium of C_{12} under $z_1z_2 = 0$, the efficiency of strengthening the synaptic coupling based on Hebb's hypothesis[7], and the time constant of C_{12}, respectively.

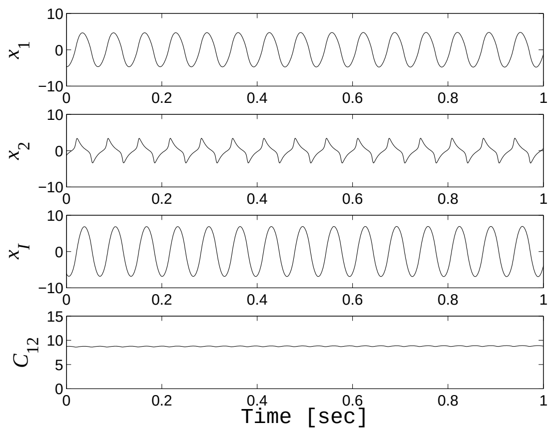
III. Numerical results

A. Oscillation and non-oscillation

We fixed the parameters in Eqs.(1)–(4) such that τ_1=0.01, τ_2=0.01, τ_I=0.02, τ_c=0.5, C_{21}=10, C_{2I}=10, C_{I2}=20, C_0=3.0, and b=20. We can easily find an equilibrium point in the dynamical system: (x_1, x_2, x_I, C_{12})=(0, 0, 0, 3). Figure 2(a) shows the behavior of a solution which starts at the initial point (x_1, x_2, x_I, C_{12})=(5, −5, 5, 7). This point is at the vicinity of the equilibrium point. The behavior eventually converges to the equilibrium point, i.e., the stable state according to the Lyapunov stability theory. On the other hand, we illustrate the behavior of another solution in Fig. 2(b); its initial point is



(a) Non-oscillatory state



(b) Oscillatory state

Fig. 2. Non-oscillatory state and oscillatory state observed under the same parameters

(x_1, x_2, x_I, C_{12})=(-5, -1, -6, 9), which is far away from the equilibrium point. As a result, the behavior converges to the oscillatory state, and its fundamental frequency is about 15Hz. Through other simulations we observed that the behavior converges to the oscillatory state whenever the initial values are arranged at any point at the vicinity. Therefore, the oscillatory state is stable, and the model has the bistable state under the same parameters. In this paper we hypothesize that the oscillation and the non-oscillation correspond to the state of perceiving tinnitus and disappearance of tinnitus, respectively.

B. Inhibition of oscillation by external stimulus

1) Sinusoidal stimulus: Previously, our team reported that the oscillation can be inhibited by supplying adequate sinusoidal stimulus[4]. Figure 3 shows an instance for inhibiting the oscillation by sinusoidal stimulus, which is $S = 2\sqrt{2}\sin 20\pi t$, for the duration of $2 \leq t \leq 8$. The value of the amplitude was fixed so that the RMS (Root Mean Square) value of the stimulus is 2.0. The left column figures show the waveforms of x_1, x_2, x_I, C_{12}, and S, respectively; and their power spectra is illustrated at the right column figures, respectively.

From the point of applying stimulus the value of C_{12} gradually reduces, and consequently the oscillation is inhibited. Note that the oscillation is accordingly inhibited under the same provided duration and the same parameters for sinusoidal stimulus. By hypothesizing that the decrement of C_{12} corresponds to the habituation of the human auditory system for tinnitus, the phenomenon could explain the fact that the habituated human auditory system temporarily inhibits perception of tinnitus after sound therapy.

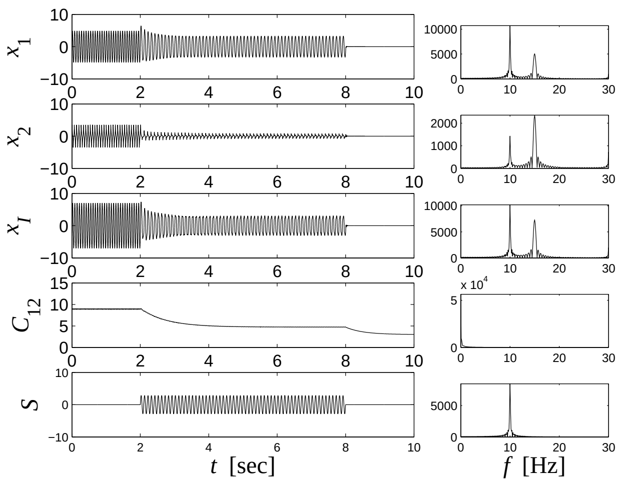
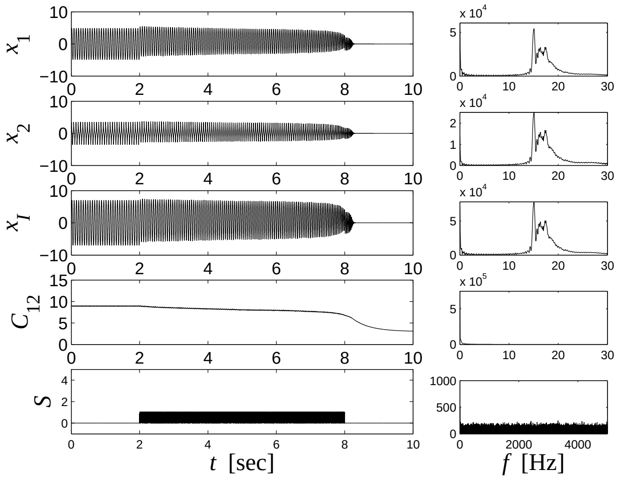
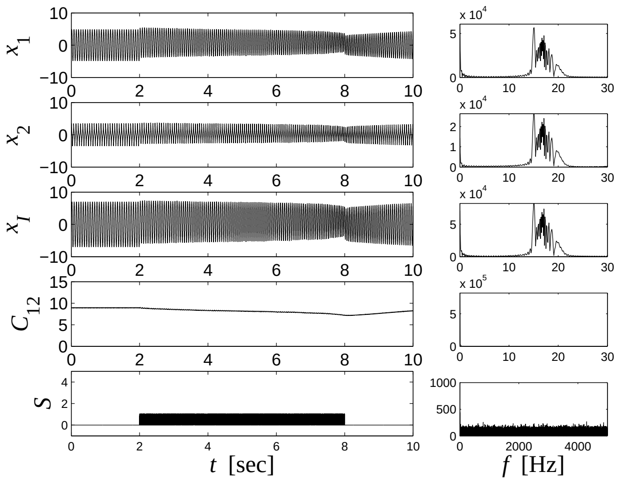


Fig. 3. Inhibition of oscillation by sinusoidal stimulus

2) Additive uniform noise stimulus: We investigated inhibition of the oscillation using additive uniform noise stimulus. Its RMS was fixed in the range of 0.6 ± 0.001 for the duration of $2 \leq t \leq 8$. Figure 4(a) shows a successful result for inhibition of the oscillation. The value of C_{12} rapidly reduces



(a) A successful result

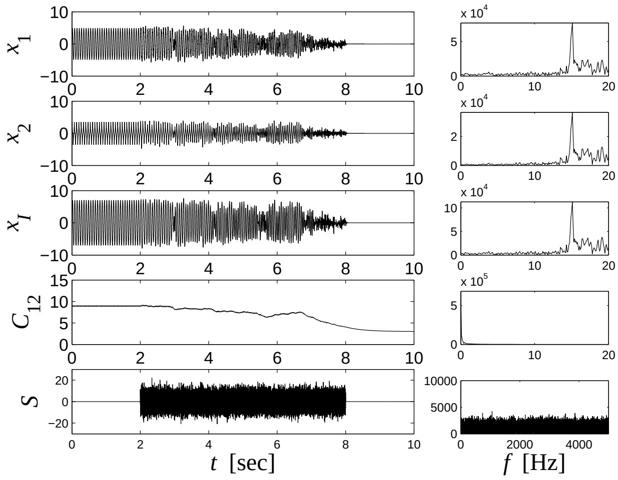


(b) An unsuccessful result

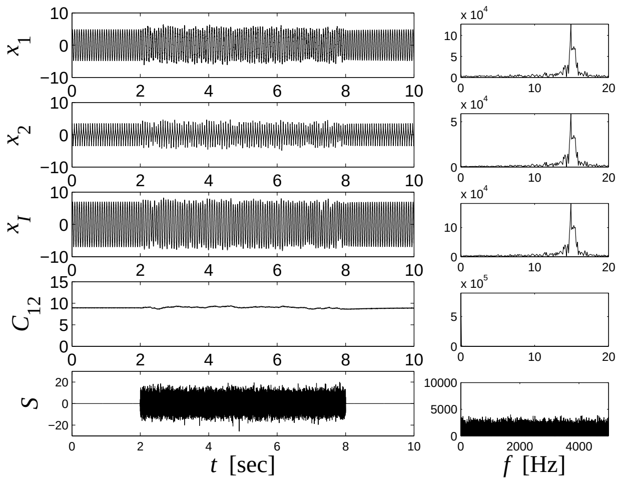
Fig. 4. Inhibition of oscillation by additive uniform noise stimulus

after approximately at $t = 7$, and consequently the oscillation gradually diminishes. On the other hand, Fig. 4(b) shows an instance for which the oscillation cannot be inhibited despite of the same condition. Thus, the additive uniform noise stimulus cannot necessarily inhibit the oscillation at all conditions.

3) Gaussian white noise stimulus: White noise stimulus is commonly used in TRT[2]. Let us add Gaussian white noise with an RMS adjusted in the range of 5.0 ± 0.001 for the duration of $2 \leq t \leq 8$. We obtained two simulation results as seen in figure 5. Figure 5(a) shows a result where the oscillatory states are inhibited; it was also observed that the value of C_{12} gradually decreases after supplying the stimulus. On the contrary, Fig. 5(b) shows an unsuccessful result in spite of the introduction of Gaussian white which is generated under the same condition. The value of C_{12} is almost unchanged during the stimulus presentation, and consequently the oscillatory state continues through the simulation. Therefore, inhibition effect by Gaussian white noise stimulus is possible.



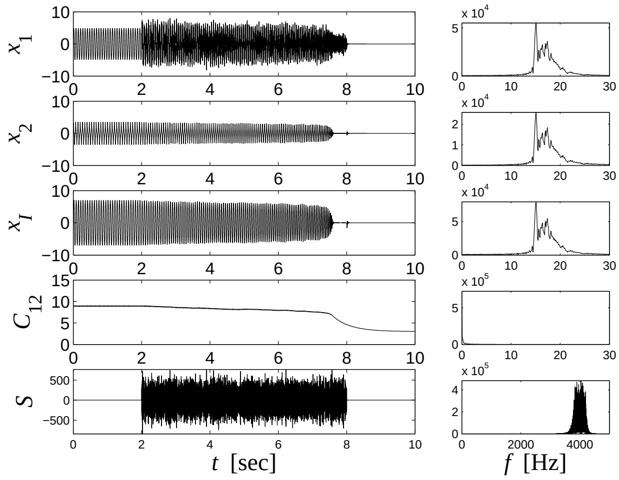
(a) A successful result



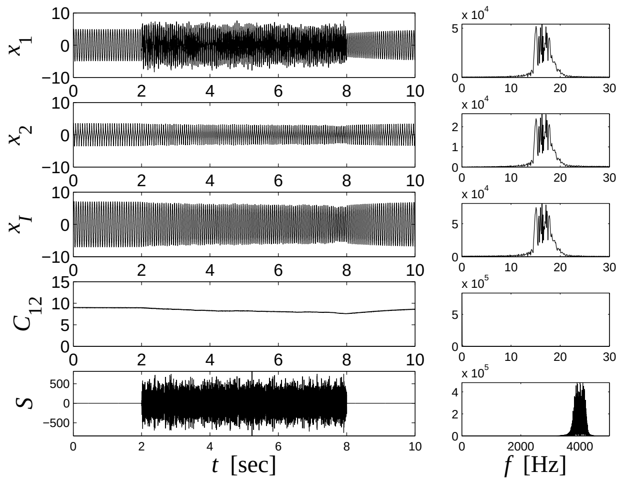
(b) An unsuccessful result

Fig. 5. Inhibition of oscillation by Gaussian white noise stimulus

4) Band noise stimulus: Band noise stimulus is also used in treatment of tinnitus using TM approach[2]. In this approach the desired noise is a band of noise with a frequency emphasis that approximates the frequency of perceived tinnitus. The frequency (pitch match) of tinnitus can range from low frequencies to high frequencies in different individuals. Most of the tinnitus sufferers perceive tinnitus at high frequencies between 2–8kHz. In this experiment we hypothesized that the frequency of perceived tinnitus is about 4000Hz and employed a band noise which is generated from Gaussian white noise through a band pass filter which operates between 3800Hz and 4200Hz. As in the case of other noise, we also adjusted its RMS in the range of 200.0 ± 0.2, and the band noise was applied for the duration of $2 \leq t \leq 8$. Figure 6 shows two different results: a successful result and an unsuccessful result for inhibition of the oscillation. It can be noted, as in the case of simulation results for the other noise stimuli, inhibition of the oscillation by band noise stimulus is also possible.



(a) A successful result



(b) An unsuccessful result

Fig. 6. Inhibition of oscillation by band noise stimulus

IV. Conclusion

In this study we demonstrated inhibition of the oscillation in the plastic neural network model using various kinds of noise stimuli: including additive uniform noise, Gaussian white noise, and band noise. Through several numerical simulations we found that all of the noise stimuli can inhibit the oscillation. Therefore, the findings of this experiment could explain the fact that the habituated human auditory system temporarily halts perception of tinnitus following sound therapy using a variety of noise stimuli.

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