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An Application of Pade Approximation and PID Tuning Technique to Improve the System Performance of Electric Ventricular Assist Device

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Abstract

The cardiac surgery is one of the significant threats in the recent time. The Electric Ventricular Assist Device (EVAD) is an initial step towards the development of artificial organs that used to stimulate the cardiovascular activity in the time of cardiac surgery.The transfer function of the above system was given in the previous research work as a exponential time delay function. It has been approximated by pade approximation method which is widely accepted and useful in practice as this approximation helps to create a polynomial form from exponential form over a small portion of its domain to reduce the errors as low as possible. To get higher performance, the device is brought with a PID controller that can define the process control architecture of the system. The traditional Ziegler Nichols (Z-N) is being used to design the controller which improves the system response. In this work, a comparative study is depicted in a standard approach through Control system aspects.

Keywords: *Electric Ventricular Assist Device (EVAD), Pade Approximation, Ziegler-Nichols(Z-N), PID Tuning.*

1. Introduction

The opening of the prosthetic research at national level started out nearly in 1964. The knowledge consequently gathered in the context of pertaining to the cardiac help. Medical clinic activity usually EVAD is a device for moving or compressing liquid for providing assistance heart activity in the human body and the blood circulation, particularly for the feeble hearted person. Fig 1 depicts the body implanted battery operated electric ventricular-assist device system [13]. In recent past EVDAs are using

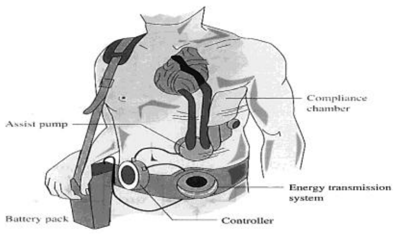

Fig1- Standard Model Approach for EVAD.

as a tool or process for destination therapy in last stage heart failure patients. Now with the recent advancement of VLSI technology moreover with the development of Nanotechnology together a composite function in a single chip or module is possible. In order to physically design a system, the performance analysis has to be optimized. The theoretical aspects of Ziegler-Nichols PID tuning [3] approach have been visualized in this study. Some other vital issue of control engineering, the Pade-approximation [7] is used to reduce the truncation errors, taken as a transfer function Electric Ventricular Assist Device (EVAD) [2], is computed in a finite expansion. Particularly PID shape will then again be optimized with the use of the steepest descent. Especially this manner has the end outcome of the above will exhibit a sustain oscillation.

2. An Overview of Control Model Analogy of EVDA System

The EVAD system has a single input and output for the applied motor voltage and the blood go with the flow ratio respectively. Mainly two predominant jobs executed by means of EVDA, it is adjusted the motor voltage to power the pusher plate and it modifications the EVDAs blood circulation or flows to fulfill the demand of the body's cardiac output. Varying the EVADs beat rate, the blood drift controller adjusts the blood flow. Richard C. Dorf et al. the EVAD machine with the manage knowledge sharing book entitled Modern Control System is regarded general machine function [10].

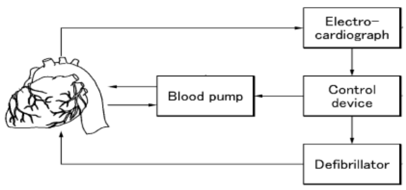

Fig 2.-.Block Representation of Ventricular Assist Device

In 2014 a ventricular assist device was patented shown in fig. no 2 that connected with electrodes and responsible for smooth blood flow [13]. The motor, pump, and blood circulation can be demonstrated with the aid of a time extend with maximum time T= 1 sec. The goal is to accomplish a step response with much less than 5% consistent country error and less than 10% overshoot [11].

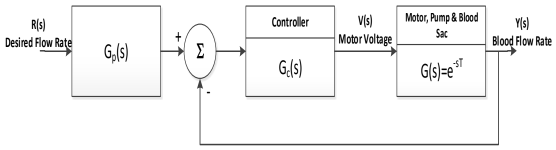

Fig-3. Standard Control Model Analogy

The fuzzy PID controller has some advantages including system robustness and advanced control precision compared with conventional PID controller [2][10].

3. Introducing Pade Approximation Technique towards EVAD System

The transfer function of Electric Ventricular Assist Device can be expressed by G(s) = $e^{-\tau s}$. But due no s-polynomials in numerator and denominator the function is irrational. In Control system engineering, the frequency response analysis of as a time delay function must be approximated in a form of the rational transfer function, otherwise the improvement of the system response will be a difficult task for a researcher. The most general wide accepted useful practice is the Pade Approximation. The rational approximation of f(x) on [a.b] is quotient of two polynomials pm(x) and qm(x) of degrees m and n, usually Rm, n(x).

$$R_{m,n}(x) = \frac{p_m(x)}{q_n(x)}\ for\ a \le x \le b \text{……..(1)}$$

The method of Padé approximation requires that the f(x) and its derivative must be continuous at x =0. The most reason to choice arbitrary x =0 is to make simpler manipulation and secondly a change of variable can be shift the calculation over the interval that contains zero. Consider a function $f(s) = c_0 + c_1 s + c_2 s^2 + \cdots$ and the rational function Rm, n (x) of polynomials of S as m ≤x ≤n is said to be Padé approximant of f(s), if and only if the first (m+n) terms of the power series expansions of f(s) and Rm ,n (x) are identical. For the function f(s) can be approximated with following Padé approximant [11].

$$R_{m,n}(x) = \frac{p_m(x)}{q_n(x)} = \frac{a_0+a_1s+a_2s^2+\cdots+a_{n-1}s^{n-1}}{b_0+b_1s+b_2s^2+\cdots+b_{n-1}s^{n-1}+s^n}\text{(2)}$$

It becomes apparent to the following set of relation

$$a_0 = b_0c_0 \text{ …. (3)}$$

$$a_1 = b_0c_1 + b_1c_0\text{…..(4)}$$

$$a_{n-1} = b_0c_{n-1} + b_1c_{n-2} + \cdots + b_{n-1}c_0\text{…….(5)}$$

Once the co-efficient $c_j, j = 0,1,2\ldots$ are found and $c_j = (-1)^j a_{j+2,1}$ the full model,

$$G(s) = \frac{d_0+d_1s+d_2s^2+\cdots+d_{n-1}s^{n-1}}{e_0+e_1s+e_2s^2+\cdots+e_{n-1}s^{n-1}+e_ns^n}\text{……..(6)}$$

This approximation method leads rational approximation of time delay function $e^{-\tau s}$ and also minimizes the truncation errors in a finite series expansion. The function $e^{-\tau s}$ can be expressed as given below.

$$e^{-\tau s} \approx \sum_{i=0}^{m+n}(-1)^i\frac{(\tau s)^i}{i!} = \frac{\sum_{i=0}^{m}p_i(\tau s)^i}{\sum_{i=0}^{n}q_i(\tau s)^i}\text{ …..(7)}$$

The important feature of this expansion has no restriction on degrees m and n in polynomials. The coefficients p_i and q_i can be chosen as follows for i=0,1,2….n. and for m=n,

$$\left.\begin{aligned} p_i &= (-1)^i\frac{(2n-i)!n!}{(2n)!i!(n-i)!} \\ q_i &= \frac{(2n-i)!n!}{(2n)!i!(n-i)!}\end{aligned}\right\}\text{ ……..(8)}$$

$$\left.\begin{aligned} p_i &= (-1)^i\frac{(m+n-i)!m!}{(m+n)!i!(m-i)!}, i=0,1,2\ldots m \\ q_i &= \frac{(m+n-i)!n!}{(m+n)!i!(n-i)!}, i=0,1,2\ldots n\end{aligned}\right\}\text{ …….(9)}$$

Now it is very important to determine the approximation polynomials so that the transfer function $e^{-\tau s}$ must be simple in realization, robust and optimized. The polynomials can be approximated for $R_{n,n}(x)$ from (9) is given below.

$$e^{-\tau s} = \frac{1-k_1s+k_2s^2-k_3s^3+\cdots\pm k_ns^n}{1+k_1s+k_2s^2+k_3s^3+\cdots+k_ns^n}\text{ …….(10)}$$

Where n is the order of the approximation and the coefficients k_i are the functions of n.

Table I. The Values of k For The Orders of n.

$\boldsymbol{n} = 1$	$\boldsymbol{n} = 2$
$\boldsymbol{k_1} = \frac{\tau}{2}$, other $\boldsymbol{k_i} = 0$	$\boldsymbol{k_1} = \frac{\tau}{2}$, $\boldsymbol{k_2} = \frac{\tau^2}{12}$, other $\boldsymbol{k_i} = 0$

To obtain a simple and optimal choice of transfer function, the 2nd order Padé approximation (n =2) is taken as referred in equation (10), $H_{pade}(s)$ has been formulated as follows.

$$H_{pade}(s) = \frac{1 - k_1 s + k_2 s^2}{1 + k_1 s + k_2 s^2} = \frac{1 - \frac{\tau}{2}s + \frac{\tau^2}{12}s^2}{1 + \frac{\tau}{2}s + \frac{\tau^2}{12}s^2}$$

$$= \frac{\tau^2 s^2 - 6\tau s + 12}{\tau^2 s^2 + 6\tau s + 12} \;\ldots\ldots\ldots\ldots(11)$$

To generate Padé approximated exact model as EVAD transfer function [17][20],step responses are taken and depicted below.

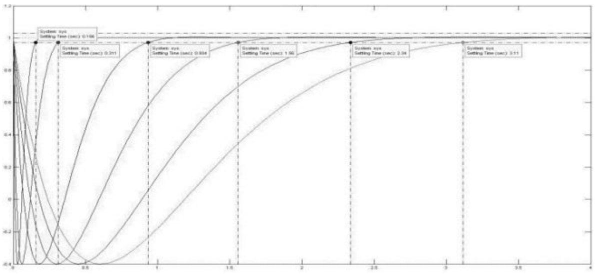

Figure 4. Step Response for realization of transfer function with time delay between $0.1 \leq T \leq 2.0$.

For different values of τ,values of settling time is observed and tabulated below in table 2 for our proposed model.

Table 2. Settling Time With Different τ Value

τ	Settling Time (Sec)
2	3.11
1.5	2.34
1	1.56
.6	0.934
.2	0.311
.1	0.156

The comparative study shows that for τ=0.1 the approximated system has the least settling time of 0.156sec. So,

$$G_{pade}(s) = \frac{0.01S^2 - 0.6S + 12}{0.01S^2 + 0.6S + 12} \ldots\ldots\ldots\ldots\ldots..(12)$$

This is taken as the Padé approximated transfer function for EVAD system.

4. Implementation of Tuning Approach for Beneficial Performance of EVAD

The PID controller system has some added advantages like robustness, simplicity, versatile adaptability and multiple degrees of freedom performance approach to the control system. Some recent study depicted [4] [5]that the PID controlling system is not properly tuned for the systematic control process. In addition to this, the PID control system does not guarantee the optimal control of a system [9]. PID controller can be designed through Zigler-Niclos method. Tuning method for the basic or base PID control is usually known as Zigler-Niclos tuning rule. The proportional gain Kp Integral time Ti,and Derivative time Td .These three above factors determined controllers when combined together can be expressed by the following transfer function[13].

$$G_c(s) = K_p\left(1 + \frac{1}{T_i s} + T_d s\right)\ldots\ldots..(13)$$

4.1 Steps to design PID Controller by using Ziegler–Nichols Tuning Approach

Initially $T_i = \infty$ and $T_d = 0$ is set is set by using proportional control action only, whereas Kp can be increased up to critical value Kcr, where output shows sustain oscillations. The above parameters according to the formula are tabulated below[1].

Table 3- Recommended PID Value Settings FOR Z-N Tunin

Type of Controller	Kp	Ti	Td
P	0.5 Kcr	∝	0
PI	0.45Kcr	1/1.2Pcr	0
PID	0.6Kcr	0.5Pcr	0.125Pcr

PID controller tuned by the Ziegler – Nichols rules for equation (13) gives

$$G_c(s) = K_p\left(1 + \frac{1}{T_i s} + T_d s\right).$$

$$= 0.6K_{cr}\left(1 + \frac{1}{0.5P_{cr}s} + 0.125P_{cr}s\right)\ldots\ldots(14)$$

The root locus method can be used to find out the critical gain Kcr and frequency of sustained oscillation w_{cr} if the system has a known mathematical model, where $\frac{2\pi}{\omega_{cr}} = P_{cr}$.

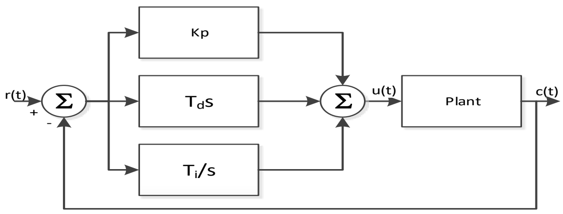

Figure 5. Z-N Base close loop controller model

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4.2 Steps Ziegler–Nichols Tuning Approach for Electric Ventricular Assist Device

The approximated open loop transfer function for EVAD system without tuning is refer to equation (12) is given below.

$G_{pade}(s) = \frac{s^2-60s+1200}{s^2+60s+1200}$.........(15)

Addition of pole to a linear time invariant system has the effect of pulling the root locus to the right (jω axis) making the system less stable. The response of a system can be determined by the location of pole .Though addition of pole makes a system less stables it is required for a system to increase the type of the system which reduces the steady state error. Except first order system all other system exhibits' oscillation. As addition of pole at origin to a system increases order of the system, oscillation increases and makes the output towards undesired value.

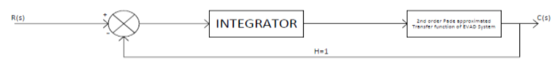

Figure 6 Represents Addition of pole in series

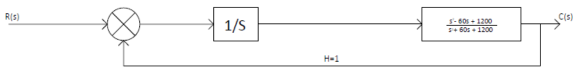

Figure 7 Represents Pole addition by an integrator with Pade approximated transfer function

In this work Pade approximated transfer function is connected with an integrator in series for providing additional pole.So the transfer function will become

$$G_{pade}(s) = \frac{s^2-60s+1200}{s^3+60s^2+1200s}..........(16)$$

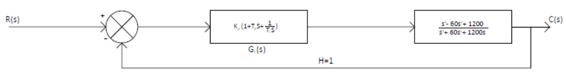

Figure 8 Represents addition of controller (Z-N tuned)with Pade approximated transfer function

By Ziegler- Nichols Tuning Method, closed loop transfer function with tuning [8][12] can be represented as follows

$$\frac{K_P}{s^3+60s^2+1200s+K_P}.............(17)$$

[Setting Ti = Td = 0] Now Routh stability criteria are to be utilized to locate the value of kp, that makes the device marginally stable. The characteristic equation [9]for the closed loop is given by $s^3+60s^2+1200s+K_P$ =0 .

s^3	1	1200
s^2	60	K_P
s^1	$\frac{[60\times(1200)-kp)]}{60}$	0
s^0	K_P	0

To find the critical gain (K_{cr}) of the system the s^1 row is made to zero. Thus, $\frac{72000-60K_P}{60} \geq 0$.

From the above condition, the value of has been calculated as K_p = 1200.Hence,K_p = K_{cr} = critical gain = 1200.Thus with K_P set equal to K_{cr} and the characteristic equation is given as follows.The auxiliary equation can be written from the R-H array as follows.

$60s^2 + K_p = 0$.........(18)

Putting the value of K_p =1200, in equation(5) we get

$60s^2 +1200 = 0$

$s^2 = -\frac{60}{1200} = -0.05$

As it is known s = jω , the equation can be replaced with the value of s. So the equation becomes

$(j\omega)^2 = -0.05$

$-\omega^2 = -0.05$.

$\omega=0.23$...............(19)

This ω is called ω_{cr}.

Now calculating $P_{cr} = \frac{2\pi}{\omega_{cr}} = \frac{2\pi}{0.23} = 27$.

According to Z-N tuning rule we can calculate the value of K_p, T_i, T_d using the values of K_{cr} & P_{cr}.

$K_P = 0.6K_{cr} = 720$........... (20)

$T_i= 0.5P_{cr} = 13.5$.............(21)

$T_d = 0.125P_{cr} = 6.75$.........(22)

As the value of K_p, T_i, T_d has been calculated, the transfer function of the PID controller (15) can also be calculated using as Gc(s) as follows.

$$Gc(s) = K_p\left(1 + T_d s + \frac{1}{T_i s}\right)$$

$$= 1200\left(1 + 6.75s + \frac{1}{13.5 s}\right)$$

$$= 1200\left(1 + \frac{1}{0.15s} + 0.07s\right)............. (23)$$

4.3 Simulation Result of the Tuned Process

Simulation result of tuned process considering second order approximation is shown below.

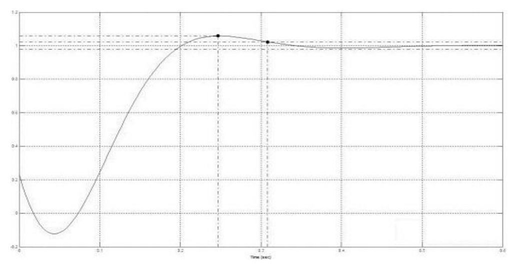

Figure 9. Response of the PID tuned EDAV system with τ=0.1.

It is observed by studying the response and stability criterion of the system that after tuning i.e., the closed loop configuration or the tuned EVAD system

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does not offer required performance and the system is being conditionally stable. So the 2nd order approximation of e−$^{\tau s}$ as referred to (12) cannot be granted as EVAD transfer function. To ensure on this conclusion the same iteration is done with T= 0.2scc. and the test leads an unsatisfactory outcome again. It is also observed By studying the response of Pade approximation for time delay or dead time e−$^{\tau s}$ [6], that the 3rd order approximation of Rm;n (x) system as referred to (12) is better responsive and more optimized than the 2nd approximation in the open loop condition. So the 2nd order approximation of $e^{-\tau s}$ as referred to (12) cannot be granted as EVAD transfer function. To ensure on this conclusion the same iteration is done with T=0.2 and the test leads an unsatisfactory outcome again. By studying the response of Padé approximation for time delay or dead time $e^{-\tau s}$ [10], it is observed that rather than the 2nd order approximation the 3rd order approximant of $R_{n,n}(x)$ as referred to (12) has a better response and the system is more optimized in open loop condition. The transfer function does response with least settling time with optimal overshoot limits on the same value of τ.

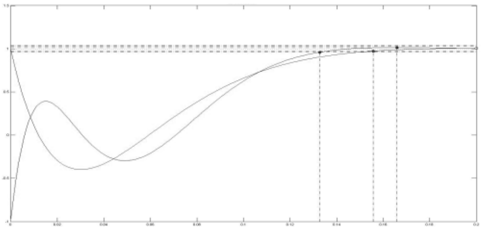

Figure 10. Step Response of 2nd and 3rd order Padé approximated $e^{-\tau s}$ for τ=0.1

4.4 Iterating Z-N Tuning Approach for PID controller on 3rd order approximated EVAD Transfer Function

As considered τ=0.1, the new transfer function of the EVAD system becomes as referred to (12) –

$$G_{pade}(s) = \frac{-0.001s^3+0.12S^2-6S+120}{0.001s^3+0.12S^2+6S+120} \quad \text{....……..(24)}$$

When pade approximated transfer function is connected with an integrator in series for providing additional pole,the transfer function will become

$$G_{pade}(s) = \frac{-0.001s^3+0.12S^2-6S+120}{0.001s^4+0.12S^3+6S^2+120s} \quad \text{………(25)}$$

Using close loop Z-N Tuning method for PID Controller designing –

$$\frac{K_P}{0.001s^4+0.12S^3+6S^2+120s+K_P} \quad \text{…….(26)}$$

The characteristic equation for the closed-loop system is given below

$0.001s^4 + 0.12S^3 + 6S^2 + 120s + K_P = 0$…….. (27)

Following the same procedure of Z-N tuning rule, Gc(s) has been evaluated and given as follows

$G_c(s) = 967\left(1 + \frac{1}{0.14s} + 0.77s\right)$…………… (28)

Simulation result of tuned process considering second order approximation is shown below.

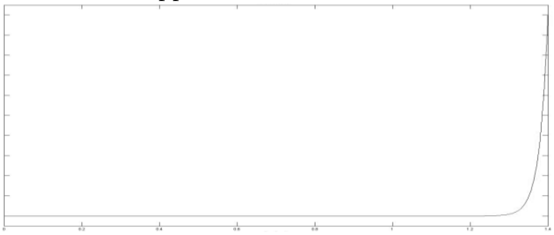

Figure 11. Response of PID tuned 3rd order EDAV system with $R_{n,n}(x)$ at τ=0.1.

The observation concludes with confirmation that the newly designed 3rd ordered Padé approximated model of EVAD with $R_{n,n}(x)$ polynomials does not converge the needs.The objective is to develop an optimal transfer function for the EVAD system and hence design the PID controller for close loop stable operation. To make simple and rationalize solution for EVAD transfer function the polynomials are chosen for Padé approximation of e$^{-\tau s}$ as (10) for the first test. It is observed that the approximation is failed to commit the need for the both cases of order 2 and 3.Now to find the optimized transfer function for EVAD which can meet the all needs and also stable. Let find the polynomials for the approximation $R_{m,n}(x)$ from (11) for e$^{-\tau s}$. But for the all cases for $m = 1,2$ and $n = 2,3$ the tuned system doesn't converge to give results in permissible range.

Table 4. Transfer Function $R_{m,n}(x)$ Padé Approximant of e$^{-\tau s}$

Order	$R_{m,n}(x)$
$m = 1, n = 2$	$\frac{-2(\tau s)+6}{(\tau s)^2+4\tau s+6}$
$m = 1, n = 3$	$\frac{-25(\tau s)+100}{4(\tau s)^3+25(\tau s)^2+75\tau s+100}$
$m = 2, n = 3$	$\frac{3(\tau s)^2-24(\tau s)+60}{(\tau s)^3+9(\tau s)^2+36\tau s+60}$

For each test of above transfer functions with different values of m and n. The close loop system response doesn't converge and hence the systems are not stable. Finally an optimal solution is found by approximating the same polynomial of $R_{m,n}(x)$ as m = 0 and n = 3 for Padéd approximation of transfer function e−τs. The tuned system is not stable only, it also leads some important conclusions with

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parameter ranges so that the design can be said as most optimized simple EVAD one.

4.5 Optimized Padéd Approximated Closed Loop EVAD with Ziegler–Nichols PID Tuning

The Padéd approximated transfer function for time delay function of EVAD $e^{-\tau s}$ is obtained here by putting the value of $m = 0$ and $n = 2$ & 3 for 2nd order and 3rd order respectively in the equation (10).

$$e^{-\tau s} = R_{m,n}(x) = \frac{1}{0.25(\tau s)^2+0.75\tau s+1}\ for\ m = 0, n = 2 \ldots(28)$$

$$= \frac{1}{0.4(\tau s)^3+0.25(\tau s)^2+0.75\tau s+1}\ for\ m = 0, n = 3 \ldots\ldots.(29)$$

These newly approximated transfer function models are test simultaneously to take the optimal decision for EVAD choice to meet all needs. The iteration is started with same value of τ=0.1.

$$G_{pade}(s) = \frac{1}{0.0025s^2+0.075s+1} \ldots\ldots\ldots(30)$$

$$= \frac{1}{0.00004s^3+0.0025s^2+0.075s+1} \ldots\ldots\ldots(31)$$

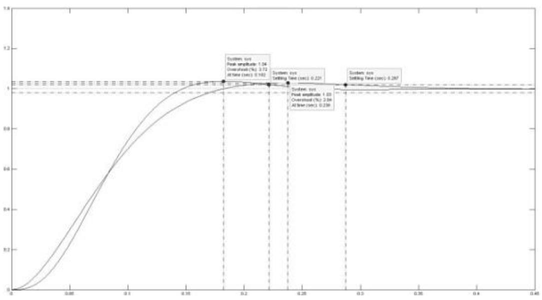

Fig. 12. Step Response of EVAD Transfer Function (30) and (31) with τ=0.1

The open loop step response in Fig. 8 shows that the settling time of newly computed transfer functions are increased slightly by 0.065sec for 2nd order and by 0.154sec for 3rd order approximations along with the overshoots values.

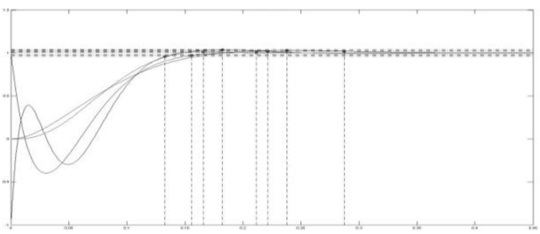

Figure 13. Step Response of examined EVAD transfer function $e^{-\tau s}$ as approximated $R_{2,2}(x), R_{3,3}(x), R_{0,2}(x), R_{0,3}(x)$ for τ=0.1.

So, for the ultimate design, the PID controller is computed for the both approximated function as referred to equations (30) and (31). To design the controller with Z-N based approach the same iteration steps are used as earlier to find the Z-N coefficients. Table 5 shows thee Z-N coefficient for approximated EVAD system.

Table 5: Z-N Coefficients for EVAD Approximated As $R_{0,2}(x), R_{0,3}(x)$

Z-N Coefficients	$R_{0,2}(x) = \frac{1}{0.0025s^2+0.075s+1}$	$R_{0,3}(x) = \frac{1}{0.00004s^3+0.0025s^2+0.075s+1}$
K_{cr}	**30**	**3.68**
ω	**111.35**	**20**
P_{cr}	**0.05**	**0.31**
K_P	**18**	**2.2**
T_i	**0.025**	**0.15**
T_d	**0.006**	**0.03**
$G_c(s)$	$\frac{0.108s^2+18s+720}{s}$	$\frac{0.06s^2+2.2s+14.7}{s}$

5. Results and Discussion

The observing the simulated response of the approximation $R_{0,2}(x)$, $R_{0,3}(x)$ in Fig. 10, it is being a conclusion that both of the tuned models are absolute stable with suitable parameter ranges for realization. Even the 2nd order approximation has the least settling time of 0.246s whereas the other has 0.477s. But taking the overshoot criterion in mind, the 2nd order approximation fails to satisfy that condition. In other words, the overshoot limit is not in permissible range of below 10% whereas the 3rd order approximation is satisfying this criterion about to slightly more than 1% which can be granted as absolute for an EVAD system with settling time within the permissible range of below 0.8s assumed for single pulse of normal heart beat rate.

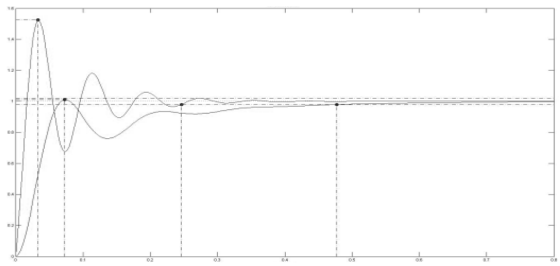

Figure 14. Step Response of Tuned EVAD for $R_{0,2}(x), R_{0,3}(x)$ for τ=0.1

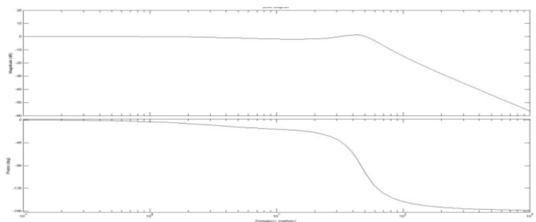

Figure 15. Bode Diagram of 3rd ordered Tuned EVAD Mode

It also determined from the study on stability criterion of the system is that the system is absolutely stable and the gain margin of the system is infinite and phase margin 73.1° at 50.9 rad/sec. To verify and conclude the stability factor of the system with other control theory aspects, the controllability and observe ability matrix of the system can be evaluated from the state space representation of the system

.

$$A = \begin{bmatrix} -0.0006 & -0.0338 & -0.8000 & -3.6750 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} \qquad C = \begin{bmatrix} 0 & 0.015 & 0.55 & 3.675 \end{bmatrix}$$

The Rank of this controllability matrix is also 4.After observation and from the simulative study, it is concluded that the 3rd order Padéd approximation of $e^{-\tau s}$ with polynomial settings of $R_{0,3}(x)$ has the best fitness outcomes for EVAD transfer function realization.

6. Conclusion

The primary model for the EVAD device had already been established in previous research work. The Pade approximation method is one of the best approximation method which gives a good mathematical approximation for the machine configuration and simulation. Here this approximation helps to create a polynomial form of system transfer function from its given exponential form used in previous research work and over a small portion of its domain ,it reduces the errors as low as possible. The numerous things with this EVDA system had already been modified by the researchers in different way. The optimization technique has also been applied by some researcher with the implementation using control analogy. In this research work, a PID controller has been introduced using Z-N tuning rule in series with the EVAD system for the improvement of system response. By doing repeated simulation of the system considering different order of polynomial, optimum value of reset time is selected for the proposed design and it is found that, system is controllable and also observable for the optimized value. Finally, this paper proposed a better method introducing Pade approximation technique along with Z-N tuning rule to improve the overall system performance of EVAD system.

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