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Human Heart Stabilization using Mathematical Based Model with Proportional Integral and Derivative Controller

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Abstract: This paper presents human heart stabilization using mathematical based with Proportional Integral and Derivative (PID) controller. In order to improve the Hydro Electromechanical System (HEMS) of human heart models found in prior studies, the present paper introduced a PID model that integrates a low pass filter (F) to give a PIDF that provides control signal to adjust the heartbeat rate if it is disturbed and to command the cardiovascular system. The entire system was built and simulated in MATLAB/Simulink environment. The heartbeat model has been applied for steady state study of cardiovascular system when a disease attacks the heart. The result obtained proves the effectiveness of the developed control strategy. Simulation result revealed that the introduction of the PIDF controller ensured the stabilization of the heart to its right working state when compared to the heartbeat response of normal heartbeat.

Keywords: Heartbeat, Human heart, PID controller, Stabilization

I. Introduction

Cardiovascular disease is a major public health issues which has attracted much concern in the medical field worldwide. It has been reported that almost one third of the deaths worldwide is caused by cardiovascular disease. With physical models available to simulate real physiological data that provide the dynamic expression of heartbeat from Electrocardiogram (ECG), the stabilization of human heart as a Hydro Electromechanical System (HEMS) is possible.

The human health is one of the most important concerns in the world today. Anything or everything becomes meaningless when disease/ anger/anxiety/fear attacks or overwhelms the heart. There are two diseases of the heart and vessels which present a risk to public health associated with high mortality and hospitalizations, and also having direct and indirect economic cost consequences. Cardiovascular disease is a major risk to human heartbeat. This has been a major reason for consultation in health and medical centres. There are physical (mathematical) models that are able to stimulate real physiological data to the appropriate experimental base set up. Hence there is possibility offered by bioengineering wherein medical related diseases are represented using mathematical equations in literature that provides theoretical and practical knowledge of designing and implementing electronic controller (PID controller or Proportional Integral Controller, PIC) for controlling human heartbeat or heartbeat rate through continuous monitoring and control.

In view of the significant function the human heart plays, making an improvement on patient's quality of life, especially the development of an optimized technique for Hydro-electromechanical (HEM) stimulation and regulation of the Human Heart is of essence. This is because the physical models are able to simulate real physiological data to the appropriate experimental base set up [1]. There fore a mathematical model with Hydro Electromechanical System (HEM) parameters described in [1, 2] has been adopted to represent the human heartbeat rate. This paper aims to solve the problem of heartbeat abnormality occasioned by cardiovascular disease, which is a control and stabilization of the human heart as a Hydro Electromechanical System (HEMS). A system is designed for controlling and stabilizing the human heart using a proportional integral and derivative (PID) controller that combines a filter termed (PIDF).

Some studies involving the use of mathematical models with control techniques to stabilize human heart have been developed. The Zeeman nonlinear heart model was adopted to discuss its stability and control its operation using emotional learning control (ELC) in [3]. A feedback control method for stabilizing some pathological behaviours of a nonlinear heartbeat model, with and without additive random noise was carried out by Brandt et al [4]. The study by Aabid et al. [1] stimulates the control and the command of human heart based on three main functions: hydraulic, electrical and mechanical parameters. In the study carried out by Jonathan et al. [5], two-degree of freedom PID (2-DOFPID) was used for stabilization of human heart using mathematical based model. A nonlinear feedback linearization technique is applied to force the output of the systems to generate artificial electrocardiogram

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIII, Issue III, March 2024

(ECG) signal using discrete data as the reference inputs, which is a novel application of nonlinear control theory to heartbeat models [6].

This paper presents an application of nonlinear control system theory – feedback linearization – to the heartbeat systems adopted from the work of Aabid et al. [1] and improve the response performance. This is achieved by developing a PIDF controller instead of the PID controller used in the studied system. The F-component in the controller represents a low pass filter that helps to ensure the stability performance of the PID controller when disturbance enters the system through the derivative component [7]. The proposed system is aimed at stabilizing the human heart when subjected to attack in form of cardiovascular disease.

II. Theoretical Concept

Many electrical mathematical models for the circulatory system have appeared in the literature, but few of them are based on the use of an actual physical model. In order to realize the beat-by-beat dynamic control of the heart, an explanatory model of the behaviour of the heart such as a hydro-electromechanical system is used as shown in Fig.1 [1]. It explain the general function of cardiovascular system, the PIN(t) is the input of the system (pressure input), C_{BL} Right atrium systemic capacitance, C_{CL} Left-atrium systemic capacitance, C_{DL} Right-ventricle systemic capacitance, C_{EL} Left-ventricle systemic capacitance, L_F Ventricle and atrium interaction inductance, L_E Left-ventricle inductance, L_D Right ventricle inductance, L_B Right-atrium inductance, L_C Left-atrium inductance , the right atrium is like a first pump and it's declared on the circuit like a capacitor, the same things go for the left atrium. For the right ventricle it received the pressure coming from the atrium like an input and the same goes for the left one.

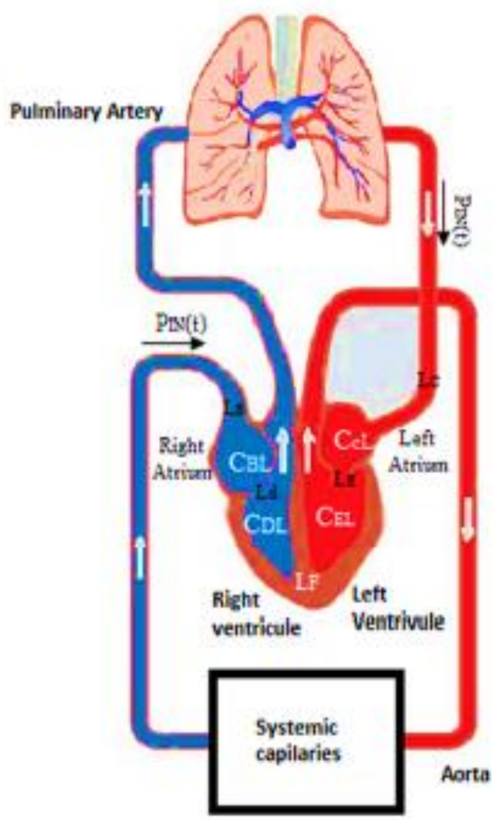

Fig. 1 The Hydro-Electro mecanical behaviour of the System (Aabid et al., 2016)

b) Analysis of Cardiovascular System

There are different electric models of the human heart, partial or complete, with linear or nonlinear models that have been developed [1, 2] in literature. There are some applications of mathematics and physical analogue models total artificial heart (TAH), a baro-

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIII, Issue III, March 2024

receptor model, a state-space model, an electromechanical biventricular model of the heart, and a mathematical model for the artificial generation of signals electrocardiogram (ECG). The normal heartbeat from ECG is shown in Fig. 2.

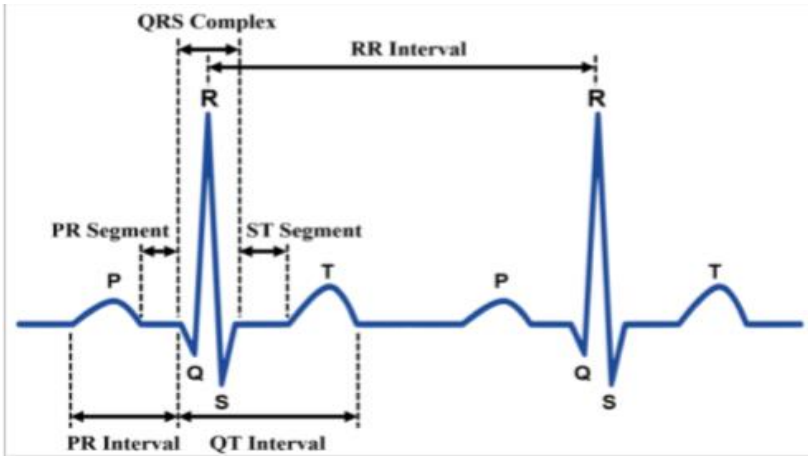

Fig. 2 Normal Heartbeat from ECG [8]

The based model [2] constitutes a significant extension of a mathematical model described in several papers; it explains the electrical and hydraulic model. The main improvements are as follows [1]:

i. TThe heart is described as a hydro-electromechanical pump. To this end, the activity of the ventricles is simulated by an elastic variable model.

ii. Since arterial pressure is pulsatile in nature, a more accurate description of the systemic and pulmonary input impedances is required, valuable also in the mid frequency range. For this reason, the new based model discriminates between large arterial vessels and peripheral arterioles, and includes the inertial effects of blood.

III. System Desing

a) Normal State of the Cardiovascular System

The modelling of a human heart stabilization system considered in this paper is presented considering the following [1, 5]:

For the heart beat:

$$F(s) = \frac{7}{s+32} \qquad (1)$$

For the peacemaker (a medical device that sends electrical impulses to specific parts of heart):

$$G(s) = \frac{40s^2 + 30s + 7}{3s^2 + 0.5s20} \qquad (2)$$

For the circulatory system:

$$P(s) = \frac{3s^2 + 25s + 99}{9s^2 + 0.5s + 10} \qquad (3)$$

For the feedback sensor:

$$H(s) = \frac{15}{2s+20} \qquad (4)$$

Figure 3 shows the Simulink model of the uncompensated closed loop system of human heart stabilization. The peacemaker and the heartbeat transfer functions are on the forward path while the circulatory system is on the feedback path. This closed loop is

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIII, Issue III, March 2024

the simulation model of the heartbeat based on nominal conditions. Figures 4 and 5 show the cascade combination of the forward path gains and feedback gains respectively.

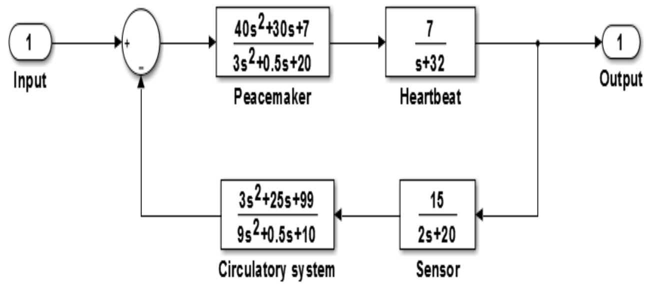

Fig. 3 Simulink model of uncompensated system

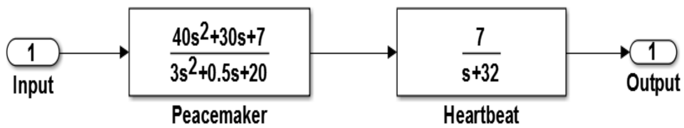

Fig. 4. Forward gains cascade combination

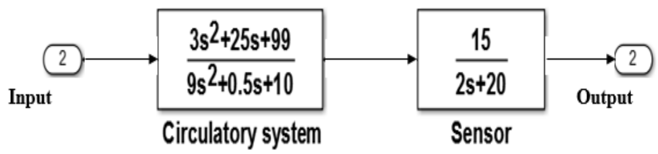

Fig. 5 Feedback path gains cascade combination

b) Cascade Combination

In order to modify the modelling technique used in (Aabid et al, 2016), the approach of cascade combination is taken to design the heartbeat stabilization control system. Figure 6 shows the closed-loop representation of the cascade combination of the forward path gains and the feedback gains.

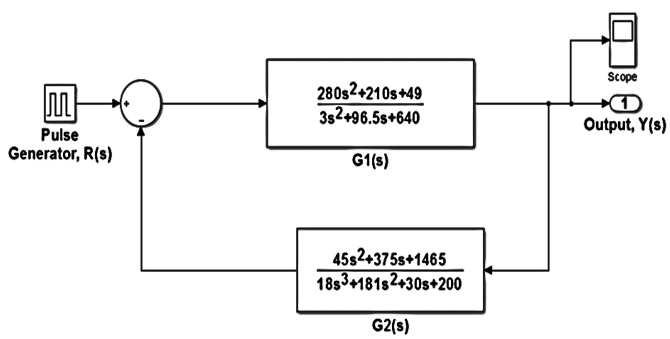

Fig. 6 Simulink cascade model for forward path and feedback gains

The cascade combination of the forward path gains and feedback gains gives the following:

Forward Path Gain, $G_1(s)$:

$$G_1(s) = G(s) \times F(s) \quad (5)$$

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIII, Issue III, March 2024

$$G_1(s) = \frac{280s^2 + 210s + 49}{3s^3 + 96.5s^2 + 36s + 640} \tag{6}$$

Feedback Gain, $G_2(s)$:

$$G_2(s) = P(s) \times H(s) \tag{7}$$

$$G_2(s) = \frac{45s^2 + 375s + 1465}{18s^3 + 181s^2 + 30s + 200} \tag{8}$$

Generally the transfer function of the closed-loop system in Figure 6 with negative feedback is given by:

$$L(s) = \frac{G_1(s)}{1 + G_1(s)G_2(s)} \tag{9}$$

$$G_3(s) = \frac{54s^6 + 2280s^5 + 30800^4 + 135981s^3 + 632975s^2 + 356625s + 200765}{54s^6 + 2280s^5 + 18200s^4 + 21531s^3 + 136220s^2 26400s + 128000} \tag{10}$$

where $G_3(s) = 1 + G_1(s)G_2(s)$

So far, the cardiovascular system has been modelled considering normal working condition of the human heart.

c) Cardiovascular System with Noise

In this case, a fictitious noise in taken as the band limited white noise (BLWN) of the MATLAB/Simulink is applied to the loop to serve as disturbance to the system. This noise represents a typical cardiovascular disease that could affect the state of the heartbeat. Figure 7 shows the Simulink model of the system with a fictitious noise applied to disturb it. The fictitious noise is represented as $D(s)$. The cascade combinations of the loop gains with disturbance is shown in Fig. 8.

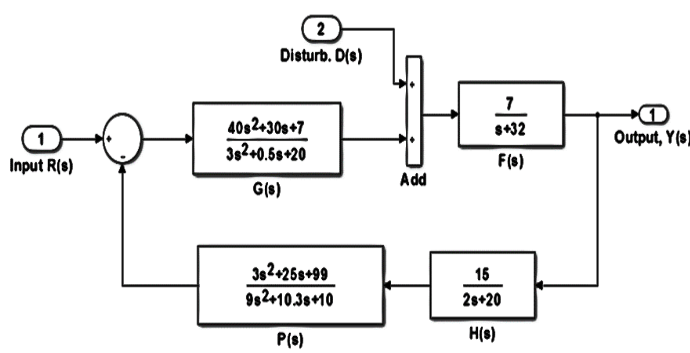

Fig. 7 Simulink model of system with fictitious noise

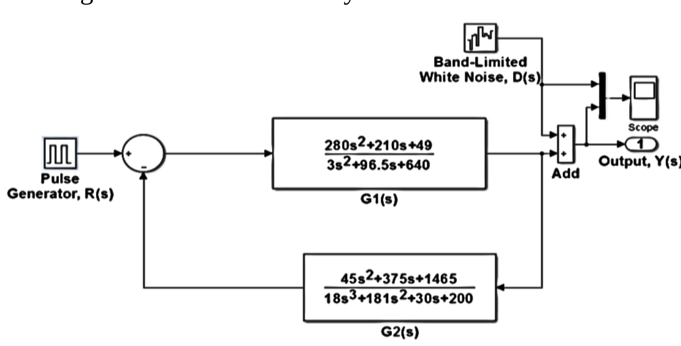

Fig. 8 Simulink cascade model with disturbance

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIII, Issue III, March 2024

The response of the uncompensated close-loop system with fictitious noise is given by:

$$Y(s) = R(s)\left[\frac{G_1(s)}{1+G_1(s)G_2(s)}\right] + D(s)\left[\frac{G_1(s)}{1+G_1(s)G_2(s)}\right] \quad (11)$$

The modelling so far has carried out for uncompensated system. That is a system without a controller in the closed loop.

d) Closed-loop with Controller

The Simulink model of the compensated system considering the normal condition of the heartbeat and the time disturbance is applied to the system to represent the abnormal state of the heartbeat considering a cardiovascular disease affecting the working of the heart are shown in Fig. 9 and 10.

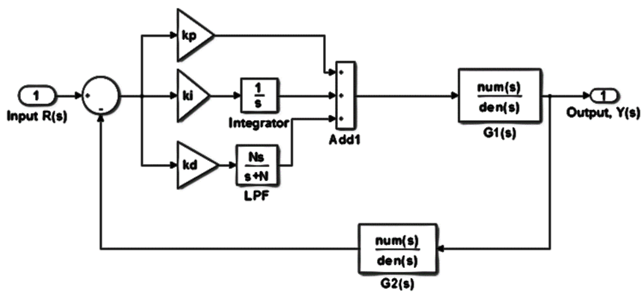

Fig. 9 Simulink model of PIDF control heart beat at normal condition

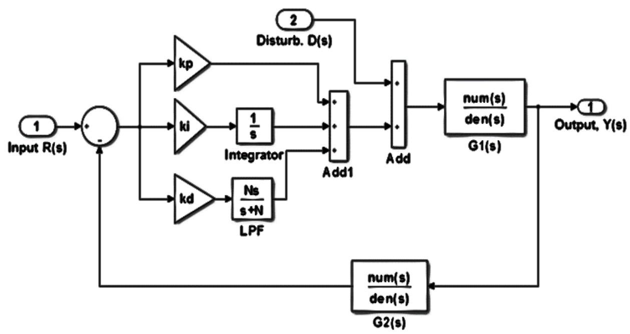

Fig. 10 Simulink model of PIDF control heart beat when infected with disease

The values of the parameters of the designed PIDF control algorithm designed in this work are presented in Table 1. The PIDF controller is given by Equation (12).

Table 1 Designed PIDF Compensator Parameters

Parameter Definition	Symbol	Values
Proportional gain	k_p	12.6074
Integral gain	k_i	118.384
Derivative gain	k_d	0.005557
Filter coefficient	N	28.7494

$$C(s) = 12.6074 + 118.384\,\frac{1}{s} + \frac{12.6074\,s}{s + 28.7494} \quad (12)$$

IV. Results and Discussion

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIII, Issue III, March 2024

This subsection presents the simulations results for the condition of human heart at different working conditions. Figures 11 and 12 are the simulation results of the normal state of the heart and the state of the heart when disturbance in the form noise attack the heart. In Figure 13, the simulation signal when diseases/anger/anxiety/fear attack the human heartbeat system is shown. Figure 14 shows the simulation plot of heartbeat system controlled heartbeat infected by diseases/ anger/anxiety/fear.

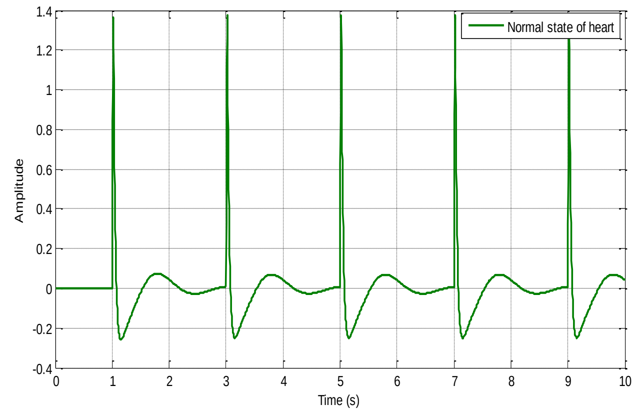

Fig. 11 Normal state of the heart (no disturbance)

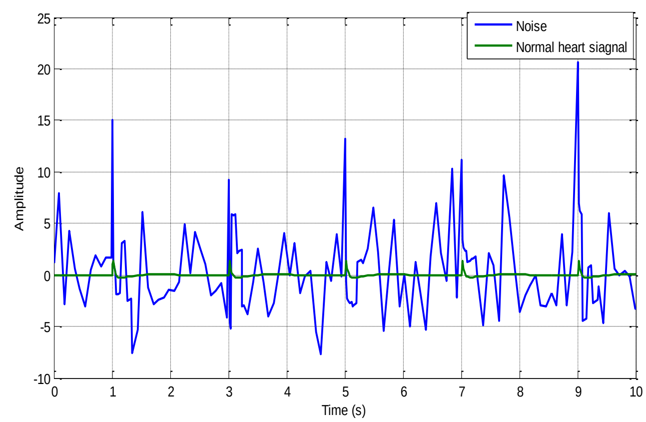

Fig. 12 Simulation signal of the human heartbeat with disturbance in form of noise

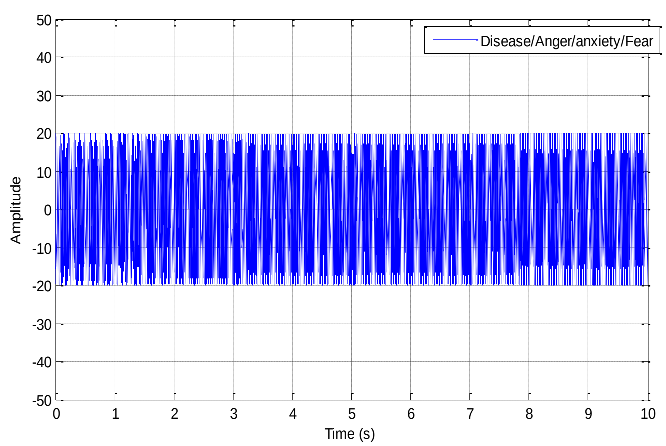

Fig. 13 Simulation signal when diseases/anger/anxiety/fear attack the human heartbeat system

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIII, Issue III, March 2024

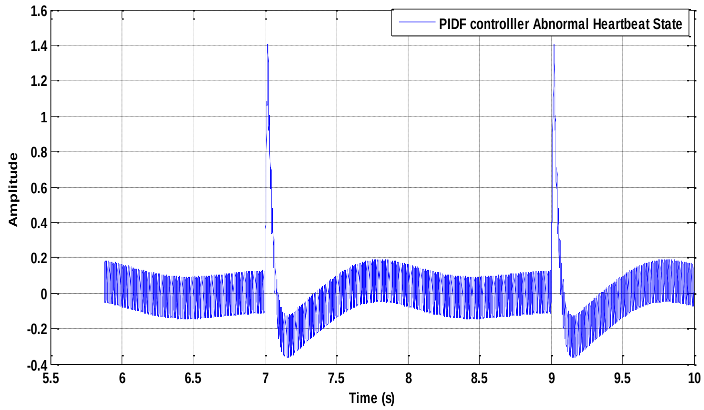

Fig. 14 PIDF control disease infected heartbeat stabilization response

The periodic action of heart (cardiovascular system) is largely due to frequently occurring action potentials originating from the peacemaker located in senatorial node. Each periodic heartbeat signal (impulse) will be transmitted to the Atria ventricular node through the myocardium. A typical electrocardiogram (ECG) signal (Figure 2) is characterised as a periodic sequence of three waves namely: the P wave, QRS complex wave (combination of Q, R and S waves) and T wave.

Among the three waves, the QRS complex wave has more energy with higher amplitude than P and T waves over the RR interval (interval between two adjacent R waves). In order to precisely monitor the heartbeat rate of patients, QRS complex (or simply the R wave) must be detected with high accuracy. The normal heartbeat depends on the continuous and periodic performance of the natural peacemaker and integrity of neurons in conducting pathways as shown by the simulation result Fig. 11. Hence, the response performance of the human heartbeat in Fig. 11 during normal working condition compares very well with the normal heartbeat scheme from a typical electrocardiogram (ECG) shown in Fig. 2 such that P-wave (1.68s), PR-interval (2.80), QT-interval (4.375s), and QRS-complex (3.139s). The amplitude or strength of the QRS is 1.4 and this remains consistent throughout the working of the heart.

In Fig. 12, the heart is assumed to be infected by noise such that the heartbeat response of the heart is shattered. It can be seen that strength or amplitude of the heartbeat wave drops to almost zero with the noise or disturbance continuously rising and dropping in amplitude irregular manner. This indicates that the noise seriously reduced the working of the cardiovascular system. In Figure 13, the heartbeat is infected by cardiovascular disease such as arousal, anxiety, and disease. It can be seen that the performance of the heart is largely marred. In this case the heartbeat maintains steady peak to peak amplitude of -20 to 20 which is above the peak amplitude of the heartbeat during normal condition. This is an abnormal state, and as such can lead to heart failure.

In order to stabilize the heart and restore the working integrity, a proportional integral and derivative controller with a low pass filter is added to the regulating loop of the heartbeat. The controller ensures that the heart is automatically restored to its appropriate working state as shown in Fig. 14. It can be seen that the controller was able to stabilize the heart to its right working state when compared to the heartbeat response of Fig. 11. That is the amplitude of the heartbeat corresponding to the QRS wave whose action is responsible for the ventricular activities is being restored to the appropriate amplitude or strength of 1.4.

V. Conclusion

This work is based on automatic control of human heartbeat rate as a hydro electro mechanical system (HEMS) using mathematical model. The mathematical model and the response present some of the important features of the human cardiovascular system when it is disturbed by an arousal (provocation), anxiety, disease or fight and the way to cure the disturbances. The approach employed is to determine the appropriate physical analogy, write the system equations, and formulate the computer simulation. This allowed for consideration on the methods of transforming physiological data into useful model parameters, and to establish the analogies between electrical, mechanical and hydraulic systems. It also helps to build an entire regulation of the human cardiovascular system based on brainwaves like a disturbances.

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