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Non Linear Control System Based Modeling of Cardiac Muscle using Describing Function and Lyapnuov Stability.

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***Abstract:** Main focus of this research work is aims towards the nonlinear analysis of human cardiac muscle by describing function technique and finding stability using lyapnuov stability theory. The nature of cardiac muscle can be modeled by mass, spring with a damper where for simplicity spring and damper are considered a linear element. In reality, it has been observed that, the characteristics of spring and damper are not linear rather nonlinear. Not only that, transportation delay (non-zero reaction time) or lag phase of cardiac muscle plays an important role to make the overall model nonlinear. The range of transportation delay for which the system is stable has been calculated here to ensure the presence of dead zone type nonlinearity in cardiac muscle. In this paper a nonlinear characteristics of the model has been analyzed considering dead zone combined with saturation. The describing function technique is used here to represent the nonlinearity. A converging stable limit cycle has been found after the analysis. Finally, lyapnuov stability theorem is applied on our proposed model and it has been that the system is asymptotically stable in the sense of lyapnuov.*

***Keywords:** Nonlinearity, Describing function, Lyapnuov stability, Cardiac muscle.*

I. INTRODUCTION

Human cardiovascular system and its abnormities nowadays play an important role for research. To analyze cardiovascular system and its effects, control system based modeling of cardiovascular muscle is very much needed for researchers. Consideration is focused on the fact that, the dynamics of cardiovascular muscle can be represented as a simple second order system and comprised of high damping coefficient along withthe natural frequency of 1.2 hertz. In the previous research work,the model of cardiac muscle has already been developed using linear control theory [1][2]. Cardiovascular muscle senses the force generated due to the contraction and expansion of muscle wall . This can be well understood by the analytical approach of the transfer function generated by using a mechanical model of force displacement analogy.

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In linear control theory, the form the output of a system is independent of magnitude but homogeneity property is maintained. In practical, most of the system does not show linearity where the system does not possess homogeneity or superposition property. Human cardiac muscle has been modeled with mass, spring and damper, in which spring and damper shows incidental non linearity. In this paper the nonlinear modeling of cardiac muscle has been depicted using describing function technique and then stability of the developed model has been verified by lyapnuov stability theorem.

Table 1:Represents the notation used in the problem formulation-

x	Displacement
t	Time
s	Frequency Domain
ω	Angular frequency
f_d	Damping frequency
f_n	Natural frequency
ξ	Damping Factor
f(t)	Force
M	Mass
B	Viscous Drug
K	Spring Constant
G(s)	Transfer Function of Plant
t_0	Transportation Delay
N	Describing Function
X	Amplitude of input sinusoid
Y_1	Output signal of the proposed model

The above notation has been used in this dissertation to design the proposed model of cardiovascular muscle considering nonlinearities

II. LINEAR CONTROL THEORY BASED APPROACH OF CARDIAC MUSCLE

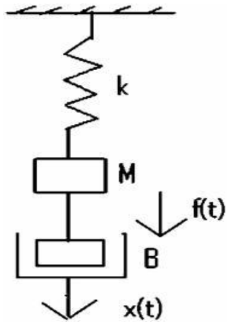

Figure- 1: .Basic mechanical model of cardiac muscle.

So from the above figure it is possible to derive the dynamical equation for the movement of cardiac muscle with the help of control modeling as given below.

$M\frac{d^2x}{dt^2} + B\frac{dx(t)}{dt} + K.[x(t)] = f(t)$……………………………..(i)

Here 'M'denotes the mass of cardiac muscle, 'B' is the constant of viscous drag of one myocardial cell,and 'K' represents the elasticity of cardiac muscle. Now x(t) is the movement of cardiac wall which is generated due to exerted force f(t)by electrical and electrochemical activity effects on the cardiovascular system[3]. The viscous damping is proportional to the muscle wall movement of the specimen, so that the contribution to this viscous damping may be represented by the expression $B\frac{dx(t)}{dt}$.Tensional drag is proportion to the displacement of the specimen, so that its contribution is given by the expression $K._x(t)$. Sometime 'K'is also called the constant of proportionality [4]. Taking the Laplace transform of equation (i) the following equation can be written as follows.

$(Ms^2).X(s) + (Bs).X(s) + (K).X(s) = F(s)$……….(ii)

Here we have taken the Laplace Transform of the equation, where X(s) = L[x(t)] and F(s) = L[f(t)]

So from equation (ii) it is possible to write

$\frac{X(s)}{F(s)} = \frac{1}{Ms^2+B\,s+k}$……………………………………………(iii)

$\frac{X(s)}{F(s)} = \frac{K_1}{s^2+K_2s+K_3}$ =T(s)………………………………….(iv)

where K_1= 1/M, K_2 = B/M, K_3= K/M.

The transfer function of the cardiac muscle movement due to the force can also be written with the help of three constants K_1, K_2, K_3.The cardiovascular wall makes its movement incurring displacement despite hindrance due to frictional and torsional effects of the cardiovascular wall cells. The input force causing the displacement of cardiac muscle is generated by the electrical and electrochemical activity in the cells. The expression of the above transfer function thus gives the measure of the cardiovascular muscle cell wall due to the inherent force generated in the cardiovascular system. The values of the constants K_1, K_2, K_3 in the expression (3) of the transfer function can be determined by experimentation on a cardiovascular system, and the expression (3) thus may be standardized. Thus for known forcing function, the nature of the displacement (movement) of cardiovascular muscle, as function of time can be well predicted taking the Laplace inverse transformation on that equation[5][6].The above stated equation can also be compared with the transfer function of standard second order system. The transfer function of a 2nd order system can be represented by the following transfer function:

$T(s) = \frac{X(s)}{F(s)} = \frac{\omega_n^2}{s^2+2\xi\omega_n s+\omega_n^2}$……………………………..(v)

wheredamping ratio of our proposed system is defined by$'\xi'$, whereas natural frequency is denoted by $'\omega_n'$. Now the characteristic polynomial of the above equation (v) $s^2 + 2\xi\omega_n s + \omega_n^2 = 0$.

The human cardiovascular system is beating at an average rate of 72 beats per minute. The frequency of heart beat is f = 72/60 = 1.2 Hz,which is considered to be the damping frequency. As critically damped system practically does not exist and over damped system shows large time constant, so for modeling purpose cardiovascular systemhas been considered as an under damped system in this research work. So the relation between f_d, f_n, ξ is given by the equation$f_d = f_n\sqrt{(1-\xi^2)}$,$f_d$where is damping frequency,f_n is natural frequency andξ is the damping coefficient. Putting f_d is equals to 1.2 and varying the value of mass (M) and considering $\xi = 0.9$ different transfer functions has been obtained in previous research work. Response analysis has also been done in MATLAB 6.0.Finally the model parameter has been chosen based on response analysis means from the best result obtained from the step response analysis.

III. TYPE OF NONLINEARITY PRESENT IN CARDIAC MUSCLE

Nonlinear control theory is a part of control theory which deals with the systems which are nonlinear and mainly time-variant. There are so many type of nonlinearity exists in a system which had been examined and explained in previous research work, like dead zone, backlash, saturation or the combination of any two. Here in this paper the nonlinearity exists in cardiac muscle has been investigated after considering the transportation delay with the transfer function [7].The transportation delay or lag phase is the delay measured between the applied input signal to a system and the reaction time of the system to that input signal, which makes a system unstable in linear domain. From the previous research work, the transfer function of cardiac muscle is given by $\frac{1}{1+5280.s+264s^2}$. Now, it is found from the experimental clinical data, the minimum response time of cardiac muscle is 0.2 to 0.5 millisecond. The electrical pulse input for the cardiac muscle is generated by the electrical depolarization and re-polarization of signal. Due to the transportation delay of cardiac muscle output response is obtained after some milliseconds, which ensures dead zone nonlinearity in the system .Let the transportation delay is denoted by t_0. So the open transfer function will be multiplied by the e^{-st_0}. Hence our cardiac muscle transfer function will become$\frac{1}{5280.s+264s^2}.e^{-st_0}$.

For 0.2 milli seconds, the characteristics equation is

$264s^2 + 5280.s + (1 - .0002.s) = 0.$ ………….(vi)
$264s^2 + 5279.9998\, s + 1 = 0$ ….……………..(vii)
$s_{1,}s_2 = -9.999 \mp j\, 9.981$,represents the system stability in time domain.. Similarly the calculation has also been done with 0.3, 0.4, 0.5 milliseconds.
The result is tabulated in table 2 and given below-

Table 2:Represents the position of poles system with different Transportation delay.

Transportation delay	$s_{1,}s_2$(Poles)
0.2 milliseconds	$-9.999 \mp j\, 9.981$
0.3 milliseconds	$-9.989 \mp j\, 9.986$
0.4 milliseconds	$-9.977 \mp j\, 9.990$
0.5 milliseconds	$-9.969 \mp j\, 9.999$

From the above result it is confirmed that, the poles moves towards the right half of the s plane, if we keeps on increasing of the transportation delay of cardiac muscle. For 0.6ms delay the system loses its stability. For our proposed cardiac muscle, the range of transportation delay for which the system gives stability is $0.2ms \leq t_0 \leq 0.5ms$.The transportation delay of cardiac muscle ensures dead zone nonlinearity and range of dead zone can also be predicted by the above range of delay.

IV. METHOD APPLIED FOR NONLINEARITY

The describing function is very popular and is used to analyze the nonlinear function in an approximate procedure in modern control engineering.For the modeling of the proposed nonlinear system, describing function techniques been used here along with lyapnuov stability theory.It is nothing but aapproximated extension version of frequency domain analysis of linear control system [8]. Describing function method of a nonlinear system can be defined as the complex ratio of two things.The numerator is represented by the amplitudes along with phase angle of fundamental harmonic components for the output being produced by the system, whereas the denominator is represented by the same for input sinusoid. Sometime it is also known as sinusoidal describing function. Mathematically it can be represented as $N(X,\omega) = \frac{Y_1}{X} \angle \Phi$. Here, Φ represents the phase shift of the fundamental harmonic component produced at the output by the proposed system[9]. Figure 2 represents the basic block diagram of describing function analysis.

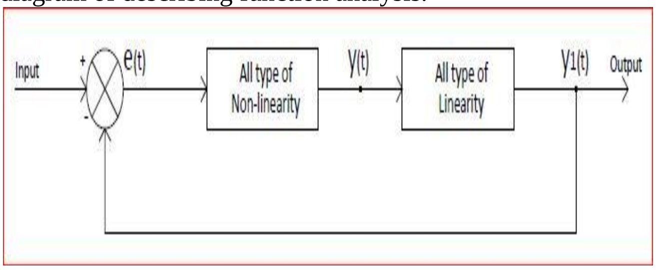

Figure 2:Basic block diagram of describing function analysis.

According to our above previous result, the nonlinearity presents in cardiac muscle is dead zone combined with saturation.

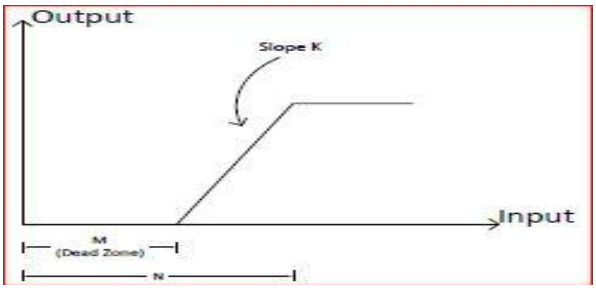

Figure 3:Input output characteristics of overall nonlinearity

The input verses output characteristics of the proposed system considering only nonlinearity has been depicted in figure 3 whereas figure 4 and 5 represents the input and output waveform individually given below-

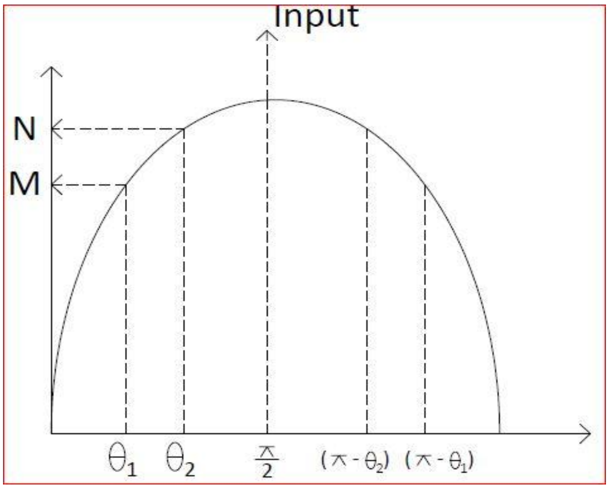

Figure 4: Input Waveform

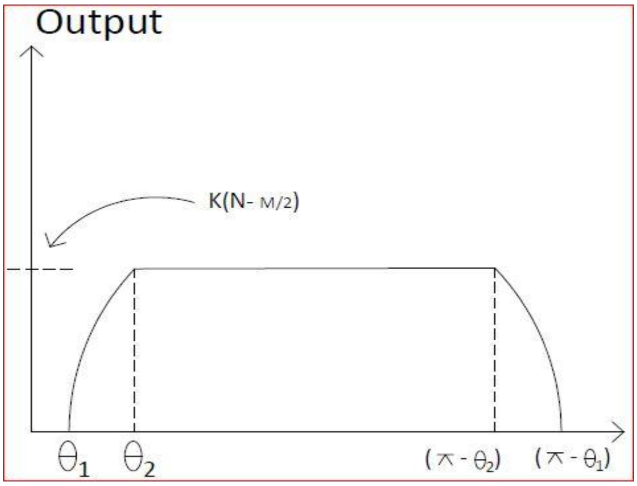

Figure 5:Output Waveform

Let input is x=Xsinωt, and corresponding output is given by

$y = 0, for 0 \leq \omega t \leq \theta 1,$
$= k.\left(x - \frac{M}{2}\right), for \theta 1 \leq \omega t \leq \theta 2,$
$= k.\left(N - \frac{M}{2}\right), for \theta 2 \leq \omega t \leq (\boldsymbol{\pi} - \theta 2),$
$=k.\left(N - \frac{M}{2}\right), for (\boldsymbol{\pi} - \theta 2) \leq \omega t \leq (\boldsymbol{\pi} - \theta 1),$
$=0,\ for (\boldsymbol{\pi} - \theta 1) \leq \theta 1$ …………………………….(viii)

$A_1 = \frac{2}{\pi}\left[\int_{\theta1}^{\theta2} k\left(X.Sin\omega t - \frac{M}{2}\right) cos\omega td(\omega t) + \int_{\theta2}^{\pi-\theta2} k\left(s - \right.\right.$ *M2cosωtdωt+π−θ2π−θ1kX.Sinωt−M2cosωtdωt* ……………………………………….…..(ix)

$A_1 =$
$\frac{2K}{\pi}\left[\frac{X}{2}\int_{\theta1}^{\theta2} 2sin\omega t.cos\omega td(\omega t) - \frac{M}{2}\int_{\theta1}^{\theta2} cos\omega td(\omega t) + \right.$
(N−M2)θ2π−θ2cosωtdωt+X2π−θ2π−θ12sinωt.cosωt dωt−M2π−θ2π−θ1cosωtdωt
…………………………………….…(x)

$$A_1 = \frac{2K}{\pi}\left[\frac{X}{2}\int_{\theta1}^{\theta2} 2sin\omega t.d(\omega t) - \frac{M}{2}\int_{\theta1}^{\theta2} cos\omega td(\omega t) + (s - \frac{M}{2})\int_{\theta2}^{\pi-\theta2} cos\omega td(\omega t) + \frac{X}{2}\int_{\pi-\theta2}^{\pi-\theta1} sin2\omega t.d(\omega t) - \frac{M}{2}\int_{\pi-\theta2}^{\pi-\theta1} cos\omega td(\omega t)\right]$$

$A_1 = 0$……………………………………………..….(xi)

Now we are going to calculate the value of B_1.

$$B_1 = \frac{2}{\pi}\int_0^{\pi} y(t)sin\omega t.d(\omega t)$$

$B_1 = \frac{2}{\pi}\left[\int_{\theta1}^{\theta2} K\left(Xsin\omega t - \frac{M}{2}\right) sin\omega t.d(\omega t) + \right.$
θ2π−θ2K(N−M2)sinωtdωt+π−θ2π−θ1KXsinωt−M2sinωtdωt …………………………………………(xii)

$B_1 = \frac{2K}{\pi}\left[\int_{\theta1}^{\theta2} Xsin^2\omega t.d(\omega t) - \int_{\theta1}^{\theta2} -\frac{M}{2} sin\omega td(\omega t) + \right.$
(s−M2)θ2π−θ2sinωtdωt+Xπ−θ2π−θ1sin2ωt.dωt−M2π−θ2π−θ1sinωtdωt ……………………………..(xiii)

$B_1 = \frac{2K}{\pi}\left[X.\theta2 - X.\theta1 - \frac{X}{2}\sin 2\theta2 + \frac{X}{2}sin2\theta1 + \right.$
2Ncosθ2−Mcosθ1…………………………….….(xiv)

As input is x=Xsinωt, and at $\omega t = \theta1, amplitude is \frac{M}{2}.M = 2Xsin\theta1$. So, $sin\theta1 = \frac{M}{2X}$. Similarly at $\omega t = \theta2, amplitude is s$.So $N = Xsin\theta2$. So, $sin\theta2 = \frac{N}{X}$.Putting these values

$$B_1 = \frac{2K}{\pi}\left[X.\theta2 - X.\theta1 - \frac{X}{2}\sin 2\theta2 + \frac{X}{2}sin2\theta1 + 2Xsin\theta2\ cos\theta2 - 2Xsin\theta1 cos\theta1\right]$$

$$B_1 = \frac{2KX}{\pi}\left[X.(\theta2 - \theta1) - \frac{X}{2}\sin 2\theta2 + \frac{X}{2}sin2\theta1 + Xsin2\theta2\ - Xsin2\theta1\right]$$

$$B_1 = \frac{2KX}{\pi}\left[X.(\theta2 - \theta1) - \frac{X}{2}\sin 2\theta2 + \frac{X}{2}sin2\theta1 + Xsin2\theta2\ - Xsin2\theta1\right]$$

$$B_1 = \frac{2KX}{\pi}\left[X.(\theta2 - \theta1) - \frac{X}{2}\sin 2\theta2 + \frac{X}{2}sin2\theta1 + Xsin2\theta2\ - Xsin2\theta1\right]$$

$B_1 = \frac{KX}{\pi}[2(\theta2 - \theta1) - sin2\theta1 + sin2\theta2\ ]$……..(xv)

Hence describing function for the nonlinearity is given by

$$N(X,\omega) = \frac{\sqrt{{A_1}^2 + {B_1}^2}}{X}\angle \tan^{-1}\frac{A_1}{B_1}$$

$= \frac{B_1}{X}\angle 0$…………………………………(xvi)

$N(X,\omega) = \frac{K}{\pi}[2(\theta2 - \theta1) - sin2\theta1 - sin2\theta2\ ]\ for\ X > N$

$= 1 - \frac{2}{\pi}[2(\theta2 - \theta1) - sin2\theta1 + sin2\theta2\ ]\ for\ N > X > \frac{M}{2}$……………………………………………(xvii)

Equation (xvi) represents the necessary describing function for our proposed nonlinear design.

V. ANALYSIS OF NONLINEARITY USING DESCRIBING FUNCTION AND SIMULATION RESULT

Here all type of nonlinearity presents in Cardiac muscle system are kept together and put in a single block representing the input output characteristics of nonlinearity whose describing function has already been calculated in previous section, whereas all type of linarites are kept in another block. Figure 6 shown below shows the connection block diagrams of the proposed system having all linarites and all type of nonlinearities.

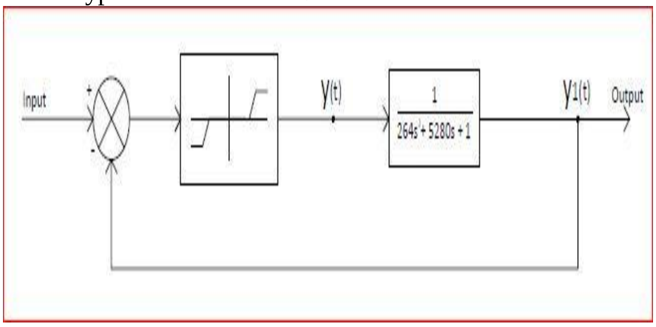

Figure 6: Connection of block diagrams of the Cardiac muscle having all linarites and all type of nonlinearities.

Polar plot of cardiac muscle model is simulated in MATLAB and given in the figure 7 considering its transfer function. It is the very initial step for nonlinear analysis. The polar plot is indicating by red color. It has been observed that without considering nonlinearity means only transfer function of cardiac muscle is completely stable as the curve crosses beyond $(-1 + j.0)$ point. So we will go for nonlinear analysis further. In the next step the nonlinear section means describing function of cardiovascular muscle will have been plotted.

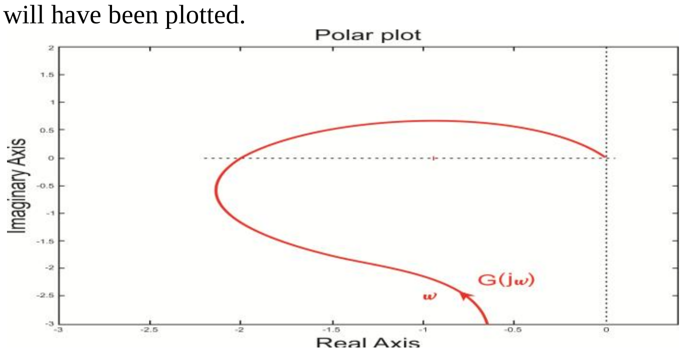

Figure 7:Represents the Polar plot of linear cardiac muscle system.

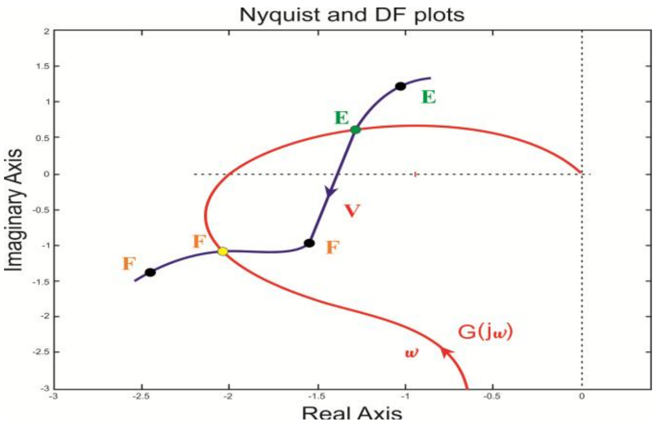

Figure 8: Represents the Nyquist plot of linear cardiac muscle system along with Describing function.

In the figure 8, Nyquist plot of linear cardiac muscle system along with its describing function has been simulated.In the MATLAB simulation, it is clearly observed from the simulation result that, a stable limit cycle is formed for our proposed nonlinear design of the cardiac muscle system. Hence it can also be concluded from the design can work in real life implementation.

VI. LYAPNUOV STABILITY

Here direct method of lyapnuov is applies on our proposed design. The dynamical equation of mass, spring, damper system is given by$M\ddot{x} + B\dot{x} + K.x = 0$, where mass is denoted by ‘M’, ‘B’ denotes the viscous drug and ‘K’ is proportionality constant of spring. Human cardiovascular system is an autonomous system. For an autonomous system, external input is zero[10][11]. Actually the cardiovascular muscle senses the force generated due to the contraction and expansion of muscle wall. The state equations are given as follows.

$\dot{x_1} = x_2$……………………………………………(xviii)

$\dot{x_2} = -\frac{B}{M}x_2 + \frac{K}{M}x_1$………………………………(xix)

x_1 and $x_2$representsthe state of the equation.

According to the Lyapnouv, there is a fictitious function which is positive for any value of x_1 and $x_2$and zero at origin and if the time derivative is negative then the system is asymptotically stable. For our proposed model let the energy function is $v(t)$,which is nothing but the summation of kinetic energy and potential energy.

$v(t)$ = Kinetic energy + Potential energy

$= \frac{1}{2}M\dot{x}^2 + \int_0^x K.xdx$

Now let $x = x_1$ $and\dot{x} = \dot{x_1} = x_2$.

Putting this value, we get

$V(t) = \frac{1}{2}M{x_2}^2 + \frac{1}{2}K{x_1}^2$ …………………………(xx)

To ensure stability, $\dot{v(t)}$ has to be verified whether it is negative or not.

Now, $\dot{v(t)} = (gradientofscalarfunctionv \times \dot{x})$.

$$\dot{v(t)} = \frac{\delta v}{\delta x_1}.\dot{x_1} + \frac{\delta v}{\delta x_2}.\dot{x_2}$$

$= K.x_1.\dot{x_1} + M.x_2.\dot{x_2}$ ……………..(xxi)

Putting the value of $\dot{x_1} and \dot{x_2}$,

$$\dot{v(t)} = K.x_1.x_2 + M.x_2.(-\frac{B}{M}x_2 - \frac{K}{M}x_1)$$

$\dot{v(t)} = -B{x_2}^2$ ………………………………………(xxii)

So, $\dot{v(t)}$ is independent of x_1 and for any value of x_2 , $\dot{v(t)}$ gives negative quantity which shows the stability of the system. Here in this model, spring is considered as nonlinear element and for simplicity we consider M=B=1. So the differential equation becomes

$\ddot{y} + \dot{y} + (y + y^3) = 0$…………………………….(xxiii)

In the above equation the last part represents the nonlinear spring. Here for analysis, Lyapnuov Direct method has been applied.

Let, $y = x_1, \dot{y} = \dot{x_1} = x_2$and $\ddot{y} = \dot{x_2}$.

Putting the values of $\dot{y}$ and$\ddot{y}$ in the above equation (xxiii), the state equations are formed and given below.

$\dot{x_1} = x_2$ …………………………………………..(xxiv)

$\dot{x_2} = -x_1 - x_2 + x_1^3$ …………………………..(xxv)

Here the equilibrium point is (0,0). As direct method is applied, Jacobian is to be calculated.

$$J = \begin{vmatrix} \frac{\delta f}{\delta x_1} & \frac{\delta f}{\delta x_2} \\ \frac{\delta g}{\delta x_1} & \frac{\delta g}{\delta x_2} \end{vmatrix} = \begin{vmatrix} 0 & 1 \\ -1 & -1 \end{vmatrix}$$ …………………(xxvi)

The characteristics equation $|\lambda I - A| = 0$ has been solved, which gives $\lambda_1$and $\lambda_2$are negative and imaginary. So the proposed nonlinear model of cardiac muscle is asymptotically stable. Phase portrait of the proposed model is given in the following figure 9.

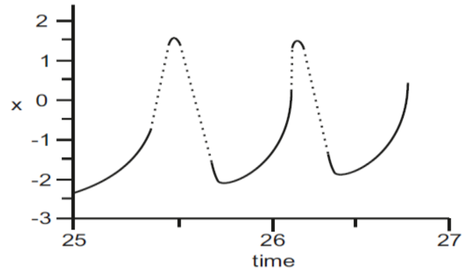

Figure 9: Phase portrait of the proposed cardiac muscle model

VII. CONCLUSION

The nature or input output characteristics of cardiac muscle is not linear rather nonlinear. In practical the transportation delay (non-zero reaction time) or lag phase of cardiac muscle plays an important role for nonlinearity. The range of transportation delay for which the system is stable has been calculated here to ensure the presence of dead zone type nonlinearity in cardiac muscle. The describing function technique is used here to analyses the nonlinearities. A converging stable limit cycle has been found after the analysis. Finally,lyapnuov stability theorem is applied on our proposed nonlinear model and it has been observed that the system is asymptotically stable in the sense of lyapnuov as the system has a positive definite energy function and negative derivative of energy function is also positive. Phase portrait has also been verified after finding the roots of the characteristics equation of which will be very much helpful for future research work.

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