Signal Processing and Renewable Energy

September 2022, (pp. 91-102)
ISSN: 2588-7327
eISSN: 2588-7335

Real-Time CANFIS and ANFIS Based Pacemaker Controller Design and Analysis

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Received: 20-Feb-2022, Revised: 02-May-2022, Accepted: 04-May-2022.

Abstract

This paper describes ANFIS introduced by R. Jang et al. ANFIS actually is an offline method in fuzzy control systems. First, a fuzzy file called FIS (Fuzzy Inference System) is designed that relates the input and output of the system by membership functions that are optimized during the learning process. Input and output learning data are given to the ANFIS (MATLAB command line or ANFSI utility) and the output file is used to test or predict new input data. We can then construct a SIMULINK file to simulate the control system. This simulation is not real-time and if the environmental or input conditions are changed, the output will be altered because the FIS file is fixed and not adapted to input variations. The library of online ANFIS and CANFIS introduced does not have that problem and easily learns the online training data and then can mitigate the output in real-time. To avoid the unsuitable patient data itself as training data, we should use a healthy person ECG (heart rate) data in memory to train our fuzzy system and then switch the input data from healthy data to the patient original heart rate as input data. If the heartbeat falls below (60 bpm that is called Bradycardia) or exceeds (100bpm that is called Tachycardia) from a predetermined value. The online controller will switch the controller to healthy data and will stimulate heart muscles at a right beat rate (70-75 bpm). To distinguish tachycardia from body natural states like running, practicing, walking, sleeping and resting, MEMS accelerometer and in some situations, gyros are used. The Bode diagram stability shows gain and phase margin as follows: GM (dB)= 42.1 and PM (deg) = 100. FIS file is saved after an acceptable rms error (0.38). The simulation results of unity step input response (Rise time, settling time, overshoot) will be demonstrated in chapter 4. The overshoot was less than 2 percent and rise time of 2 seconds with settling time of less than 2 seconds. The parameters have been shown for 60 and 72 and 85 bpm.

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Keywords: ANFIS, PID, Artificial Pacemaker, CANFIS, ECG, Heartbeat, Bradycardia, Tachycardia, Atrial fibrillation, Ventricular Tachycardia.

1. INTRODUCTION

This paper describes ANFIS introduced by R. Jang et al [1]. ANFIS actually is an offline method in fuzzy control systems. First, a fuzzy file called FIS (Fuzzy Inference System) is designed that relates the input and output of the system by membership functions that are optimized during the learning process. Input and output learning data are given to the ANFIS (MATLAB command line or ANFSI utility) and the output file is used to test or predict new input data. We can then construct a SIMULINK file to simulate the control system. This simulation is not real-time and if the environmental or input conditions are changed, the output will be altered because the FIS file is fixed and not adapted to input variations. The introduced library of online ANFIS and CANFIS does not have that problem and easily learns the online training data and then can mitigate the output in real-time. To avoid the unsuitable patient data itself as training data, we should use a healthy person's ECG (heart rate) data in memory to train our fuzzy system and then switch the input data from healthy data to the patient original heart rate as input data. If the heartbeat falls below (60 bpm that is called Bradycardia) or exceeds (100bpm that is called Tachycardia) from a predetermined value. The online controller will switch the controller to healthy data and will stimulate heart muscles at a right beat rate (70-75 bpm). To distinguish tachycardia from the body natural states like running, practicing, walking, sleeping and resting, MEMS accelerometer and in some situations, gyros are used.

In reference [2], we designed and analyzed an ANFIS based controller in offline mode. The library of online ANFIS and CANFIS introduced in [3], does not have this problem and it easily learns the online training data and then can mitigate the output in real-time.

The FIS file for fuzzy system has been generated by using patient heart model response to a unity step input data and capturing input and output data to be used in designing an ANFIS controller. The best, fast and efficient method was FCM (Fuzzy C means) method. Some works were previously achieved by PID and Fuzzy PID controllers to regulate heart rate. [4,5]

2. MATERIAL AND METHODS

2.1. Conventional Control Scheme for Pacemaker Systems

The conventional control schemes including PID and Fuzzy PID have already been used to design and implement in new pacemakers. The FPID methods have better response with respect to PID controller. They have used dual sensors (Accelerometers and QT interval detection) to find the patients' various physical states (Resting, Walking, Running).The best, fastest and the most efficient method was FCM (Fuzzy C means) method, Also PSO and GA were investigated [12].

2.2. ANFIS Controller Design

Neural network has a powerful learning capability. Fuzzy logic has a good capability of inference and can combine it with expert knowledge. Neural networks combine learning capabilities and previous expert knowledge. Neural networks can be used to train membership values for fuzzy system construction of IF-then rules and or for decision making construction. ANFIS uses the merits of both neural network and fuzzy logic [4].

2.3. ANFIS Model

ANFIS model architecture is a graphical representation of Takagi-Sugeno fuzzy controller.

General ANFIS controller structure has been shown in figure 1. Functions of various layers as an algorithm are as follows:

The network has 5 layers, L1 is the input variable, L2 is the membership function, L3 is fuzzy rules, L4 is output membership functions, and L5 is output variable.

ANFIS is tuned automatically with least mean square and back propagation algorithm [4].

2.4. Online CANFIS and ANFIS controllers

In this paper, the operation and application of CANFIS library are described. The library contains 6 different ANFIS models. ANFIS is a hybrid complex network that belongs to ANN.The main reference for this library is from a paper by Mizutani and et al. [1]. The library is run under MATLAB Simulink and is consisted of using six S-functions (Compiled MATLAB functions as library). ANFIS is realized previously in MATLAB built-in toolboxes. This library is designed to be run in SIMULINK online. It contains various ANFIS systems including:
Scatter-Grid- ART-MISO-MIMO

ANFIS multi-input and single-output and multi-input and multi-output systems called CANFIS (figure 2 and 3). Each of them includes 3 states, Scatter Grid and ART.This naming shows the input space partitioning. Generally, the grid type grows by calculation with respect to the number of network input

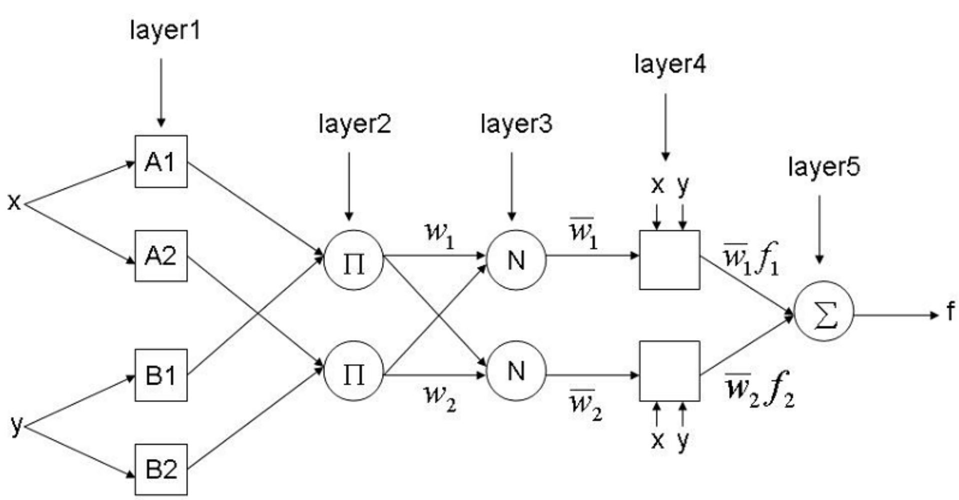

Fig. 1. ANFIS model with two input and single output.

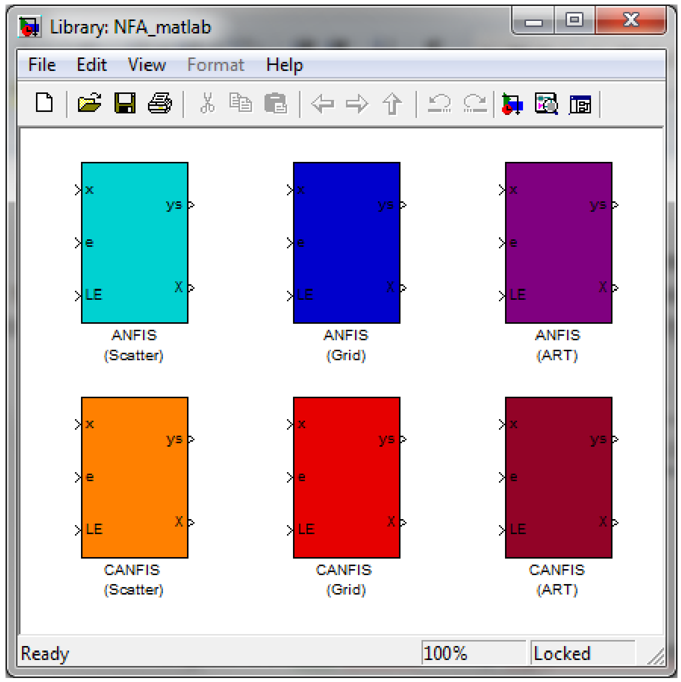

Fig. 2. ANFIS online library for Simulink.

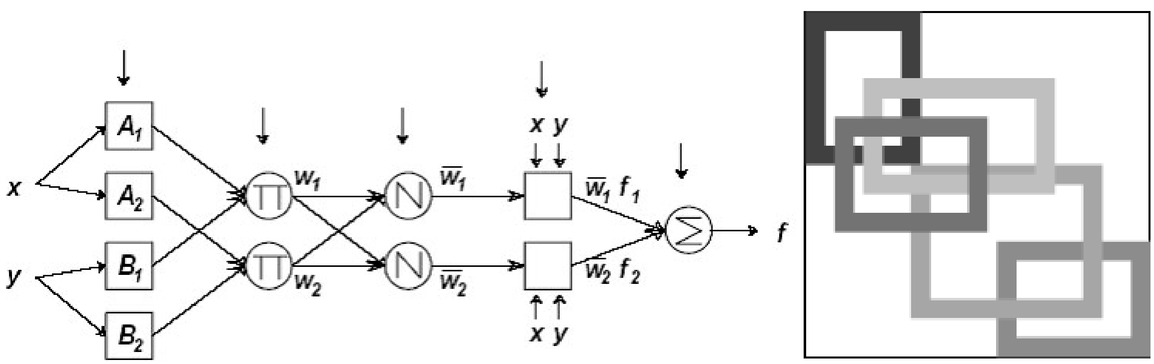

Fig. 3. Network Architecture of online ANFIS of Scatter type.

variables and it is called the curse of dimensionality and is shown by the following relation (1):

$$N_{Rules} = {N_{Input_{Terms}}}^{N_{Inputs}} \qquad (1)$$

To solve this problem, we use the scatter method for input partitioning in which the number of fuzzy rules are equal to the number of each input subset with relation (2):

$$N_{Rules} = N_{Input_{Terms}} \qquad (2)$$

This reduces the computing time substantially but reduces ANFSIS approximation capability.

This happens because this architecture does not cluster the input space completely, but it covers the main diagonal space that has been developed by inputs. If the data may be out of the main diagonal, the scatter model may be insufficient for ANFIS.

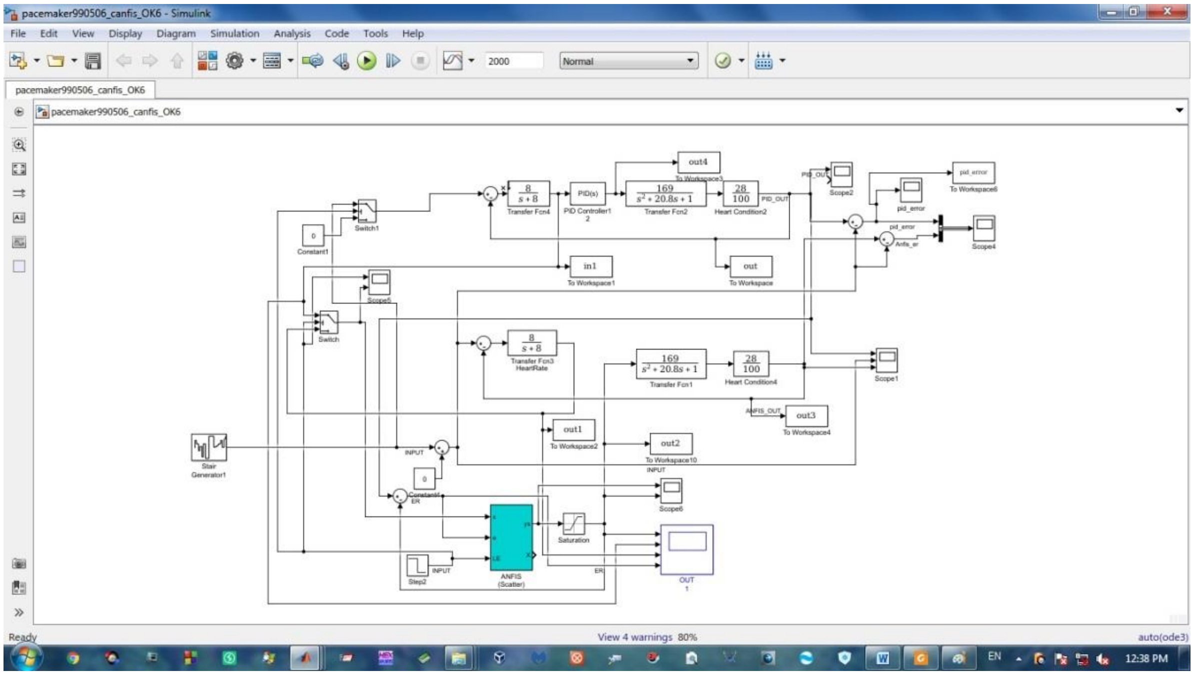

Fig. 4. Simulink diagram for online ANFIS simulation of the designed pacemaker controller.

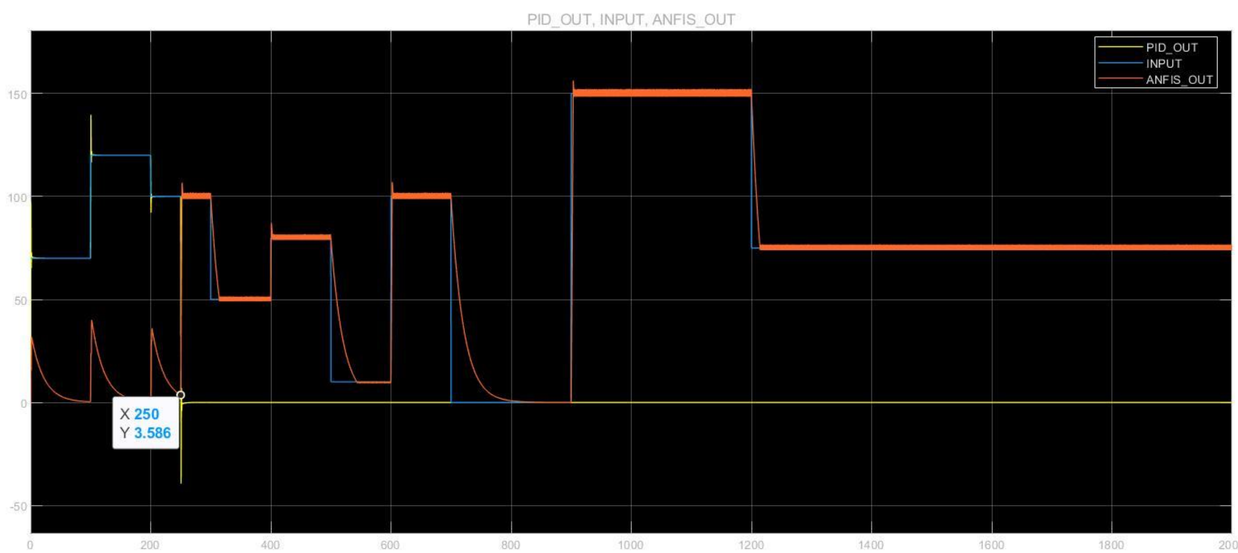

Fig. 6. Various pulse input response of online ANFIS after 64 seconds.

A smarter input clustering method is to use Fuzzy-ART[1] algorithm that is the method shown by Carpenter et. al. [6], This method resembles the same method as scattering but smarter in clustering inputs.

In this research, we have used scatter method in Simulink.

[1] Adaptive Resonance Theory

The Simulink diagram for online ANFIS simulation of the controller is shown in figure 4.

At first, 64 seconds of simulation training is done on PID portion of the diagram and

2.5. Data Preparation

The subject will be investigated in chapter 5 in detail.

2.6. DESIGN and Analysis Tools

The MATLAB Simulink is used for design and analysis of proposed algorithms.

2.7. Stabilty

The stability will be shown at following chapters.

3. STABILITY ANALYSIS OF ANFIS BASED CONTROLLER IN SIMULINK IN TIME DOMAIN

Time domain design and analysis of the controller were done in Simulink (figure 7). First, the training data is generated by a PID heart rate controller and then this data is used to generate FIS file (both command line and ANFIS GUI is used). FIS file generation is done by hybrid back propagation and grid partitioning methods and recursive least square is used to optimize the membership functions. The FIS file is the result of these process. The heart and pacemaker mathematical model shown in the figure are from Jyoti Yadav and et al. work. [7]

FIS file saved after an acceptable rms error (0.38). The simulation result of unity step input response (Rise time, settling time, overshoot) is shown in Figure 8.

The overshoot was less than 2 percent and rise time of 2 seconds with settling time of less than 2 seconds. The parameters have been shown for 60 and 72 and 85 bpm inputs are shown in the following table:

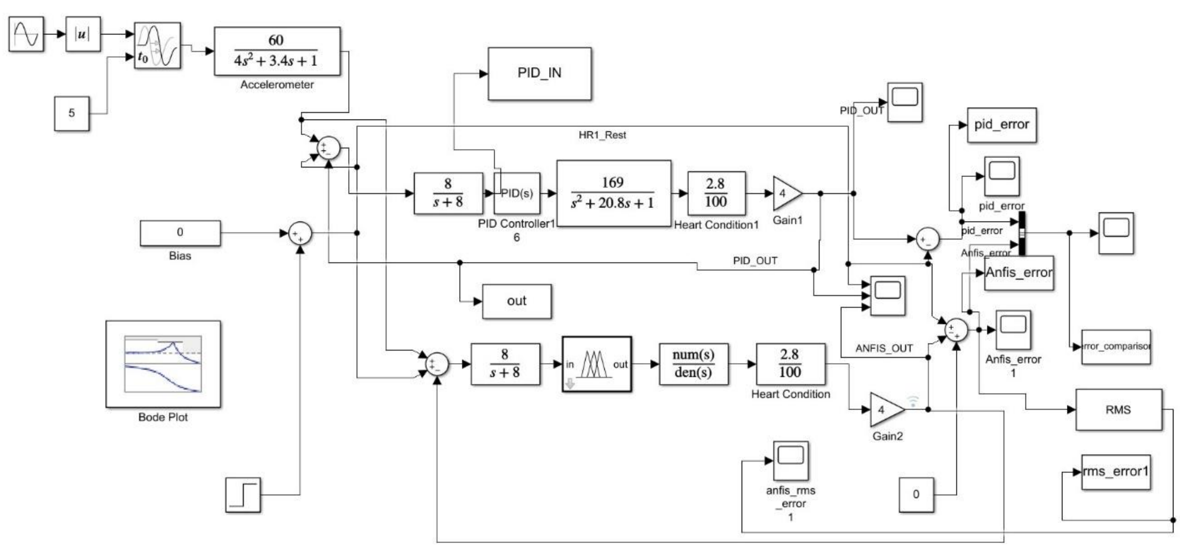

Fig. 7. Time domain simulation of PID and ANFIS controller done at Simulink.

Table 1. ***Response parameters of ANFIS controller with various heart rates*.**

HR(bpm)	Rise Time(s)	Settling Time(s)	Max Overshoot (%)
60	1.63	1.23	0.5
72	1.97	1.23	1.53
85	1.7	1.55	1.08

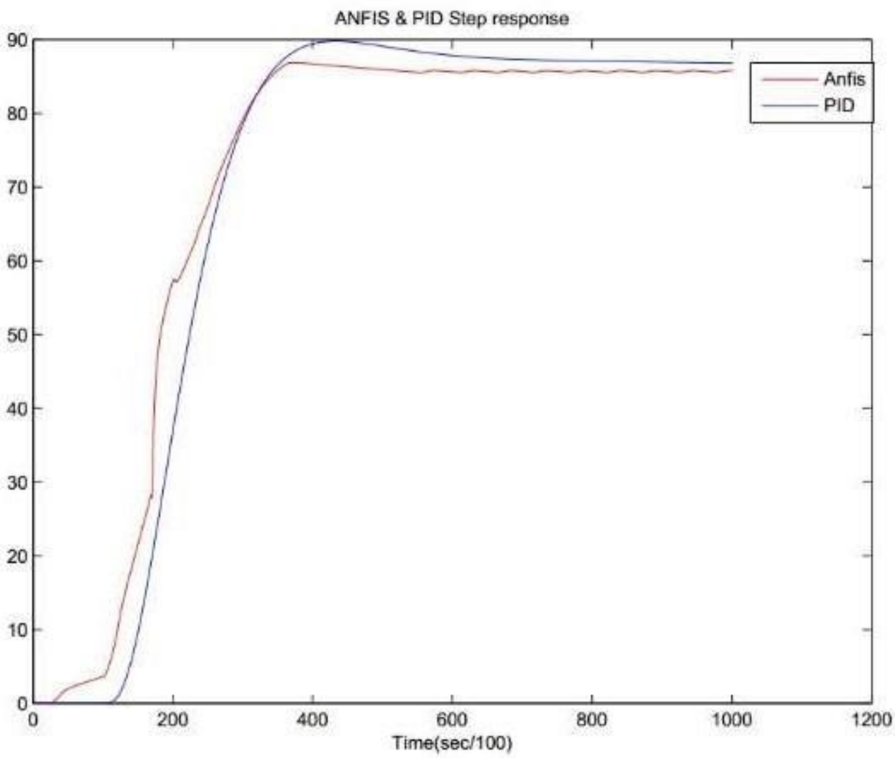

Fig. 8. Unity step input response.

4. STABILITY ANALYSIS IN FREQUENCY DOMAIN BY BODE DIAGRAM METHOD

The frequency domain stability analysis (figure 9). has been done in Simulink by Bode diagram [9].

The Bode diagram stability shows gain and phase margin as following:

GM (dB)= 42.1 and PM (deg) = 100

5. DATA SETS:

Data sets used from real and artificially generated ECG data.
Real Data set for the input reference has been chosen from the following databases:

5.1. Real Data

Real ECG data used from following Databases [10]:

- MIT DB: The Massachusetts Institute of Technology-Beth Israel Hospital Arrhythmia Database: MIT-BIH Arrhythmia Database (physionet.org)
- ESC DB: The European Society of Cardiology ST-T Database (90 records, two hours each): European ST-T Database v1.0.0 (physionet.org)
- NST DB: The Noise Stress Test Database (12 records, 30 minutes each): MIT-BIH Noise Stress Test Database v1.0.0 (physionet.org)
- CU DB: The Creighton University Sustained Ventricular Arrhythmia Database (35 records, 8 minutes each): CU Ventricular Tachyarrhythmia Database v1.0.0 (physionet.org)
- Pacemaker recorded diagnostics data [11]
- AHA DB: The American Heart Association Database for Evaluation of Ventricular Arrhythmia Detectors: American Heart Association ECG Database USB (ecri.org)

5.2. Synthetic Data Generated by MATLAB code

These data generated by this method described at (ECGHOSM) ECG Heterogeneous Oscillator Simulation Model [8]. The 12 lead ECG is generated synthetically by a MATLAB code. Because they are generated by code, we can alter the beat rate and introduce some errors on signals. Moreover, we can add some noise and other artifacts to test our designed ANFIS controller.

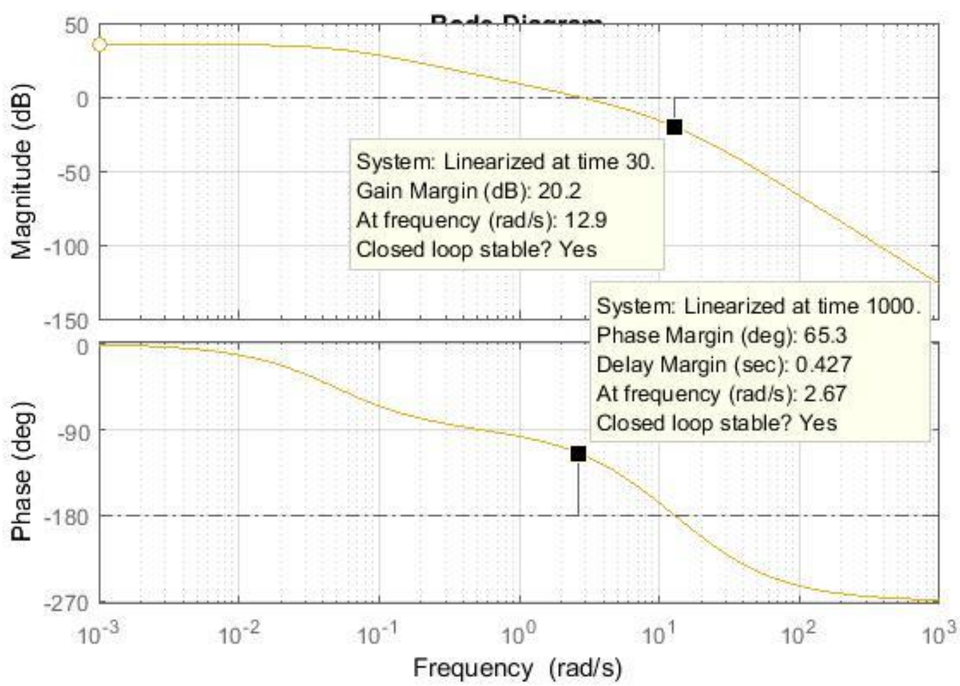

Fig. 9. The Bode diagram stability analysis.

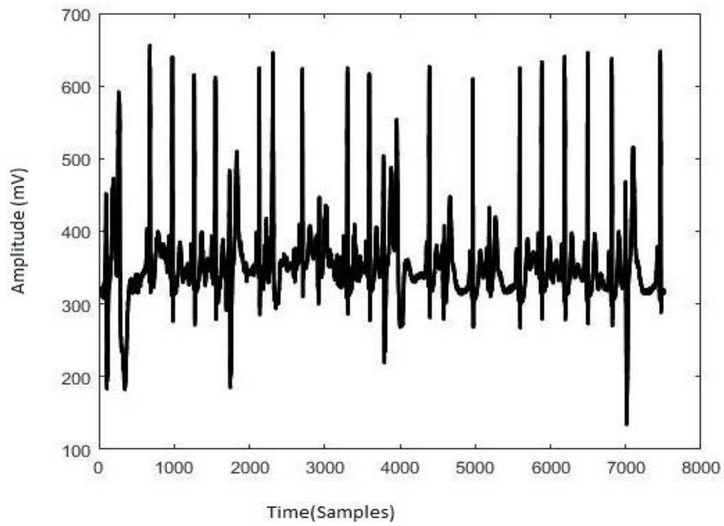

Fig. 10. Data converted from image to MATLAB data format.

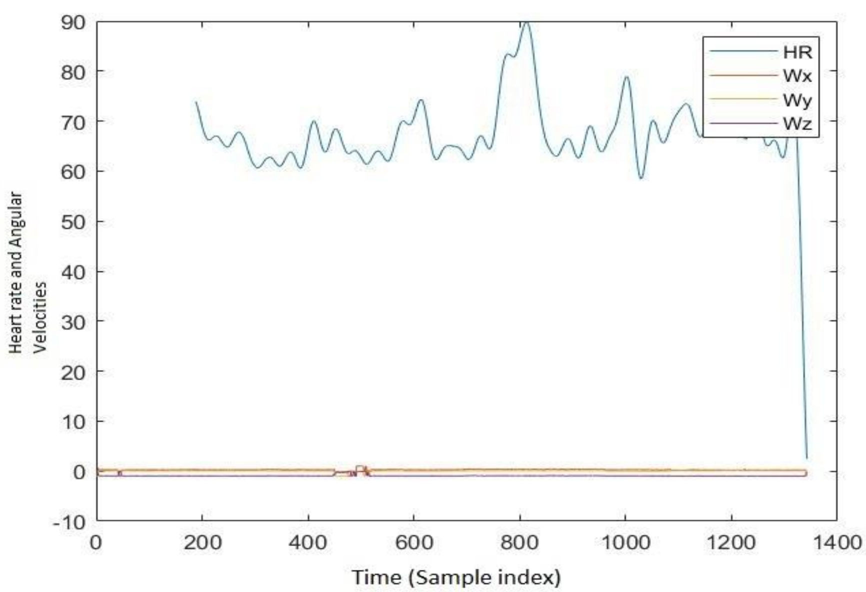

Fig. 11. Heart rate(HR) and rate angular velocities (Wx -Wy-Wz).

However, in practice we use other data's that are real and will be described later.

5.3. Image Data Converted From Stress Test Equipment Manufactured by AVICINA Company[2]:

These data were generated from image files (JPG format) from AVICINA stress test equipment. They are converted to MATLAB datasets by image processing techniques. The converted data are shown in Figure 10:

[2] http://www.avecinna.com/

5.4. Data Collected from a Mi-Band Smart Watch and a 5s Apple Mobile Phone

Both accelerometer's data from mobile phone and heart rate from the smart watch gathered. Because sample rates were different, they are resampled and used as input data to the ANFIS controller and PID controller. Collected by using the mobile phone and the smart watch and resampled data, heart rate and rate angular velocities (Wx -Wy-Wz) shown in Figure 11.

6. RESULTS AND DISCUSSIONS

Jyoti et al. compared a fuzzy controlled and a PID controller tuned with Ziegler-Nichols, Tyreus, Luyben, and relay methods; the work simulated and demonstrated that the fuzzy controller had a maximum overshoot less than all tuned PID controllers and improved rise time and settling time than at least two of the three tuning methods. There is no data for frequency domain stability analysis available to be compared with our proposed ANFIS method. The online method introduced and used in our work to show how we can control artificial pacemaker beat rate to stimulate heart muscles to avoid heart diseases such as AF (Atrial fibrillation) and VT (ventricular tachycardia) and other heart beat rate arrhythmias.

7. CONCLUSION

Various stability analysis methods including time and frequency methods are tested, and finally because of nonlinear nature of ANFIS, bode diagram and step response methods are chosen. These HR signals form the basis of the functioning of a pacemaker. Pacemaker performance depends not only on the sensors and the pacemaker circuitry but also on the performance of controller. In the present work, different control techniques are analyzed to design the heart rate controller. As has been seen in our previous work, the designed system was not really online, but the current work used the online Simulink library to simulate pacemaker heart rate control in real time. Because in real time we need to use patient data to train the fuzzy system and as we know that the data is not well, we use healthy person or patient healthy data that has been recorded before and during health time. Therefore, during patient heart rate failure times, especially tachycardia, we switch the input reference data to healthy data. Later, we will use the current method to simulate the system as an external pacemaker. And it should be noted that to realize the system, we need high speed and new versatile DSP processors to realize ANFIS in real time. In the next article, stability and robustness of system will be enhanced using type-2 fuzzy controller.[13]

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