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Development of Biological Feedback Model for the Analysis of Physiological Homeostasis

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ABSTRACT*:* in this paper, a comprehensive model of a biological feedback system is proposed. It adopts a new approach to modeling. This model incorporates input from sensory organs and a transduction phase mediated through catecholamine production in the feedback path. The features of physiological homeostasis are represented in this comprehensive model, which is based on catecholamine activation. It is not easy to obtain a dynamic response that reflects dependence on hormone production. So a great effort is put forth to design an approach that focuses on the internal state of the subject consequent on feedback stimulation.

KEYWORDS: Biological feedback System, Homeostasis, EDR, GSR, EMG, Transduction Phase, Catecholamine's, Adrenergic Receptors, Conservative System.

I. INTRODUCTION

A biological feedback system involves a sensory organ and an appropriate stimulus. The stimulus is mediated through organs derived from specific biosensors [2-8]. If a subject has disorders involving parenchymal lesions, his or her internal state is likely to indicate exhaustion, as evident from output responses in a conservative system. Thus, it is or may be possible to establish the internal state of the subject from the output responses. The model described in this paper has been developed primarily with a focus on the galvanic skin response (GSR) in biofeedback [9]; galvanic skin response training is also known as the electro dermal response (EDR). The device measures electrical conductance in the skin, which is associated with the activity of the sweat glands [9,10]. Sweat gland activity is due to catecholamine secretion resulting from the stimulation of adrenergic receptors The GSR in a biofeedback system is caused by a stimulus that activates the sweat glands. This activation can be indicated by recording bio-potentials by placing the electrodes on the body surface. The instrumentation for recording consists of a set of amplifiers and filters designed for the purpose [9, 10]

II. NEED OF BIOLOGICAL FEEDBACK

Biological feedback systems are purported to alert a patient or individual to potential problems in his or her body that may not normally be noticeable. These systems typically use special sensors, such as electrodes or thermometers, to detect the automatic processes at work. This equipment may alert the individual of changes or happenings by some sensory cue, such as a flashing light or a beep. For example, a light may blink whenever a heart beats on a heart-monitoring machine.

A biofeedback system may also help an individual to consciously alter the problem area, simply because he or she is aware of it. Many of these systems train people in relaxation techniques, such as deep breathing and meditation, because patients who are alerted to irregular body functions by a biofeedback system may work to alter responses. An individual who utilizes these relaxation methods while being monitored by the machine may be able both to track and to promote positive change to the problem area.

Clinical feedback techniques that have grown out of the early laboratory procedures are now widely used to treat an ever-lengthening list of conditions such as the following.

Migraine headaches, tension headaches, and many other types of pain Disorders of the digestive system

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- High blood pressure and low blood pressure
- Cardiac arrhythmias
- Paralysis and other movement disorders
- Epilepsy
- Raynaud's disease (a circulatory disorder that causes uncomfortably cold hands)

III. CURRENT TECHNOLOGY

There are many types of machines used in biological feedback therapy, and each feedback system typically targets a different set of stress indicators. An example of this is the electromyography (EMG). An EMG senses muscle tension using electrodes that detect the level of muscle activity. Many practitioners use EMGs to detect tension in facial, neck, or shoulder muscles which may indicate stress. Others may use EMG in biofeedback therapy to assist people with paralysis, migraines, and cluster headaches.

A feedback thermometer is another type of biological feedback machine. It detects changes in the skin's temperature, typically in the fingers or feet. A drop in temperature at these areas may be associated with an increased level of stress because blood is diverted to the muscles and internal organs. This system may also be helpful in treating circulatory diseases, such as Raynaud's disease.

An electro dermal response (EDR) indicator is another piece of biological feedback equipment. This machine measures the productivity of the sweat glands by detecting changes in the electrical conductivity of the skin, or dermis. Periods of stress or high emotion are often accompanied by an increase in sweat. This biofeedback system is often useful for treating anxiety, phobias, and even stress-induced stuttering.

Another major type of biological feedback machine is the electroencephalograph (EEG). This device focuses on changes in brainwaves. With it, the patient is alerted to what brainwaves are working during different states of alertness from wakefulness to deep sleep. Such a system may help the patient promote desired changes in his or her brainwaves at a given time, like helping a person suffering from insomnia to increase the brainwaves present during sleep.

IV. GALVANIC SKIN RESPONSE

Electro dermal Response EDR is actually the medically preferred term for changing of electrical skin resistance due to psychological condition. In GSR the change is caused by the degree to which a person's sweat glands are active. Psychological stress tends to make the glands more active and this lowers the skin's resistance.

The principle or theory behind functioning of galvanic skin response sensor is to measure electrical skin resistance based on sweat produced by the body, when high level of sweating takes place, the electrical skin resistance drops down. A dryer skin records much higher resistance. The galvanic skin response sensor measures the psycho galvanic reflex of the body. Emotions such as excitement, stress, shock, etc. can result in the fluctuation of skin conductivity. Aluminum foil and Lego motor wire form important components of the sensor.

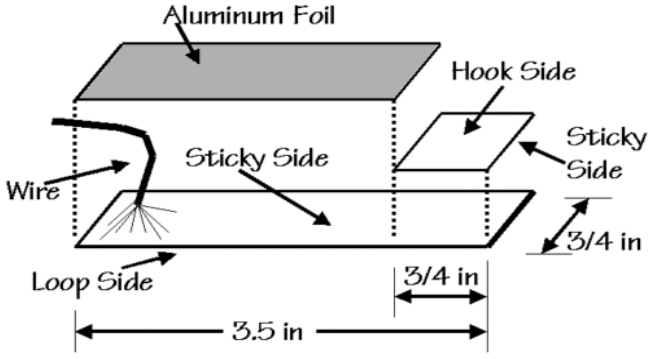

Figure 2: Basic GSR Sensor

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In the galvanic skin response method, conductivity of skin is measured at fingers of the palm. The method can be highly effective and sensitive in gauging emotions. The different applications of galvanic skin response method can be found in treating various dermatological conditions. It is also used in desensitization training and relaxing. The medical condition of excessive sweating is also treated with galvanic skin response. The skin conductance of electrical charge can be classified as Tonic and Phasic skin conductance. Tonic skin conductance rises sharply as the subject being measured wakes up. Level of this type of conductance rises further with stress or other mental activities which are demanding, on the basis of psychological arousal, tonic skin conductance can vary a lot. The responses associated with phasic skin conductance can be observed 1 - 2 seconds after the stimulus has been provided. Skin conductance achieves its peak after about 5 seconds of the stimulus.

V. HOMEOSTASIS AND CONSERVATISM

The ability or tendency of an organism or cell to maintain internal equilibrium by adjusting its physiological processes is called physiological homeostasis.

A. WORKING OF HOMEOSTASIS

In a human being, when the amount of fluid in the extra cellular space begins to decrease below certain fairly specific limits (there is a dynamic range), various ions, chiefly sodium, increase in concentration. Through various routes which have not been fully elaborated, cells in the Hypothalamus react to this with a signal to the pituitary gland which then releases a hormone, anti-diuretic hormone (ADH), which not only causes the kidneys to more efficiently conserve water, but also signals the brain/mind that it is time to seek out some libations. Once the person drinks his fill, the sodium concentration returns to within normal limits and the sensation of thirst fade away. The stomach and mouth react, the blood vessels of the periphery are involved and many other things are affected as well, it is essentially how thirst and fluid regulation work in human. If the dynamic equilibrium cannot be maintained,

The next steps in homeostasis would involve shutting down unnecessary bodily functions. The person would stop sweating, which can then impair temperature regulation. This is followed by more urgent emergency efforts to save electrolytes. The kidneys shut down completely. The "goal" is to maintain the osmotic balance in the brain as long as possible. Once the concentration of Sodium goes too high, the neurons in the brain can no longer function properly, some fire chaotically, leading to seizures, and when enough cells are damaged, death follows.

B. TRANSDUCTION PHASE

The transduction phase of a subject reflects physiological changes caused by hormone release consequent on stimulation. This phase is characteristic of an individual subject [2-7]. For example, the transduction phase of a psychosomatic patient is sometimes reflected during a journey in a high-speed vehicle, when the physiological outcome can adversely affect his mental condition, associated with headache and vomiting.

C. CATECHOLAMINE'S

The brain processes and transmits information through the use of chemical transmitters. Catecholamines are a group of biogenic amines that are neural transmitters, and include dopamine, norepinephrine and epinephrine (adrenaline). Imbalance of catecholamine's can result in autonomic dysfunction.

Catecholamine interactions are very important in biofeedback systems. Catecholamines are excitatory or inhibitory neurotransmitters or hormonal agents. The catecholamine neuron-hormones are epinephrine, norepinephrine, dopamine and serotonin. Epinephrine and norepinephrine function as excitatory hormones. Serotonin functions as an inhibitory hormone, and dopamine is excitatory in some areas and inhibitory in others. Stimulation of sympathetic nerves in the adrenal medullae causes large quantities of epinephrine and norepinephrine to be released into the circulating blood, which carries them to all tissues of the body. Norepinephrine increases the total peripheral resistance and thus elevates the arterial pressure; epinephrine raises the arterial pressure to lesser extent but increases the cardiac output more. Epinephrine has a 5 to 10 times greater metabolic effect than norepinephrine [11].

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D. ADRENERGIC RECEPTORS

The adrenergic receptors include α and β receptors. The α- receptors control such physiological activities as vasoconstriction, iris dilatation, intestinal relaxation, intestinal sphincter contraction, pilomotor contraction and bladder sphincter contraction; β-receptors control (e.g.) vasodilatation, cardio-acceleration, increased myocardial strength, intestinal relaxation, uterus relaxation, bronchi dilatation, calorigenesis, glycogenesis, lipolysis and bladder wall relaxation. It is therefore evident that both α and β receptors have inhibitory and excitatory functions [11]. Blood pressure transduction phases are associated with activation of α and β receptors [4-6].

VI. SYSTEM MODEL AND ITS WORKING

In biological feedback systems, the subject undergoes different transduction phases. Depending on the nature of transduction phase a system can be classified as dissipative or conservative. A dissipative system diverges from its original state during biofeedback; it may undergo successive stages during which the response decreases exponentially, with the characteristic features of a normal physiological system. A conservative system, in contrast, has an output characterized by exponentially rising phases due to sustained levels of catecholamines.

Adrenergic and cholinergic receptors in the autonomic nervous system play opposite roles. De-activation of the sympathetic innervation (which operates via adrenergic receptors) is followed by enhancement of the cholinergic receptors involved in parasympathetic stimulation in smooth muscle. Conversely, noradrenergic enhancement is diminished as cholinergic neurotransmission becomes established [14].

In the model discussed in this paper, the stimulation of adrenergic receptors diminishes concomitantly with blood pressure and pulse-rate (a dissipative system). This diminishing of the adrenergic receptor effect enhances cholinergic receptor activity automatically in the control of smooth muscle function. Similarly, in a conservative system, adrenergic receptor stimulation is enhanced concomitantly with the blood pressure and the pulse rate. This increasing effect of the adrenergic receptors will diminish the effects of cholinergic receptors automatically in the control of smooth muscle activity. Thus, cholinergic receptors automatically operate in conjunction with adrenergic receptors in the autonomic nervous system control of mammalian smooth muscle.

In the paper, emphasis is placed on catecholamine stimulation and a temporal pattern of responses is obtained. It has been established that catecholamine secretion is not only of short duration but also persists for long periods (minutes or even hours) [11]. To take account of this, the authors have designed 1st order and 2nd order systems. In the 1st order system the response decays without oscillation during a short catecholamine secretion phase, whereas the 2nd order system represents a prolonged period marked with oscillation, concomitant with adrenergic stimulation leading to vasoconstriction and vasodilatation.

VII. BIOLOGICAL FEEDBACK MODEL

A comprehensive biofeedback model consists of a brain, homeostatic and transduction phase (Fig.3). The sensory organs are responsible for biofeedback stimulation. Biofeedback stimulates the nervous system concomitantly with homeostatic regulation of the body through hormonal activation.

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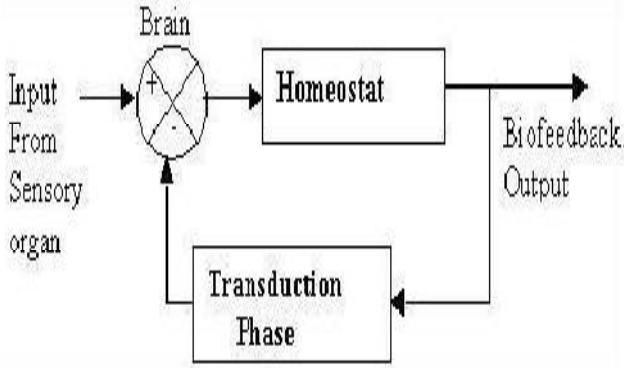

Figure 3. Biofeedback Model

The role of the brain is central, adjusting the system in accordance with the biofeedback stimulus received from the sensory organ. Without the brain there would be no output response. Biofeedback stimulates the subconscious part of the brain, and depends upon the nature of stimulus received from the sensory organ in the subject's particular current environment. Both the conscious and subconscious parts of the brain are important in biofeedback. Dreams during sleep are sometimes responsible for locomotors action evoked through stimulation of subconscious parts of the brain. Here, input stimulus to the biofeedback system is a step function while the homeostatic output response is exponential. The input stimulus may be optical (e.g. flash of light), auditory (e.g. tone), tactile (e.g. a blow to the Achilles tendon), or a direct electrical stimulation of some part of the nervous system.[8] Any sinusoidal or ramp input can be simplified by expressing it as a function of step inputs. For this reason the input is taken as a step. In this particular model, the output responses are of two types: exponential rise and exponential decay. Exponential rise signifies that the system is unable to withstand the biofeedback stimulus, depending on the responses of hemostat. Exponential decay signifies a normal homeostatic response. The homeostatic responses are regulated mainly by the functioning of the kidney and heart in tandem.

A complex biological feedback output with multiple responses is shown in Fig. 3. ΔV is the residual homeostatic output level. In practice, subsequent biofeedback output responses occur, as shown in Fig. 4.

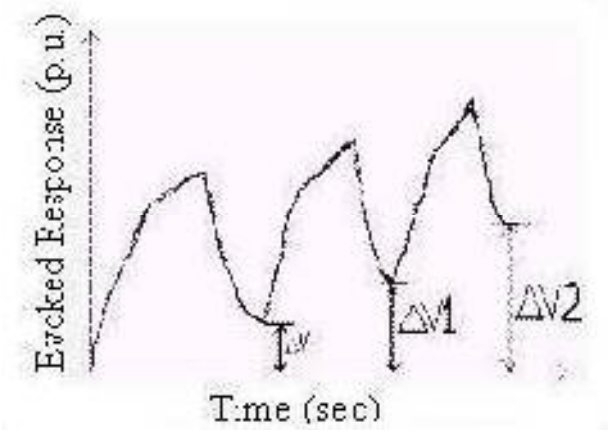

Figure 4: Biological feedback Output with Multiple responses.

The residual homeostatic output level at each stage can sometimes exceed the corresponding value in the previous stage, depending on homeostatic responses.

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A generalized GSR model was chosen. For a step input, the body's feedback output response is identical to that illustrated in Fig 1. The GSR output was simulated using MATLAB 6.0. Different time constants for the rising and decaying phases were considered for simulation within a fixed interval.

A. SINGLE RESPONSE AND MULTIPLE RESPONSE SYSTEM

In a single response system where the input is step and the output exponential, the entire transfer function of the system could be represented by the respective blocks (Fig.5). K1 and K2 are the inverse time constants for the rising and decaying phases of the feedback output respectively; a1 is the peak value of the of the feedback output response.

In certain cases as shown in (Fig. 6) the output is a single response. The values of K1 and K2 are taken as 0.2 and 0.3 and the time periods for the rising and decaying phases are taken as 5s, to correlate with the characteristic GSR response in biofeedback [9].

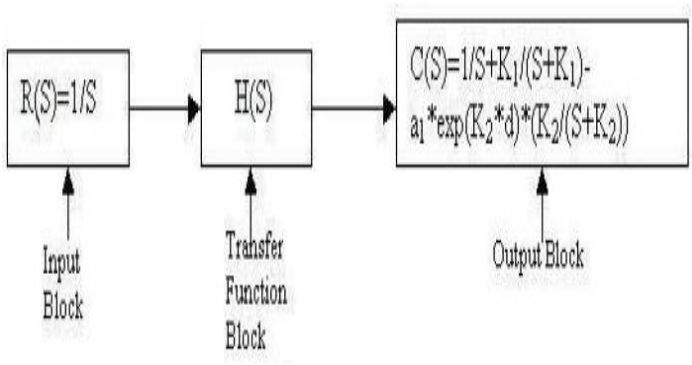

Figure 5: Block diagram representation of biological feedback output with single response.

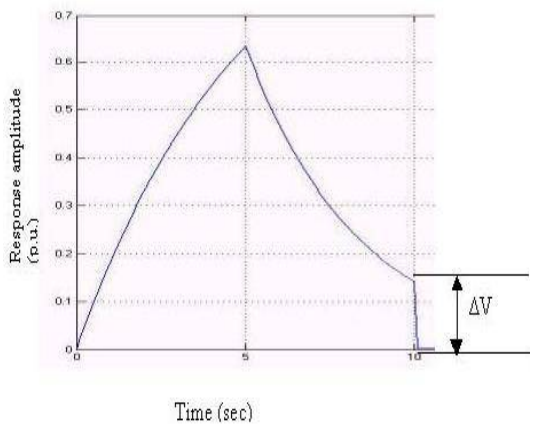

Figure 6: Biological feedback output with single response.

From Fig. 6 the residual homeostatic output level, ΔV, is calculated as 0.142 p.u. Now by keeping K2 fixed change the value of K1 and observe changes in the value of the residual homeostatic output. For i) K1 = 0.2, ΔV = 0.1418 p.u; ii) K1 = 0.25, ΔV = 0.142 p.u; and iii) K1 = 0.15, ΔV = 0.1422 p.u. It can be concluded that the residual homeostatic output level does not depend on the time constant of the rising phase of the biofeedback output response. In a real biofeedback system (in this case GSR), there may be more than one response. In that case the entire transfer function can be represented by a block diagram (Fig. 7).

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With unity feedback the closed loop biofeedback transfer function is given by

$$H(S) = G(S)/(1+G(S)) \quad (1)$$

Where G(S) is the open loop transfer function and the feedback output is given by Fig. 13. Now the whole system can be shown by a block diagram representation in Fig. 8.

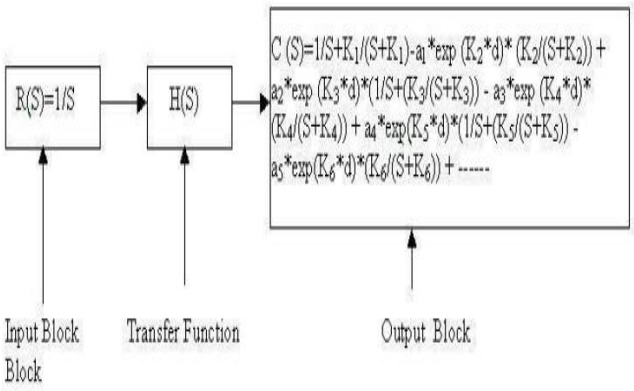

Figure 7: Block diagram representation of biofeedback output with multiple responses.

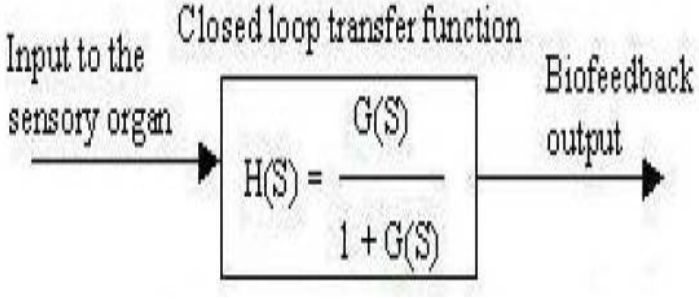

Figure 8: Block diagram representation of closed loop transfer function with unit feedback.

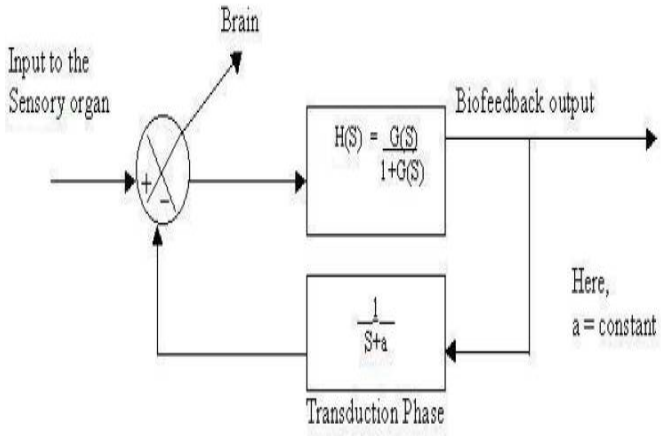

Figure 9: Block diagram representation of system incorporating 1st order transduction phase.

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Here the unit feedback control system is converted into an open loop control system, where the closed loop transfer function becomes an open loop transfer function. The output response when the transduction phase was incorporated into the feedback loop of the feedback system is shown below. The result can again be shown by a block diagram (Fig. 9). In the first order transduction phase, the constant 'a' represents exponential rise or decay during the phase of catecholamine activation [4-6].

VIII. RESULTS AND CONCLUSION

The transduction phase can be either conservative or dissipative. Depending on the nature of the transduction phases, the feedback output of a closed loop model as shown in Fig. 10 will typically show the relevant characteristic responses.

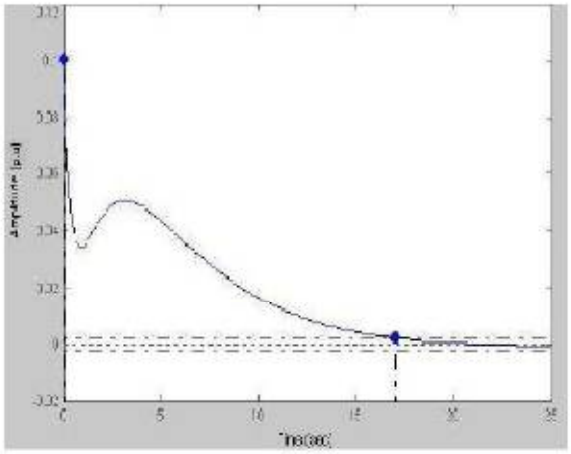

Figure 10: The biofeedback output response when the 1st order transduction phase is incorporated in the feedback loop.

The expression for dissipative and conservative systems due to incorporation of the transduction phase is:

$$Tp(\Phi c) = \Phi c0 \pm \int(\psi c)dt \quad (2)$$

where Φc0 is the initial states of the conservative system, ψc is the time dependent 1st order conservative system. Here, the transduction phase signifies the state of the internal environment of the subject [11]. It reflects the topological asymmetry of cellular organization, which shows a relaxation jump associated with hydrophobic linkages among polar heads [1].

Depending on the state of the subject, homeostasis is perturbed in a conservative system. This is the first order system transduction phase where the value of a is taken as 2 and the output appears as:

In first observation setting peak amplitude = 0.101 p.u and settling time = 17 s from Fig.10 it is observed that the exponentially decaying output phase indicates that the subject returns to the original state within a time frame depending on the duration of the catecholamine signal.

In second observation setting Peak amplitude = 2.41 p.u and damping freq = 0.002463Hz the result is shown below. In third observation setting Peak amplitude = 1.76 p.u and damped frequency = 1/(126-40.7) = 1/85.3 = 0.01172Hz the result is shown below. Below observations represent a subject with a permanent disorder; the feedback stimuli cause the disorder to be manifest. By putting a = 0 the output response can be generated. Here it can be clearly seen that sustained oscillations amplify in a conservative transduction phase due to the prolonged period of catecholamine activation.

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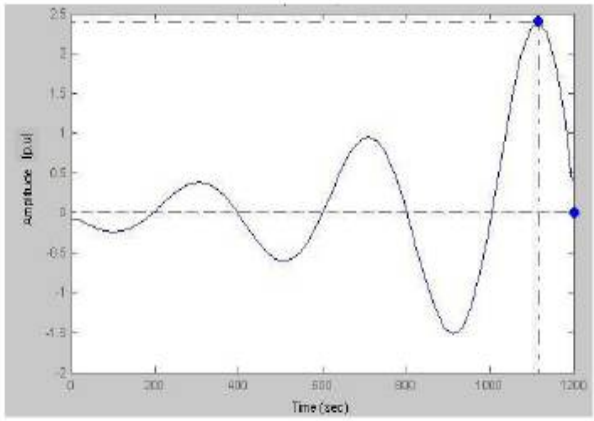

Figure 11: Response amplitude V/S Time

(a = 0.015).

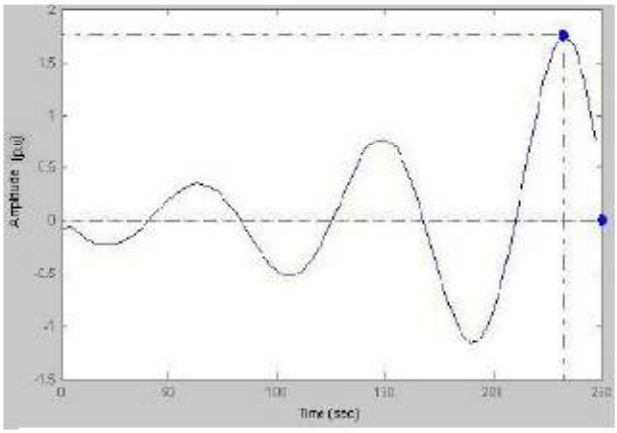

Figure 12: Response V/S Time

(When damping is absent, i.e. a = 0).

The features of conservative systems are represented in this model, which is based on catecholamine activation. For a conservative system the catecholamine signal is of a longer period. Feedback can sometimes produce complex responses in biological systems depending on how sustained the catecholamine signal is; these complexities are represented by the present model.

Adrenergic and cholinergic receptors have opposing roles in the autonomic nervous system. Down regulation of sympathetic innervations via adrenergic receptor is followed by enhancement of the cholinergic receptors involved in parasympathetic stimulation in smooth muscle. Conversely, noradrenergic enhancement is diminished as cholinergic neurotransmission becomes established. Thus it may be concluded that cholinergic receptors automatically participate, along with adrenergic receptors, in the autonomic nervous system control of mammalian smooth muscle function.

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